NUREG/CR–5631
PNL–7445
Rev. 2

Contribution of Maternal Radionuclide Burdens to Prenatal Radiation Doses

Prepared by
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Operated by
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NUREG/CR-5631
PNL-7445
Rev. 2

Contribution of Maternal Radionuclide Burdens to Prenatal Radiation Doses

Manuscript Completed: April 1996
Date Published: May 1996

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UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

May 17, 1996

FOREWORD

The Nuclear Regulatory Commission (NRC) has sponsored a study designed to improve the understanding of the contribution of maternal radionuclide burdens to prenatal radiation exposure. In March 1992 the NRC published Revision 1 to NUREG/CR-5631, "Contribution of Maternal Radionuclide Burdens to Prenatal Radiation Doses," which provided a method for calculating embryo/fetus dose resulting from radionuclide content in maternal blood.

The recommendations and methods described in Revision 1 of NUREG/CR-5631 served, to a large extent, as the basis for Regulatory Guide 8.36 "Radiation Dose to Embryo/Fetus," published in July 1992. In October 1993, the NRC published Addendum 1 to NUREG/CR-5631. That addendum was developed to facilitate dosimetric assessments in operational radiation protection situations. The addendum provided a method to relate embryo/fetus doses to chronic or repeated intakes, expressed in terms of fractions or multiples of Annual Limits on Intake (ALI), during pregnancy and to preexisting body burdens.

As part of NRC's sponsored study, Pacific Northwest Laboratory (PNL), issued in November 1993 a report entitled "Contribution of Maternal Radionuclide Burden to Prenatal Radiation Doses; Dose to the Embryo/Fetus from selected Radiopharmaceuticals - Preliminary Recommendations," PNL-8977. That report was prepared to provide preliminary information for determining absorbed doses to the embryo/fetus from selected NRC regulated radiopharmaceuticals.

The current Revision 2 of NUREG/CR-5631 incorporates and expands the previously published reports (NUREG/CR-5631, Rev. 1; Addendum 1 to NUREG/CR-5631 and the PNL-8977 report). These reports are superseded. The present document addresses additional radionuclides, uses more up-to-date biokinetic models and presents wider array of dosimetric tables.

It is possible that publication of Revision 2 of NUREG/CR-5631 will lead to revision of Regulatory Guide 8.36. Until such time, however, the July 1992 edition of Regulatory Guide 8.36 remains in effect.

NUREG/CR-5631, Revision 2 is not a substitute for NRC regulations, and compliance is not required. The approaches and/or methods described in this NUREG are provided for information only. Publication of this report does not necessarily constitute NRC approval or agreement with the information contained herein.

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Office of Nuclear Regulatory Research

ABSTRACT

This report describes approaches to calculating and expressing radiation doses to the embryo/fetus from internal radionuclides. Information was obtained for selected, occupationally significant radioelements that provide a spectrum of metabolic and dosimetric characteristics. Evaluations are also presented for inhaled inert gases and for selected radiopharmaceuticals. Fractional placental transfer and/or ratios of concentration in the embryo/fetus to that in the woman were calculated for these materials. The ratios were integrated with data from biokinetic transfer models to estimate radioactivity levels in the embryo/fetus as a function of stage of pregnancy and time after entry into the transfer compartment or blood of the pregnant woman. These results are given as tables of deposition and retention in the embryo/fetus as a function of gestational age at exposure and elapsed time following exposure.

Methodologies described by MIRD were extended to formalize and describe details for calculating radiation absorbed doses to the embryo/fetus. Calculations were performed using a model situation that assumed a single injection of 1 μCi into a woman's blood; independent calculations were performed for administration at successive months of pregnancy. This approach accommodated the stage dependence of geometric relationships and biological behaviors of radionuclides in simple chemical forms. Gestational-stage-dependent dosimetric tabulations are given together with tables of correlations and relationships. Generalized surrogate dose factors and categorizations are provided in the report to provide for use in operational radiological protection situations.

These approaches to calculation yield radiation absorbed doses that can be converted to dose equivalent by multiplication by quality factor. Dose equivalent is the most common quantity for stating prenatal dose limits in the United States and is appropriate for the types of effect that are usually associated with prenatal exposure. If it is desired to obtain alternatives for other purposes, this value can be multiplied by appropriate weighting factors.

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EXECUTIVE SUMMARY

International concern about the irradiation of embryos and fetuses has led to ongoing efforts to develop recommendations and draft regulations to limit the exposure of the embryo/fetus to radioactive materials. Recommendations for restricting prenatal dose often have been accompanied by comments regarding the difficulties associated with calculating prenatal radiation doses from internally deposited radionuclides and the inadequate quantitative information about prenatal radionuclide concentrations and placental transfer and kinetics. This project was undertaken to develop recommendations to the U.S. Nuclear Regulatory Commission (NRC) concerning the calculation of radiation dose to the embryo/fetus from internal radionuclides.

In preparing this report, staff of the Pacific Northwest National Laboratory have assembled the available literature, analyzed and tabulated data on placental transfer and concentrations in the embryo/fetus and pregnant woman, determined ways to estimate prenatal radioactivity levels from minimal information, and developed dosimetric approaches for calculating radiation absorbed doses to the embryo or fetus from incorporated radionuclides. This report reviews the current status of our approaches to these issues and discusses the applicability of expressions that have been proposed for stating radiation doses to the conceptus from deposited radionuclides. The appendices provide an array of calculations and tabulations of dosimetric factors and radiation doses.

Two types of approaches could be used to estimate concentrations or activities of radionuclides in the embryo/fetus and to calculate radiation absorbed doses. When combined, these approaches can provide complementary analytical and dosimetric information. When minimal information is available, the most convenient approach is to use measured or extrapolated ratios of concentrations in the embryo/fetus to those in the pregnant animal or woman. These ratios are more meaningful after accounting for fetal growth and thus dilution of radionuclide concentration. Another approach is to estimate fractional transfer from maternal blood to the embryo/fetus, analyzing transfer kinetics and patterns to the conceptus according to stages of pregnancy, route of intake by the pregnant individual, and time after intake or placental transfer.

Our interim recommendations were based on biological data for a selected set of radionuclides that were expected to be of greatest significance for prenatal exposure in the work environment. These materials, which were referred to as the "priority radionuclides," included tritium and carbon in typical organic and inorganic forms, cobalt in inorganic form and as vitamin B-12, strontium, ruthenium, iodine, cesium and plutonium. These widely available elements and elemental forms provided a reasonable spectrum of metabolic characteristics. Substantial comparative information was available for many of them in human and animal pregnancies, which facilitated analyses.

In this report, the data for the priority radionuclides were used as the primary basis for developing approaches to calculations of concentrations and doses for the embryo/fetus. In response to suggestions, the metabolic models for these materials have been expanded and more isotopes were included. Additionally, this report includes radioelements and categories of materials such as radiopharmaceuticals and inert gases. Tables compare the biokinetic and dosimetric differences of biological and physical properties and present dose rates and monthly doses.

The MIRD methodologies were used as a basis for developing procedures to make direct calculations of concentrations in cases where dosimetric values were available and to calculate radiation absorbed doses based on such maternal radionuclide burdens.

The MIRD-based approaches have also been used to provide representative examples of the calculations and to prepare results for relevant radioisotopes and forms of additional materials. A burden of 1 μCi was assumed to be in the transfer compartment (blood) of the pregnant woman at the start of each month of gestation. Activity in the woman and the embryo/fetus at each successive month was estimated from the biological considerations and biokinetic behaviors. These values were used to select, or calculate when necessary, corresponding values of specific absorbed fractions and S-values (for self-dose) for each stage of gestation and the dose contribution from activity in the woman (allowing for the configuration and size of the embryo/fetus and woman throughout pregnancy).

Application of these methodologies for determining dose to the embryo/fetus is limited for radioelements about which there is no information on placental transfer and biokinetics. The suggested approach to approximation is to use the sum of the self-dose to the uterus or uterine contents, if available, plus the dose from radioactivity in the pregnant woman; these could be based on published geometrical models determined for specific gestational stages.

The approaches to calculation suggested in this report yield radiation absorbed dose. For some tabulations and comparisons, values of radiation absorbed dose have been multiplied by quality factors to convert to dose equivalent. This quantity is used in the United States for regulatory statement of prenatal dose limits from radiation, including radionuclides, and is appropriate for considering many of the types of effect commonly associated with prenatal irradiation. Some have proposed that radiation protection considerations might be best met if prenatal dose limits were stated in terms of effective dose or comparable expressions. Because of critical limitations in our knowledge, it seems advisable to defer use of derived quantities until further information becomes available.

PREFACE

This report expands upon the previous interim recommendations and report addendum published by the Nuclear Regulatory Commission. In particular, this report addresses additional radionuclides and a wider array of biokinetic and dosimetric tables. The useful comments and suggestions received have facilitated revisions that have made the document more acceptable and useful.

As in previous versions, most numerical information is presented in tables in appendices. This approach allows future calculations and findings to be easily made available. Biokinetic and dosimetric information have been integrated and calculations enhanced. Subsequent analyses of information and calculated values may be disseminated as supplemental appendices or revisions to this document.

We are happy to have this opportunity to acknowledge the professional guidance and support provided by the NRC Project Manager, Shlomo S. Yaniv. The project and this report have benefited from his helpful scientific suggestions. We also thank our colleagues Richard J. Traub, Huei K. Meznarich, and Karla D. Thrall for their substantive scientific contributions; they were among the authors of prior versions. These contributions are incorporated, in part, in the present report. We are grateful for the helpful suggestions that members of the radiological protection community offered concerning the reports that presented preliminary and interim recommendations and other reports that are incorporated in this document. These contributions led to the revisions and expansions of content that form the basis for this comprehensive report.

Preparation of Section VII, which deals with radiopharmaceuticals, was facilitated through the cooperation of staff of the Radiation Internal Dose Information Center (RIDIC) of the Oak Ridge Institute for Science and Education (ORISE). This includes ongoing discussions with Evelyn E. Watson, who helped to select approaches for incorporating RIDIC biokinetic models for the adult and values from their dosimetric tables as well as the subsequent review of drafts of this section and of the whole report. Michael G. Stabin provided dosimetric tables; he and his graduate student, Joy R. Russell, sent advance copies of now-published tabulations that are quoted in that section of the report.

Appreciation is again extended to colleagues at the Pacific Northwest National Laboratory (PNNL), NRC staff, and investigators from other institutions who took time for personal discussions and to review drafts of the present report. In particular, we are grateful to Antone L. Brooks of PNNL for his technical review that identified items that have been corrected or revised in this version.

We thank A. Bertrand Brill, John W. Poston, and Evelyn E. Watson who reviewed the penultimate draft of the report and made helpful suggestions regarding presentation and discrepancies. Shlomo S. Yaniv and his colleagues at NRC also reviewed this draft and identified other areas for enhancement. Particular thanks are offered to James R. Weber for performing the technical editing of the final revision that attempted to incorporate the several changes suggested by these reviewers. The authors accept all responsibility for errors remaining after these efforts by others.

I. INTRODUCTION

A. Rationale and Need

This report describes evaluations that were performed in the project "Contribution of Maternal Radionuclide Burdens to Prenatal Radiation Doses" and presents recommendations that evolved from these evaluations. A major underlying consideration for initiation of the project was recognition of the radiosensitivity and unique responses that were associated with irradiation of the embryo or fetus. The project did not include evaluation of the specific effects associated with prenatal irradiation, nor did it address the basis for establishing dose limits or their appropriateness. A brief summary of the information involved in these considerations, which are the responsibility of others, is presented in later paragraphs of this section. Factors unique to exposure via internal radionuclides are emphasized to highlight the differences relative to expectations based on exposures via external beams.

The initial direction of efforts on the project was guided by an overt recognition that there had been inadequate utilization of available information. This increased the uncertainties about approaches for calculation of radiation doses that the human embryo or fetus would receive as a result of radioactive materials in the pregnant woman. Irrespective of the values that are established as dose limits, these uncertainties in dose determination lead to difficulties in defining appropriate operational procedures and in establishing meaningful regulations. The Pacific Northwest National Laboratory (PNNL) undertook this project to provide the Nuclear Regulatory Commission with specific types of dosimetric information that are considered to be useful in regulating and guiding the use of radionuclides in situations in which there is a possibility of radiation dose to the embryo/fetus.

B. Scope of Report

This report presents the composite results of our efforts to collate, analyze, and integrate available information concerning the placental transfer of radionuclides, to develop strategies to approximate their placental transfer, and to estimate their concentrations or the content of radioactivity in the embryo/fetus as a function of stage of gestation at exposure and time after exposure. Several alternative expressions for stating radiation doses to the human embryo or fetus from radionuclides in the pregnant woman have been examined. In particular, this effort has included developing recommendations concerning general methodologies for calculating prenatal doses from radionuclides, and using these methods to perform dose calculations and develop tabulations that are based on the placental transfer, metabolic, and dosimetric considerations that were developed.

Previous versions of the report described evolving approaches and results from the project. They were disseminated as drafts for comment and subsequently for use on an interim basis. This report is issued as Revision 2 of the same NUREG designation that identified previous revisions and addenda. Positive reinforcement as well as suggestions and reactions from the radiological protection community helped to form a basis for the contents and approaches of the present document, which includes information from previous versions.

In addition, subsequent efforts here and elsewhere have allowed inclusion of refined approaches as well as greater detail and/or sophistication to some analyses. These include revisions that are based on the recent availability of additional, broadened, or more accurate information and procedures. In particular, a commercial programming language, STELLA II®, was used for dynamic modeling. This language provided techniques for biokinetic approaches that enabled estimation of radioactivity in the embryo/fetus and the newborn relative to stage of gestation and time after administration.

The MIRDOSE computer program and code facilitated the radiation dose calculations. When appropriate, Version 3 (Stabin 1996) was used for the last series of calculations. The full array of Oak Ridge Pregnant-Woman Phantoms (Stabin et al. 1995a), also became available

during the final phases of preparation of tables of dose factors and provided an additional basis for verification of calculations. Keith F. Eckerman of Oak Ridge National Laboratory supplied electronic files on computer disk that provided the data used in ICRP Publications 30 and 56. These data files facilitated development of surrogates and estimation of postnatal doses associated with residual radioactivity in the newborn.

Increased detail and sophistication are among the major differences from previous versions of the report. Also of importance is inclusion of information and modification of some models, as based on information in ICRP Publications 56 and 67 (1989, 1993). Calculations of deposition and retention and of dose factors have been developed for a substantially increased array of radionuclides in general elemental forms or compounds, for additional classes of radionuclidic materials such as inert or noble gases, and for radiopharmaceuticals. It is important that the present report is to be regarded as an independent and more definitive document. Accordingly, no indications will be provided as to which text materials or tabulations are repeated or revised from prior versions or have been newly generated.

C. Background

Mammalian embryos and fetuses can be adversely affected by acute exposure to radiation at doses that do not produce overt effects in adults. Prenatal irradiation can result in intrauterine growth retardation, increased prenatal and postnatal mortality, and malformations or congenital deficits of central nervous system function. The likelihood of producing these various effects at a given level of dose are related to the specific stages of prenatal development during the period of exposure.

The intent and requirements of 10 CFR 20 are consistent with previous and concurrent regulatory guidance statements of the Nuclear Regulatory Commission as well as with recommendations of other national and international organizations. In general, these approaches involve limiting total radiation dose to the conceptus through 1) placing more stringent restrictions on exposure of declared pregnant women than on other members of the occupational population and 2) specifying that the allowable dose should not vary markedly from a uniform monthly rate throughout gestation.

Historically, this more restrictive limit was based on the potential for producing developmental abnormalities or carcinogenesis; this limit and its rationale are described in sequential versions of NRC Regulatory Guide 8.13 (NRC 1996). The evolution of the relevant concepts was reviewed in NCRP Report No. 53 (NCRP 1977b) among other documents, but the limit has long remained at a total of 500 mrem (5 mSv) to the embryo/fetus throughout gestation. Epidemiological evaluations were performed and dose-response relationships were analyzed for central nervous system function in Japanese offspring who had received atomic bomb irradiation during specific stages of gestation. Reports suggested that the response was linear and non-threshold although the relationship was not unanimously accepted (UNSCEAR 1986; NEA 1988). Resulting concern led the NCRP to recommend in their Report No. 91 (NCRP 1987) that the monthly permissible radiation dose should be no more than one-tenth of this total.

Tumor development following prenatal or neonatal exposure of experimental animals has been studied for external photons and for a limited number of internally deposited radioisotopes. The UNSCEAR (1986) calculated that the risk for mental retardation by prenatal irradiation was greater than that for carcinogenesis, but the question of carcinogenesis by prenatal radionuclide exposure presents special problems. Radionuclides for which perinatal carcinogenesis has been studied include hydrogen, carbon, strontium, iodine, and plutonium; these are among the nuclides that have been evaluated in this project. As a broad generalization, perinatal exposure of experimental animals to given radiation doses may produce a greater incidence than the same doses to adult animals (Sikov 1989).

Broader interpretation of the results of these studies illustrate some of the difficulties in deriving direct relation-

ships between maternal exposure to radionuclides and the resulting prenatal concentrations of radioactivity and radiation doses as well as the role of the metabolic impact of stage of gestation and associated inhomogeneities of radiation doses to fetal and neonatal tissues and differing effectiveness among particulate radiations.

When considered relative to exposures of short duration from external photon beams, the specific dose-effect relationships for various radionuclides differ among indices of early or prenatal effect, as well as for delayed embryo/fetal toxic effects, such as life shortening and oncogenesis. These relationships further change throughout progressive developmental stages, and interact with the well-known stage-dependent sensitivity differences (critical periods). Moreover, these are superimposed on dose-rate effectiveness factors associated with protraction of the radiation exposure from internal radionuclides, all of which can lead to apparent differences in responsiveness. Thus, the combined contributions of dosimetric factors and developmental considerations help explain the observations of stage-related differences in responses. These range through nuclide specificity in target organs and tissues, morphologic lesions, predominant tumor types, and sites at which tumors develop. These factors also bear on the question of appropriate approaches to determine and interpret doses to the embryo/fetus.

D. Concepts and Components of Radiation Dose to the Embryo/Fetus

1. Sources Contributing to Total Dose

As noted, concern about potential effects of exposures from sources external to the pregnant woman provided the initial stimulus for setting special limits for radiation doses to the embryo/fetus. Irradiation of the conceptus from such external sources can be terminated by discontinuing the generation of radiation, physically separating the woman from the source, or introducing shielding. Radionuclide intakes by a woman before or during pregnancy also may lead to deposition of radionuclides in the woman's body, and especially in certain organs, which may serve as persistent sources for irradiating the embryo and/or fetus. The radioisotopic materials may be transferred to and deposited in the embryo/fetus, resulting in internal irradiation. Both types of exposure from radionuclides sometimes continue for extended periods. In addition, there may be residual radioactivity in the child at the time of its birth, which can result in radiation exposure during postnatal life.

This project was originated to develop recommendations concerning determination of prenatal dose from maternal radionuclide burdens. Initial evaluations were restricted to this aspect of the problem and this emphasis has continued. Additional approaches that have become available to address prenatal dosimetry have facilitated the evaluation of the dose attributable to radionuclides in the embryo/fetus, or in the immediately surrounding placental and uterine tissues, and so these received special consideration. Brief consideration, however, has now been directed to dose contributions of the residual activity in the neonate.

It is necessary to include radiation doses from nuclides that are distributed throughout the body of the pregnant woman or contained in major organs or structures such as liver or bladder. Dosimetry of nuclides external to the uterus are essentially direct calculations, but may be complex in some situations. Together with the physical factors (presented herein or indicated in references), computation may be made from knowledge of the anatomy and physiology of the woman, dimensions and masses of the embryo, fetus, uterus, and nuclide disposition or activities with time and stage of gestation.

Neither the factors related to the intake of radioactivity external to the woman nor its contribution to radiation dose were included in most evaluations performed for this report. Rate of intake is a necessary aspect in the dosimetry of noble gases, however, and is considered in Section VI. Intake times and rates during operations also must be

evaluated for their relation to Annual Limits on Intake (ALI); these are described in Section VIII.

2. Components of Internal Dose

Estimating the placental transfer of radionuclides and resulting amounts in the embryo and fetus, compared to those in the pregnant woman, was a major part of this research. Procedures were developed for estimating exposure of the embryo/fetus from radionuclides deposited in the embryo/fetus or remaining in the tissues of the woman. These calculations provided values relating to energy deposition, which are expressed as radiation absorbed doses (rad or Gy).

For some considerations of radionuclide exposure, it may be useful to distinguish between the two general categories of biological deficits that can result from irradiation during gestation. One category involves early effects, such as malformations, intrauterine growth retardation, and congenital reduction of postnatal mental capacities that specifically result from exposure of the embryo/fetus. Such effects have been considered in setting special limits for exposure during gestation. The other category is the contribution of the prenatal irradiation to lifetime exposure, particularly in its long-term effects, including carcinogenesis. (The derivation, validity, and magnitude of the limits for either prenatal or cumulative exposure do not fall within the scope of this project.)

3. Expression of Prenatal Radiation Doses

Current recommendations and regulations of the NCRP and NRC for prenatal exposure limits are stated in terms of dose equivalent (rem or Sv), which accommodates differences among biological effectiveness of photons and some particulate radiations. Conversions are readily accomplished by multiplying absorbed dose values by appropriate quality factors (Q), which provides the corresponding values of dose equivalent. The values of Q for specific particles are established and occasionally revised; use of this approach accommodates any subsequent revisions in its value. Likewise, multiplication by radiation-weighting factors or tissue-weighting factors could be used if desired. However, these quality and weighting factors have not been validated for the responses by the conceptus that led to establishing of special dose limits.

Concepts that were developed for protecting adults from delayed or cumulative effects led to radiation exposure limits that have been expressed as complex dosimetric quantities, such as effective and committed dose equivalent. Suggestions that effective dose or effective dose equivalent might be used in stating prenatal radionuclide dose limits have certain merits. This addition is considered to be premature because the current lack of needed information does not permit acceptable approaches to be established for determining these quantities. The question warrants being addressed at a later date, however, when adequate information becomes available to calculate doses from a wider range of nuclides and isotopes to prenatal tissues and organs at relevant stages of gestation and to define dose-response relationships that will allow the assigning of weighting factors.

The suggested approaches and analyses lead to estimates of radionuclide content at birth following administration at the start of any given month of gestation. These calculated values are tabulated for the selected isotopes and forms of most radioelements at the start of each sequential gestational month and for the residual content at term.

Taken together, these considerations previously led us to offer the suggestion that exposure regulations should be expressed in terms of our best estimates of the absorbed dose and dose equivalent to the embryo or fetus. Our recommendations regarding modeling of biological behavior and application of physical factors used in calculations of dose have been and continue to be directed toward providing the least complex values.

E. Biological Considerations and Resulting Limitations

1. Extrapolations from Animal Data: Basis and Validity

Most available data regarding placental transfer to the human conceptus and the resulting radionuclide concentrations in the conceptus have been obtained following exposures to labeled metabolites or radiopharmaceuticals. Other data concerning radionuclides of occupational and environmental concern were obtained from radioanalyses of abortuses, stillbirths, neonatal decedents, and placentas. Interpretations are often clouded by uncertainties regarding the corresponding maternal body burden or exposure level. Additional information, primarily applicable to calculation of kinetics, has been obtained through in vitro perfusion studies using human placentas.

The limited breadth and depth of the human database makes it necessary to use data from studies of placental transfer and fetoplacental distribution in experimental animals despite uncertainties associated with extrapolation. These animal data range from values that are derived from toxicity studies, in which terminal measurements of fetoplacental concentrations were performed, to values obtained from sequences of deliberate, dynamic measurements, which provide a basis for calculating kinetic parameters. The latter types of study were directed at measuring concentrations in maternal blood and tissues throughout the placental structures and in tissues of the conceptus as a function of time after exposure.

Other studies have investigated transport processes and mechanisms and have examined factors that affect or modify placental transfer and fetoplacental distribution. There are important similarities and dissimilarities between the prenatal development and the placental structure and function of laboratory animals as compared to the human conceptus (Shepard 1980). Detailed comparisons of differences in their responses to irradiation are readily available (Sikov and Mahlum 1969, UNSCEAR 1986, Brent et al. 1987, NEA 1988).

2. Factors Confounding Extrapolations

a. Metabolism: The general aspects of mammalian gestation are remarkably similar among mammalian spe cies, but the developmental stages that are attained at specific elapsed fractions of the gestation period and the degree of maturity at birth differ greatly. Moreover, there are metabolic differences among prenatal, juvenile, and adult stages and among members of different species, which may affect transport, the rate of clearance from blood, and tissue deposition. As a consequence, the temporal patterns of amounts available for placental transfer and components of kinetic calculations may differ.

b. Litter size: In contrast to human pregnancies, in which a single fetus is the usual situation (monotocous), most of the animal species from which transfer and deposition data have been obtained bear litters consisting of multiple offspring (polytocous). In these species, the total mass of the fetuses or fetoplacental units relative to that of the pregnant animal tends to be much greater than in the human. The quantitative impact of this situation has not been evaluated in detail, but it appears that total stage-adjusted transfer to the products of conception is greater in polytocous than in monotocous pregnancies, but the concentration in each individual fetus or placenta is less.

c. Acute versus chronic exposure: Many of the data from animal studies were obtained following a single exposure to readily measurable amounts of activity. Despite applicable caveats, such experiments provide data that are primarily applicable to an accidental exposure of a pregnant woman or an administered radiopharmaceutical. Many human exposures, however, may involve repeated intakes of low levels of activity. In some instances, radioanalyses of human autopsy materials have resulted in calculated ratios of fetal to adult concentration that are greater than those that would be expected from animal data obtained after acute exposure. It appears that these differences may result from the contribution and/or

interaction of several factors, including mass effects, summation of the contributions of different time periods, available time for postexposure excretion, and kinetic and deposition differences relating to the metabolically different stages of gestation during the successive intakes.

3. Gestational-Stage-Dependence of Dose Factors

It should be noted that radiation exposures may be received from sources of radionuclides that are external to the woman; these radiation doses are not considered in this report, which is directed only to the radionuclides that enter the woman. The concepts of the resulting internal dosimetry must be evaluated relative to stage of gestation because of the quantitatively differing contributions by the major components of potential radiation dose to the embryo/fetus from radionuclide exposure. These components consist of exposure from internally deposited radionuclides throughout the pregnant woman, dose from radionuclides in her uterus, and especially from radionuclides that are deposited internal to the embryo/fetus. The tables of embryo/fetus dose factors and dose rates given in this report present the sum of doses from these sources, including the maternal contributions.

There are gestational-stage-related patterns of localization of certain radionuclides in tissues of the embryo/fetus as well as inhomogeneities of deposition. These can affect the quantitative and temporal patterns of placental transfer, influence total amounts of radioactivity that are transferred, and result in higher radiation doses to the tissues in which localized. The functional aspects will be given in Subsection II C that describes placental transfer and detailed examples for specific radioelements under biokinetics in Subsection IVB.

The above factors all can lead to differences among specific radioelements in radiation doses relative to gestational stage at the times of maternal exposure. Accordingly, relationships are most usefully and conveniently given as a series of gestation-stage-dependent dose factors that are expressed as dose rates (rad/h) and doses (rad) that are expected to result from introduction of unit dose (1 μCi) into the woman's transfer compartment.

F. Overview of the Report

It is expected that the report and the information will be utilized by readership with disparate backgrounds. Accordingly, brief overviews of needed concepts were summarized above and the following paragraphs will, as guideposts, note the contents and general order of presentation. The morphologic development of the embryo/fetus and concomitant changes in the woman will be described, with emphasis on the sizes and geometric relationships of structural components at successive stages and/or times of pregnancy. A brief overview of the accompanying nature and development of placental transfer and biological disposition in the embryo/fetus will also be presented.

Subsequent sections will review the general concepts involved in development-related dosimetry and will consider concepts that are most relevant to the exposure of the embryo/fetus. Because the report is especially directed toward radionuclides, it will give a formalized presentation of the physical concepts and methods used to establish radiation dose from the time of residence of the radioactivity, as based on the MIRD system. This will be followed by a detailed description of the concepts and approaches associated with estimation of stage-related content of radioactivity.

The report will examine the nature of maternal intakes of radioisotopes, with concentration on radioisotopes of elements of occupational, medical, and environmental significance. Descriptions of the selected elements will be presented sequentially by atomic number and will include reevaluation of those that were identified as "priority radionuclides." The information was used as a basis for developing analytical approaches and for providing illustrations for the efforts that led to interim recommendations. This grouping, which provided a general spectrum of metabolic and dosimetric characteristics,

includes inorganic and organic examples of tritium, carbon, and cobalt plus inorganic strontium, ruthenium, iodine, cesium, and plutonium. The greatest amount of comparative information tended to be available for these nuclides in human and animal pregnancies because of their properties and general availability in the work environment. These data are again presented, with enhancements, information, and analyses for additional radionuclides of importance to radiological protection.

Other than for noble gases, radioelements identified as being of interest are modeled first as primary and/or general radionuclidic compounds of interest. The approach is to describe general behavior and note major deviations for groups of compounds. Noble gases receive specific consideration in Section VI, with indications of their reactor-related or radiopharmaceutical relevance. Dosimetric approaches are developed in that section.

Radioelements that are used as radiopharmaceuticals are described in the general radionuclide section with tables of deposition and retention for one or more prototypic radioisotopes. Unique compounds, uses, and biological behaviors are described further in Section VII, Radiopharmaceuticals. Considerations applicable to development of tables of dose factors are given as well as comparisons with dose calculations by others. For example, inorganic and generic organic cobalt will appear in the general radionuclide section, but vitamin B-12 is considered primarily as a radiopharmaceutical.

The groupings of elements that are evaluated in this report are:

1 hydrogen and carbon, inorganic
2 hydrogen and carbon, organic
3 phosphorus
4 chromium
5 iron
6 cobalt
7 zinc
8 gallium
9 krypton
10 rubidium
11 strontium and yttrium
12 technetium
13 ruthenium
14 indium
15 iodine
16 xenon
17 cesium
18 cerium
19 osmium, iridium, and platinum
20 thallium
21 lead
22 bismuth
23 polonium
24 radon
25 radium
26 thorium
27 uranium
28 neptunium
29 plutonium
30 americium

II. DEVELOPMENTAL CONCEPTS AND INFORMATION

A. Overview

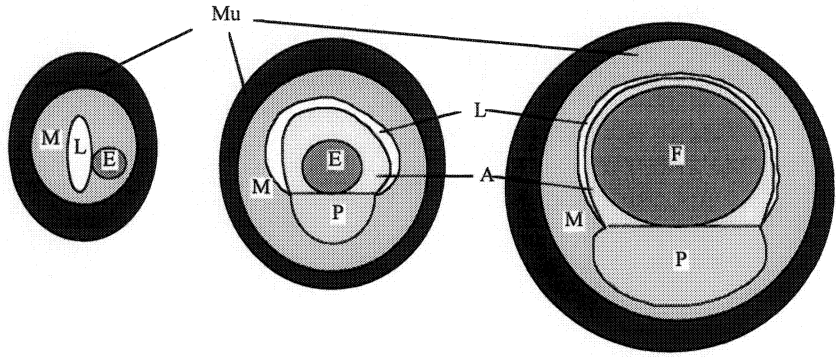
The term embryo/fetus is used as an encompassing expression in referring to prenatal stages in statements of exposure limits; this is often appropriate terminology for that purpose. It is important to distinguish between the embryo and the fetus when estimating radionuclide concentrations, performing dose calculations, or considering specific effects of prenatal irradiation.

Statements of gestational times in this report use the common convention that considers that gestation begins at the time of fertilization, which occurs at about 14 days after menses. The date of the last menses, however, is sometimes used as the reference point for stating time of pregnancy. The term embryo is used in reference to the earliest stages of development, prior to the time at which external characteristics make the conceptus recognizable as a member of the major taxonomic group to which it belongs. This transition occurs during the period between two and three months in the human conceptus, which is properly referred to as a fetus from that stage until birth. The following diagram (Figure 1), which is not to scale, shows the embryo, the early fetal stage, and the late fetus in relation to the uterus and supporting structures or adnexa. Dimensions deliberately have been omitted from the diagrams of Figure 1 to maintain their general nature.

B. Morphology and Growth

1. Developmental Stages

In most mammalian species, the ovum passes from the oviduct into the uterine lumen a few days after fertilization. Through a series of processes that begin at about 1 week, the ovum then implants in the mucosa of the uterus. The early embryo, or blastocyst as it is called at this stage, begins its internal development and initiates maternal responses that result in formation of the placenta and of related transfer and support structures.



Embryo	Transition: Embryo - Fetus	Later Fetus
E - Embryo	Mu - Muscle	P - Placenta
F - Fetus	M - Mucosa	A - Amniotic Fluid, within embryo/fetal membranes
	L - Uterine Lumen	

Figure 1. Diagrammatic representation of geometric relationships between the conceptus, supporting structures, and the uterus.

Radionuclide concentrations in the embryo prior to implantation and during early postimplantation stages are generally considered as being approximately equal to the average concentration in the uterus. Uterine muscle may have a radionuclide concentration that is different from the mucosa; energy from alpha and beta-emitters in muscle may not reach the embryo, which could decrease the effective concentration. It would be more accurate to use concentration in the uterine fluids or in the mucosa, rather than average through the uterus, but these values are rarely known.

Allowances are not generally made for possible concentration inhomogeneities throughout the early embryo. This ordinarily will not be a problem because the beta-emitters that have the greatest likelihood of inhomogeneous distribution are those with the most energetic emissions (see Subsection IV B). Calculations show that at early developmental stages, when the conceptus is approximated by a 0.1-cm-diameter sphere, beta particles of ^{3}H and ^{14}C will deposit more than 95% of emitted energy in the sphere, although this value falls to about 22% with the energetic beta particles of ^{32}P.

Thus, a straightforward approach to calculation may apply during early gestation. For beta-emitters, it will often be appropriate to regard the small developing embryo, with its extraembryonic trophoblastic structures, as being contained within a large mass of homogeneous concentration and to apply conventional calculational procedures. The anatomic relationships are such that, for photon emitters, the embryo can be regarded as a point in the center of a sphere that represents the uterus. S-factors that were developed in this project and by other various groups can be used to estimate absorbed dose (Elasser et al. 1986; Smith and Warner, 1976; Stabin et al. 1995).

The human conceptus is defined as a fetus during the second and third trimesters of gestation, and often during the last month of the first trimester. There are significant differences among species during these gestational stages. However, progressive histogenesis and growth are the characteristic processes in the human conceptus during this period. The human fetus, as well as those of almost all other mammalian species, is contained in the amniotic fluid and is surrounded by various fetal membranes and modified uterine structures. The fetus is nurtured via the closely located placenta, to which it is attached by the umbilical cord.

2. Geometry and Size

Dosimetric analyses have used geometric models and computer codes for internal dosimetry in the pregnant woman and conceptus that were reported by several groups of investigators. The most comprehensive series of publications, e.g., Watson and Stabin (1987), presented detailed models for 3 months of gestation. These models also serve as a fair approximation of morphology at 2 months, the stage at which the embryo has undergone sufficient transition to be considered a fetus, although linear dimensions and tissue masses are smaller. Their models for later stages of pregnancy (Davis et al. 1987) have been used in published dose estimates. Recently updated versions, such as the ORNL mathematical dosimetric phantoms (Stabin et al. 1995b), are incorporated into MIRDOSE 3 (Stabin 1996). These provide greater precision but do not invalidate previous dose estimates.

There have not been reported formal considerations of the dosimetric geometry of the conceptus in the period between mid-organogenesis and the fetal period. This does not greatly constrain the dosimetric approach, particularly since the models are most relevant to exposure from radioactivity throughout the pregnant woman.

Alternatively, tissue masses and dimensions are needed for biokinetic modeling. An internally consistent set of operational values was assembled using representative values from charts and tabulations in the literature. These include data from the foregoing references, equations and values obtained from ICRP Publication 23

(ICRP 1975), and information given in reports and textbooks relating to prenatal development. These sources provide adequate information to approximate the anatomy, dimensions, and masses of the pregnant woman and her embryo or fetus.

As will be discussed under dosimetric methodology, many of the methods for calculation described in this report, especially for self dose, requires the content of radioactivity rather than specific activity or concentration. Consequently, it often becomes necessary to calculate the activity in the embryo/fetus by means of ratios that use masses to adjust relative concentrations. The equation that is used for this purpose, which is described in Subsection III B, involves the mass of the embryo/fetus. For use in such calculations, the mass of the embryo/fetus and of the pregnant woman may be taken from Tables 1 and 2, respectively.

Linear distances in the pregnant uterus usually are relatively large compared to the path lengths of the beta particle. Generally, one would expect that the contribution to exposure of the fetus from photons would be mostly from radionuclides in both nearby and distant maternal organs. However, the primary contribution to the beta-radiation absorbed dose to the fetus is from its internal radionuclide content.

If total fetal activity were divided by its mass, the resulting values would be the concentrations used in traditional formulas for dose calculation, such as those described by Quimby and Feitelberg (1963). The fetal volume at this time is sufficiently large as to not require correction for unabsorbed beta particles, other than perhaps at its surface. Accurate assessment is obviously more complex than these generalities. The remainder of this document will provide details of approaches to calculations and of the component factors that are required for their implementation.

Table 1. Assumed Physical Characteristics of the Human Embryo/Fetus

Gestational Stage (days)	Length (cm)	Mass (g)	Semi-Major Axis (cm)	Semi-Minor Axis (cm)
30	0.4	0.35	0.2	0.2
60	3.3	10.7	1.7	0.9
90	10.6	71	5.3	1.1
120	18.9	276	9.5	1.9
150	26.8	617	13	2.7
180	33.7	1140	17	3.4
210	39.8	1951	20	4.1
240	45.1	2876	23	4.6
270	49.6	3471	25	5.1

Table 2. Assumed Mass of the Pregnant Woman at Various Times of Pregnancy

Stage of Gestation (days)	Female Mass (g)	Length (cm)	Mass (g)	Semi-Major Axis (cm)	Semi-Major Axis (cm)
0	52920	80	53000	5000	58000
30	52920	330	53250	5000	58250
60	52920	580	53500	5000	58500
90	52920	830	53750	5000	58750
120	52920	1190	54110	5000	59110
130	52920	1690	54610	5000	59610
180	52920	2420	55340	5000	60340
210	52920	3450	56370	5000	61370
240	52920	4920	57840	5000	62840
270	52920	7030	59950	5000	64950

C. Placental Transfer Concepts

Most approaches to prenatal radiation dosimetry require estimating the extent of transfer of radioactivity from the woman to the embryo/fetus via the placental structures. To provide a basis for initial considerations, the following provides a brief and simplified overview of placental transfer. Greater detail relating to the modeling will be given in following sections.

Activity usually must be in the blood of the pregnant woman to be available for transfer to the conceptus. Except during the earliest developmental stages when this is appreciable diffusion to the embryo, most transfer is between the maternal and fetal blood circulations. These circulations are not in actual contact, so exchange occurs across the placenta and other fetal membranes. Entry into the woman's blood varies with the specific nuclide, its chemical form, and associated route of exposure and absorption patterns. These factors have been considered and reported for many radionuclides in adults.

Biological disposition during pregnancy is less well defined but effects on biokinetics may be mediated through stage-of-pregnancy-dependent metabolic changes in the woman. The rates and amounts transfered to the embryo/fetus relate to material-specific processes of placental transfer; these range from diffusion and pinocytosis to facilitated or active transport. In addition, some nuclides are removed and deposited in placental tissues or in embryofetal membranes and related structures (adnexa). The movement of radionuclide, illustrated as arrows in Figure 2, demonstrate some of the qualitative factors that can be incorporated into analyses with compartmental models, and the enhanced understanding that can be achieved.

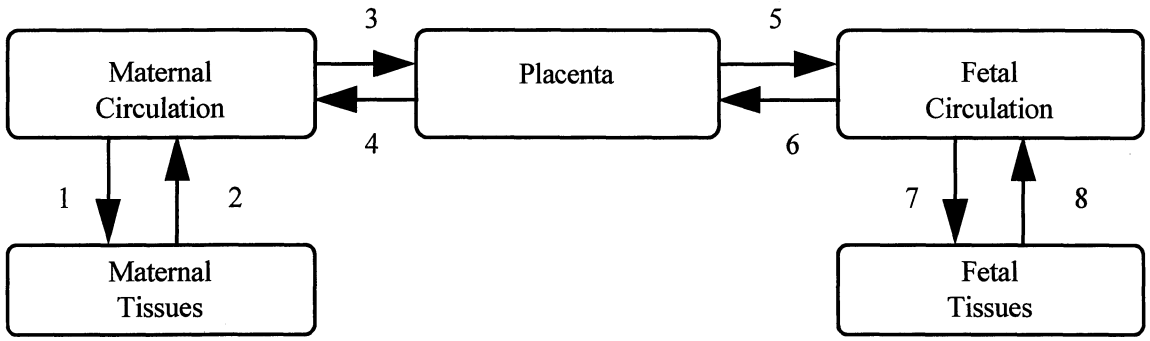


Figure 2. Generalized compartmental model to illustrate concepts of exchange between maternal and fetal circulations, and interactions relating to maturation of fetal target structures.

The rate and extent of net deposition in maternal tissue affects blood concentrations on an absolute and time-related basis, and there are comparable processes in the fetal blood and tissues. As shown, there is bidirectional transfer between the two circulations, which occurs via the placenta. The interplay of the above activities is responsible for the magnitude of concentration differences, which is the controlling factor in placental transfer. As specific deposition sites develop in the embryo/fetus, there will be increased rates of removal from fetal blood that will further drive placental transfer in the direction of the fetus.

This model also can be expressed in the more quantitative format of Figure 3, which is more compatible with nomenclature used by the ICRP. These models will be utilized in developing approaches to the dosimetric methodologies that are formally presented in Sections III and IV.

The initial component is the transfer comparment or maternal circulation and maternal tissues are not considered. The placenta together with related structures is subdivided into a labile portion that is active in transfer processes and a non-labile portion, which may sequester some radionuclides for extended periods of time. The embryo/fetus is likewise considered to consist of labile and non-labile subcompartments. As shown, transfer is modeled as taking place between the labile subcompartments although there may be less rapid exchange between the labile and non-labile subcompartments.

Placental transfer is mainly driven by quantitative availability of materials at relatively early times after introduction. These shorter term behaviors are the primary considerations in the transfer model. As will be described, bidirectional movements that represent release and return to plasma from soft tissue and bone compartments and redistribution may be included in models to explain observations during the initial days after exposure in experiments. Such cycling is included in the fetoplacental biokinetic model only when it makes a detectable impact on the resulting estimates of activity and/or radiation dose. Because of its growth,

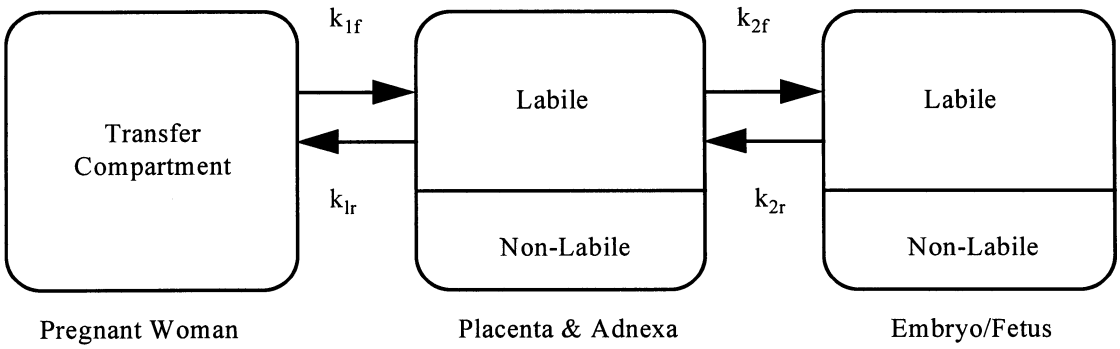


Figure 3. Compartmental model for maternal-fetal exchange as based on ICRP concepts. Kinetic coefficients or rate constants (k) are numbered consecutively (1,2, ..) and direction is indicated as forward (f) or reverse (r).

concentrations in the embryo/fetus will decrease when activity remains constant. Even though there might be continuing exchange, in practice and because of compartmental kinetic considerations, it would be expected that there would be little net return from the fetus to the woman so that net movement is used when feasible.

III. INTERNAL DOSE CALCULATIONS

A. Basic Considerations

The concepts underlying internal radionuclide dosimetry have evolved from the traditional techniques that continue to form the basis for current approaches. It may be useful to review briefly some aspects that will facilitate understanding of the suggested approaches. The most relevant consideration is that radiation absorbed doses and dose rates can be calculated directly from concentrations in the target tissue and in surrounding tissues by means of accepted constants and conversion factors. These combine the energies of the emissions, the number of emissions per unit time, the time over which the emissions are integrated, and energy losses in the target tissue.

These values must be adjusted by appropriate factors such as fractional energy absorption, which is a function of path length and dimensions of the tissue or organ - the conceptus in this instance. In addition to radiation dose from radioactivity in the embryo or fetus, it is also necessary to account for radiation dose arising from radioactivity in the maternal organs. The factors are influenced by changing biological conditions such as anatomical dimensions, which follow defined relationships.

At the inception of these efforts, it was agreed that the method for calculating radiation dose to the embryo/fetus should be compatible with internal dosimetry methodologies currently employed by practicing health physicists. The method should be sufficiently modular for other investigators to extend calculations by including additional data. Also, the methodology should be sufficiently robust to allow radiation dose calculations to be performed from a variety of input data. This will accommodate situations in which the dosimetrist may have data that are not consistent; the data sometimes might be expressed as the magnitude of an intake, at other times body burdens. The system partitions the dose calculation into two conceptually separate parts.

One part of the calculation consists of the radiation dosimetry, which is based on the physical properties of the emitted radiation. It includes interactions with anatomical characteristics such as physical dimensions, as well as with the elemental composition and density of the individual. These approaches and methodologies will be described in this section.

The other part of the calculation is the biokinetic evaluation that will be described in the next section (IV). These calculations are determined by the interactions of the physiochemical properties of the radionuclide or compound and the physiological processes of the individual. Inherent considerations allow a range of general approaches to estimating the radiation absorbed dose to the embryo or fetus from radionuclides incorporated in the conceptus or the immediately surrounding tissues. The approaches overlap in their details and underlying concepts and have several potential variations, but insufficient information may be a limiting factor. As a consequence, determination or estimation of the concentrations and activities to be used in calculations is the most uncertain aspect of the process.

B. Methodologies for Calculation of Dose

For the reasons given above, the calculational method selected for use in this project is a continuation and extension of the radiation dosimetry methodology developed by the Medical Internal Radiation Dosimetry (MIRD) Committee of the Society for Nuclear Medicine. The MIRD methodology for calculating radiation dose due to radioactive material in the body is presented in detail by Loevinger et al. (1988),

among others. Dose can be calculated to a target region, designated r_k, resulting from radioactive material contained in a source region, designated r_h. In most instances, both r_k and r_h are distinct organs, although they need not be. The MIRD system allows the two regions to be separated in space or to be the identical region.

The following briefly summarizes the MIRD calculational methodology; the reader is referred to Loevinger et al. (1988) for a more complete description. The equation for the mean dose rates to a target region, r_k, can be written in the three forms shown below:

$$R(r_k \leftarrow r_h) = \frac{A_h \sum_i \Delta_i \Phi_i (r_k \leftarrow r_h)}{m_k} \quad (1)$$

$$R(r_k \leftarrow r_h) = A_h \sum_i \Delta_i \Phi_i (r_k \leftarrow r_h) \quad (2)$$

$$R(r_k \leftarrow r_h) = A_h S(r_k \leftarrow r_h) \quad (3)$$

where $R(r_k \leftarrow r_h)$ = average absorbed dose rate in target region r_k from activity in source region r_h, rad/h (Gy/s)

A_h = activity in source organ h, μCi (Bq)

Δ_i = mean energy emitted per nuclear transition, the product of the number of particles multiplied by the mean energy per particle, g-rad/μCi-h (kg-Gy/Bq-s),

and

$$\Delta_i = K \; f_i E_i \quad (4)$$

where K = unit conversion factor, g-rad/μCi-h-MeV (kg-Gy/Bq-s-J) When the units for Δ_i are rad-g/μCi-h, the value for K is 2.13; when SI units are used, K = 1.

f_i = fraction of the disintegrations resulting in radiation, I

E_i = the mean energy of radiation, I, J.

$\phi_I(r_k \leftarrow r_h)$ = absorbed fraction, the fraction of the energy of type-I radiation emitted from the source organ absorbed in the target organ, unitless

m_k = mass of the target region, g (kg)

$\Phi_i(r_k \leftarrow r_h)$ = specific absorbed fraction, the absorbed fraction per unit mass of the target region, 1/g (1/kg) $\phi_i = \phi_i/m_k$.

S = mean absorbed dose to a target organ per unit cumulated activity in the source organ, rad/μCi-h (Gy/Bq-s) (referred to as S-value).

Because there are usually many source regions, r_h, that contribute to the dose received by the target region, r_k, the contribution from all source regions must be added together. The addition of the contributions from all source regions is shown in the following equation:

$$R(r_k) = \sum_h R(r_k \leftarrow r_h) \quad (5)$$

where $R(r_k)$ is the average absorbed dose rate in target region r_h, rad/h (Gy/s).

The internal dosimetry system adopted by the ICRP is conceptually similar to the MIRD methodology although it employs different terminology. The ICRP approach also incorporates factors to account for differences among radiation types in their ability to cause biological damage and has been expanded to consider tissue sensitivities. Basic aspects of the physical dosimetry of the ICRP methodology are described in ICRP Publication 30, Part 1 (1979); supplementary information can be found in Parts 2 and 3 of that publication (1980, 1981) as well as Appendix I of ICRP Publication 23 (1975). The MIRD notational system is employed in these recommendations because of the presence of a large body of literature that describes its use and the availability of several tabulations of dosimetric factors.

The above equations were derived for situations in which the values of the parameters that comprise the S-value are constant over the time for which the dose calculations are applicable. In the case of estimating radiation doses to the embryo/fetus, the values of the parameters that comprise the S-value are rapidly changing. As a consequence, it is not usually sufficient to compute a single S-value and then to estimate the value of the integral activity, $A_h(t)$, for the remainder of pregnancy. It is necessary to determine the dose rate to the embryo/fetus at sequential stages of pregnancy and then to integrate the time-dependent dose rates to determine the total dose:

$$R(t) = S(t)\ A_h(t) \tag{6}$$

The total average dose to the target region is then given by the integral:

$$D_{total} = \int R(t)\, dt \tag{7}$$

To obtain the solution to these equations, it is necessary to determine the proper values of S(t) and $A_h(t)$ for various values of time, t, during the gestational period.

The first part, represented by the S-value, is the radiation dosimetry portion of the problem and will be described in the remainder of this section. The radiation dosimetry calculations depend on the physical properties of the emitted radiation, the anatomical characteristics (e.g., physical dimensions) and the elemental composition and density of the individual. These factors will be discussed in the following subsections.

The second part that is represented by A_h is the biokinetic calculation that will be discussed in Section IV, following. Summaries of the biological behavior of the radionuclides of interest will be provided in Section V, following. For some radionuclides, the available data are insufficient for the derivation of even simple nonrecycling coefficients although concentration ratios are available in many cases. These generally can be converted to ratios of the activity in the embryo/fetus compared to the activity in the woman or her organs. The availability of data concerning maternal concentration varies among radioactive materials. Thus, for some radionuclides the comparison is to specific maternal organs, for others the maternal reference is her whole body.

As was mentioned in describing the growth and development of the embryo/fetus (Section II), the calculational approach described in this report requires activity content rather than specific activity or concentration. It may be necessary to use the following equation, with consistent units, to calculate activity in the embryo/fetus:

$$a = \frac{A\ R\ m}{M} \tag{8}$$

where a = activity in the embryo/fetus
A = activity in the maternal organ relevant to R
R = ratio of concentrations
m = mass of the embryo/fetus or organ
M = the mass of the relevant maternal organ.

Representative values for the dimensions and mass of the embryo/fetus may be taken from Table 1, Section II, Development. Masses for the whole body of the woman at various stages, as employed for this report, were shown in Table 2, Section II. The mass of the maternal organ may be obtained by estimation based on observation of the woman. Values are given in several data compilations, ranging from ICRP Publication 23 (ICRP 1975) to Stabin et al. (1995b).

The activity, A, in the relevant maternal organ following an intake could be estimated from the concentrations in air or ingested materials. More appropriately, it would be determined by direct bioassay (whole body counting or thyroid counting) of the female in question, or from indirect bioassay (urine or fecal assays) used in conjunction with the results of biokinetic models of radionuclide transport, such as the various commercially available internal dosimetry codes, or data compilations such as in Lessard et al. (1987). Sources of data employed for this report are indicated in descriptions of the grouping of radionuclides.

C. Radiation Dosimetry Calculations

The S-value is computed using Equation (9) (see also equations 1-3); the following paragraphs describe the calculation of the components of this equation:

$$S(r_k \leftarrow r_h) = \sum_i \Delta_i \, \Phi_i \, (r_k \leftarrow r_h) \qquad (9)$$

1. Energy Emitted per Nuclear Transition, Δ_i

The mean energy emitted per nuclear transition is tabulated in various compendia. Values of delta (Δ) for several radionuclides of importance in nuclear medicine are tabulated in *MIRD: Radionuclide Data and Decay Schemes* (Weber et al. 1989). The value may also be determined from Equation 4, which is repeated below:

$$\Delta_i = K \; f_i \; E_i \qquad (4)$$

Symbols have meanings and units are as before, i.e., when the units for Δi are rad-g/μCi-h, the value for K is 2.13. Values of f_i and E_i are published in ICRP Publication 38 (1983), among other sources. These values are physical constants and are not dependent upon the stage of gestation.

2. Mass of the Target, m_k

As a point of departure, values for the mass of the embryo/fetus were calculated using the equations given in ICRP Publication 23 (1975). These equations give reasonable approximations at gestational times of 90 days or greater although there are notable differences from values given in some textbooks of embryology and gynecology as well as in the technical literature. Estimates of mass of the embryo/fetus for 30 and 60 days were obtained by extrapolation of the curves obtained from the equations, and adjusted to be consistent with values presented in other sources. Despite minor differences, the new Oak Ridge mathematical models (Stabin et al. 1995a) give similar values and also differ from the earlier ICRP

curves. It should be noted that the extraembryonic or trophoblastic structures, which are important to the calculation, have masses that are greater than those of the embryo at early stages. The masses and lineal dimensions employed for calculations in this report are those presented in Table 1, Section II.

3. Specific Absorbed Fraction, Φ

The determination of the proper value for the specific absorbed fraction, $\Phi = ø/m_k$, and in particular the calculation of ø may require some explanation. In the MIRD schema, radiations are divided into two major categories, penetrating and nonpenetrating. Non-penetrating radiation deposits energy in a target tissue only if the source and target are the same, further if the source and target regions are the same (then, all the emitted energy is considered to be deposited). Thus, ø = 0 or 1. Penetrating radiation, on the other hand, will deposit a fraction of the emitted energy in all target regions: thus, ø ranges from 0 to 1. Alpha, beta, and electromagnetic radiations having energy less than 10 keV are usually considered non-penetrating. Electromagnetic radiation having energy greater than 10 keV and neutrons are considered penetrating radiations. In the case of the embryo/fetus, the small sizes of early gestational stages seem to require consideration of the range of beta and electron radiations. These range considerations are discussed for each radiation.

a. Alpha particles

Alpha particles have very short path lengths in tissue and are considered to be nonpenetrating radiation. In situations where $r_h = r_k$, then $\phi = 1$; otherwise, $\phi = 0$. Consequently, $\Phi = 1/m_k$, 0, respectively. It should be noted that calculation of dose from alpha particles does not readily fit into the usual MIRD methodology, but the above approach is presented in that mode to maintain consistency. It is clear that mean absorbed dose has little meaning for alpha particles in any specific volume other than perhaps during the earliest stages of gestation, and that micro-dosimetric considerations may be more relevant. Some laboratories have utilized the concept of average concentrations or specific activities under these circumstances for relating dose to potential effect, which is proper for that purpose. An appropriate modification of this approach would seem to be a logical inclusion in future formulations of prenatal dose regulation and reporting.

b. Beta particles

Beta particles are usually considered nonpenetrating radiation. However, in the case of the embryo/fetus, especially at early stages of development when the embryo/fetus is very small, ϕ may be much less than one, particularly for higher energy beta particles such as those emitted by ^{32}P, ^{90}Y, and ^{106}Rh. Conversely, ϕ for the same radionuclides will be greater than zero when the radionuclide is in tissues external to the embryo/fetus. This latter situation occurs only when the tissue that contains the radioactive material is in direct contact with the embryo/fetus.

The following describes the calculational methodology that was developed for purposes of these recommendations, to assist in accounting for the range of beta particle and other electron radiations. For the calculations of this report, the embryo/fetus was assumed to be an ellipsoid having the dimensions given in Table 1. The dose to the ellipsoid from activity contained within the ellipsoid was calculated by performing a six-dimensional numerical integration of the Berger (1971) point kernel for beta dose. The Berger kernel can be written as:

$$R_\beta(r) = \frac{Y\ k\ E_{ave}\ F_\beta(r/X_{90})}{4\ \pi\ \rho\ r^2 X_{90}} \qquad (10)$$

where $R_\beta(r)$ = the beta dose rate per unit activity from a point source at a distance r from the dose point
r = distance from source point to target point, cm
Y = beta yield per disintegration
k = unit conversion constant
E_{ave} = the average beta energy per disintegration
X_{90} = the radius of a sphere in which 90% of the beta energy is deposited
F_β = scaled absorbed dose distribution
ρ = density of the ellipsoid.

The radionuclides were considered to be point sources for the purpose of dose calculation. The beta dose to a target point is the sum of the dose contributions from all the source points within the range of the beta particles, and dose to the target organ is given by:

where A_v = the source activity per unit volume at the source point (x_h,y_h,z_h)
V_h = the source volume
V_k = the target volume

$$R_\beta(r_k \leftarrow r_h) = \frac{\iint A_v(x_h,y_h,z_h)\, R_\beta(r)\, dV_h\, dV_k}{\int dV_k} \qquad (11)$$

The distance between the source point and the target point (x_k,y_k,z_k) is given by:

$$r = \sqrt{[(x_h - x_k)^2 + (y_h - y_k)^2 + (z_h - z_k)^2]} \qquad (12)$$

For the purpose of dose calculation, the range of beta particles was estimated to be 1.8 times the X_{90} (Berger 1971). The absorbed fractions calculated using this method generally agree to about 1% with values using the electron-transport code EGS4 (Nelson et al. 1985).

The S-values computed for these recommendations are based on the continuous slowing down approximations for energy deposition by electrons. More precise calculations of energy deposition by electrons, which account for straggling effects, may be employed. For most radionuclides, the beta particles as well as the Auger and conversion electrons should be considered non penetrating radiation. In the situation where $r_h = r_k$, then $\phi = 1$; otherwise, $\phi = 0$. Consequently, $\Phi = 0, 1/m_k$.

c. Photons

Photons are penetrating radiation. The approaches to account for the penetrating ability will differ for the three potential masses in which the radioactivity may be located.

Dose to embryo from radioactivity in maternal organs: Complete compilations that presented values of specific absorbed fraction for the embryo/fetus as the target tissue were not available at the time that the initial calculations were performed. Tentative data for photons were calculated to supplement tabulated values for specific absorbed fractions. The uterine content as the target tissue can be considered to include initial developmental stages of the embryo/fetus. Initially, two compilations, the MIRDOSE 2 tables and those described by Cristy and Eckerman (1987) were used for the nongravid uterus, which serves as a surrogate for the embryo during the early stages and may be employed for the first 2 months of pregnancy. The data published by Davis et al. (1987) were suggested for the 3-month-pregnant female, with the possibility that these compilations might be employed for the third through ninth months.

As noted in prior sections, specific absorbed fractions are now available for specific radionuclides and for 3, 6, and 9 month pregnant women and were used when applicable (Stabin et al. 1995a, Stabin 1996).

Dose to embryo/fetus from radionuclide in embryo/fetus: When appropriate values were not otherwise available, the computer code MCNP, described by Briesmeister (1986) may be used to computed specific absorbed fractions for the situation in which the embryo/fetus was both source and target tissues. The embryo/fetus was assumed to be an ellipsoid having semi-major and semi-minor axes given in Table 1, with an elemental composition that was assumed to have the composition of the newborn phantoms described in Stabin et al. (1995).

Dose to the embryo/fetus from radioactivity in the extraembryonic or placental tissue: At present, methods for specific calculations of specific absorbed fractions for radioactive materials in the extraembryonic or placental tissues have not been performed. In the interim, results may be approximated by estimating the self-dose to the uterine contents. This calculation may result in some "double counting" of radiation dose to the embryo/fetus when combined with the dose calculations from radionuclides within the embryo/fetus. However, few data exist to allow calculation of the activity in the extraembryonic or placental contents and this problem should be considered on a case-by-case basis.

IV. BIOKINETIC EVALUATION OF ACTIVITIES AND CONCENTRATIONS

Radionuclides that are of interest for potential occupational exposure or health concerns were selected to provide a representative spectrum of biological, physical, and dosimetric attributes. This section presents the biological and metabolic considerations that guided evaluations of the literature that provides a basis for the biokinetic component of the dose calculations. This provided complementary information regarding the relative concentrations and data to undertake kinetic analyses.

Quantitative information that was directly applicable to radionuclide dosimetry was often insufficient for these evaluations. In these instances, the data could be supplemented using physiologic and metabolic information for these or related materials. This section will describe the concepts, constructs, and methods used for the more formal modeling approach that has been introduced into the analysis.

Pertinent characteristics of these elements will be described in Section V to provide an understanding of the metabolic assumptions and developmental relationships that underlay the calculations. The biokinetic models allowed for changes during successive gestational periods and led to estimates of the fractions of activity that were deposited in the embryo/fetus and retained at sequential times after injection into the blood circulation, or transfer compartment, of the pregnant woman. The resulting values at 30-day intervals after the time of initial administration, defined as $t = 0$, are tabulated in Appendix A for relevant radioisotopes of these elements.

These data were used in the dosimetric analyses related to typical forms in which these radionuclides may be found in work environments. Consistent with the MIRD approach, absorbed doses in rad were calculated relative to a specific total body burden or administered bolus of activity; this was considered to be 1 μCi. Tabulations of the numerical results for monthly doses, dose rates, and cumulated doses are given in Appendix B. As will be detailed in later sections, there are accepted factors that allow the dosimetrist to relate these nominal body burdens to available estimators of intake level.

The number of reports for some nuclides or forms is so large that only selected references are cited. Reviews were utilized, especially for underlying developmental physiology and biochemistry, and some general references are given. Moreover, literature was assembled for the fetoplacental disposition of some radioelements that are not evaluated in this report. Accordingly, it was decided that the bibliography, with keywords and annotations, for placental transfer of the full range of radionuclides should be made available separately.

A. Biokinetic Calculations

1. Underlying Concepts

As described in previous sections, the purpose of biokinetic calculations is to provide quantitative estimates of the radionuclide content of the maternal organs and of the embryo/fetus-placenta-uterus. The woman and the embryo/fetus, along with the placenta, may be modeled as having the three primary compartments shown in Figure 3. The maternal transport compartment shown in the figure is identical to the transport compartment that is described in ICRP Publication 30 (ICRP 1979).

Both of the other two compartments, the placenta and the embryo/fetus, may consist of (at least) two subcompartments: labile and nonlabile. The labile subcompartment represents the fraction of the radionuclide that is available for transport to some other compartment. The nonlabile subcompartment represents the fraction of the radioactive material that has been incorporated into anatomical structures, for example, and is not available for transport. For purposes of the modeling approach that is described later in this section, it is conceptually more convenient to consider the placental components as being a "placenta - transparent" to represent free transfer and a "placenta and adnexa - unavailable," which also includes the other fetal membranes such as the yolk sac,

that retains or slowly transfers materials. The embryo/fetus consists of its circulation, its main mass, and any organ, structure, or biochemical compartment that has a particular avidity for the material.

The arrows represent movements in the reverse direction and provide a possibility for cycling. An algorithm to compute the activity in compartments of a recycling system has been described (Birchall and James 1988, 1989). Sufficient data are not available to allow the use of cycling compartmental analysis in all instances and the reverse arrows of Figure 3 may be eliminated from consideration in a conceptually simpler system. In such situations, recycling of the radioactive material is not modeled and compartmental analysis methods, such as those described by Birchall (1986) or Skrable et al. (1980) or in ICRP Publication 30 (ICRP 1979), may be appropriate. Thus, a single arrow would be used to represent unidirectional movement or values of net transport that portray metabolic cyclings, in the sense used in ICRP Publications 56 and 67 (1989, 1993).

2. Estimation of Concentration and Activity

As mentioned, the possibilities include formal approaches that are compatible with the above methodology. These are based on estimates of fractional transfer from maternal blood to the conceptus or of transfer kinetics and patterns to the conceptus as a function of stage of pregnancy, route of intake by the pregnant woman, and time after intake or placental transfer. This approach may have the greatest theoretical validity and be most amenable to biologically valid extrapolation, but is limited in that it requires more information than do other methods. However, physiological information can be introduced into these calculations to circumvent this limitation and concurrently extend their potential and accuracy.

The most prominent of the other approaches to estimation is based on ratios of concentrations in the embryo/fetus to maternal concentration. These can be estimated in either specific tissues or in average or total body, usually as extrapolated from reports of animal experiments. This approach is assumed by some to serve as the basis for the most conservative (i.e., maximal) estimate of dose to the conceptus.

3. Current Status and Limitations

The process required generalizing patterns from information that was sometimes limited and involved disparate reported values relating to placental transfer and relative fetoplacental concentration. The lack of clear precedents necessitated decisions concerning the desirability and validity of ways to generalize. The alternatives include calculating means and confidence intervals, selecting a mode or median to serve as a representative of the true age-related value, and using approaches that accommodate broad ranges of values. No single approach has proven to be consistently useful so that an eclectic approach was taken. In the case of radionuclides for which reports of prenatal concentrations are not available, it has been necessary to interpolate or extrapolate from results with chemically related elements or compounds.

Extrapolation of concentration values from animals to human pregnancies must be based on anatomic and metabolic correspondence of developmental stages and, to some extent, other biological factors. However, the validity of the extrapolated values also depends on the nature, amount, and homogeneity of the calculated values. General schemes have been addressed for using concentrations or activities in the conceptus to calculate radiation doses. These were first generalized to be independent of the metabolism of the nuclide, but are highly dependent on the fetoplacental morphology that is characteristic of each major sequential stage.

B. Gestational-stage-related Deposition and Retention

1. General Considerations

The availability of reliable estimates of fetal concentrations or of relative concentration values for maternal and fetal tissues is a limiting factor in dose determinations. Continuing efforts are developing procedures for interpolation and extrapolation of the database and of broad metabolic information for eventually establishing time-integrated concentration values and their patterns in the embryo and fetus. Attempts are ongoing to manipulate such data to calculate incremental depositions from transfer coefficients or successive ratios, and to estimate concentration decreases at times subsequent to that represented by a reported ratio. Examination of data from noncontemporaneous experiments found that placental transfer kinetics from one experiment could be used to correctly predict the fetal concentrations measured in other experiments (Sikov and Kelman 1989).

Although the data are neither complete nor quantitative, it is possible to generalize important biological relationships affecting dosimetry. These include changes in transfer kinetics during pregnancy, total fetal activities or concentrations, and the role of developing target organs or tissues. Early attempts at categorization were based on stage-independent approximations of relative availability and net deposition in the conceptus. The limitations to this nonquantitative approach highlight the need to develop more objective criteria for evaluation.

2. Estimates Based on Fetal-to-Maternal Concentration Ratios

The ratio of concentration in the embryo/fetus to the maternal concentration requires the least information and is particularly applicable when few quantitative data are available because they usually consist of one or more ratios of activities or concentrations. When this ratio approach is based on values that were calculated from measurements made soon after intravenous exposures of animals, it provides estimates of maximal prenatal radiation doses because subsequent concentrations would be decreased by progressive growth. Greater precision may be achieved when ratios applicable to sequential times after exposure are available or when exposures are made at multiple stages of gestation. The growth equation could be introduced into the calculation although this addition is not included routinely in such analyses.

Ratios of concentrations (reported, calculated, or interpolated) of those in the embryo/fetus to those in a pregnant animal or woman are used to estimate activities in the embryo or fetus for calculation of radiation doses. The ratios are sometimes used to estimate the radiation doses to the embryo/fetus by explicitly using the ratio for proportionation to maternal organ doses.

The absence of reported data for radioisotopes of an element often suggests that it is not of major concern as a source of exposure, but its behavior can be extrapolated from that of chemically related nuclides. This and other aspects of the approach implicitly require invoking a number of potentially inaccurate assumptions, some of which also pertain to other approaches. For example, extrapolations from animal to human often assume the ratio to be the same, without allowance for the problem of monotocous versus polytocous pregnancies, which was considered earlier. Direct use of this concept does not require formal incorporation estimates of the greater transfer or deposition at later stages that arise from physiologic maturation, such as the functional development of target organs in the fetus and their effect on transfer coefficients-concepts that are more evident in other approaches.

3. Compartmental Analyses and Impact of Stage-Related Distribution

a. Basic Concepts

Compartmental models offer a straightforward means to integrate available information relative to time after intake. Even with limited data, simple two- or three-compartment models often can be derived using a physiologic or metabolic basis or relative to kinetics that are implied from sequential ratios. As indicated in Sec-

tion II, activity ordinarily must be in the woman's plasma to be available for transfer to the conceptus so that most transfer is between the maternal and fetal blood circulations. These circulations are not in actual contact so that exchange occurs across the placenta and other fetal membranes. This concept, illustrated in Figure 2, may be used to identify qualitative factors that may be incorporated into analyses with compartmental models.

b. Kinetics and the Placenta

Fractional absorption and entry rates into blood vary among individual radioelements and chemical forms and are affected by to route of exposure and absorption. These factors have been considered and tabulated in numerous documents and reports. The placenta has a potential for affecting kinetics via material-specific facilitated or active transport, but some nuclides may be removed and deposited in placental tissues. The rate and degree of deposition in maternal tissue also affects blood concentrations on an absolute and temporal basis. This clearance is of importance in that decreased concentrations will reduce transfer. On the other hand, as specific sites of deposition begin to develop and function in the fetus, the rate of removal from the fetal blood will increase and drive the placental transfer dynamics in the direction of the fetus. The model illustrated in Figure 2 can be expressed in the alternate format of Figure 3, which is more compatible with the nomenclature used by the ICRP. This form was utilized in developing some approaches to the dosimetric methodology described in Section III and some of the biokinetic models in Section V.

c. Localized Deposition

The indicated stage-dependent deposition patterns may also involve inhomogeneous tissue and dose distributions. These have not been identified as posing special radiological protection problems from a regulatory aspect. Therefore, in the present context, consideration mostly will be limited to their general influence on kinetics, concentrations, and total activity in the fetus, but the resulting net dosimetric consequence will be discussed. The resulting localized radiation doses may have broader implications, as has been noted in the literature, and these will be identified in later sections of this report.

These considerations also pose cautionary implications for extrapolations. The skeletal deposition of elements such as strontium, which resembles that of calcium, becomes progressively greater as the fetus approaches term. This is especially prominent in human development. Bone maturation occurs relatively much earlier in the human fetus than in some common laboratory rodent species, such as the mouse and rat, in which major calcification takes place in the postnatal period. Accordingly, one-to-one temporal extrapolations of results from rat or mouse experiments to the human fetus may yield incorrect results.

4. Calculation Based on Formalized Kinetics

Biokinetic evaluations provide the most accurate information in the selected situations where they are best applied. These results would have greater theoretical validity and be more amenable to biologically valid extrapolations than static concentration ratios, but proper implementation requires greater amounts of information. This approach would pertain most commonly for radionuclides that have been of greatest interest for radiological protection or of metabolic importance.

Under ideal conditions, the biokinetic approach is based on use of transfer quantities and rates together with metabolic data to determine the time course of fractional movement from maternal blood to the embryo/fetus. From such information, it is possible to calculate deposition or infer kinetics and patterns of transfer to the conceptus as a function of stage of pregnancy, route of intake by the pregnant woman, and time after intake or

placental transfer. It is appropriate to superimpose modifications to account for retention and growth functions.

In subsequent practice, the formalized approach could be applied to evaluation of repeated or chronic exposures. Calculation would involve estimating each of the fractional amounts that would be transferred, the dilution of each increment by subsequent growth, and the sums of the resulting integrals of concentration in the conceptus with time. The total contributions from sequential depositions give estimates of time-weighted activities that can be used for calculating radiation doses to the conceptus. These calculations must allow for the continually changing kinetics relating to stage of gestation, fetal growth, and localization within specific tissues of the conceptus.

These sorts of interactions may partially explain the differing concentration ratios that have been reported. Moreover, the known placental sequestration and redistribution functions influence concentration ratios at subsequent times so that the transfer process may not be simply inferred from a single-time determination of ratio. Likewise, measurements that find the same concentration in cord blood at term as in the woman's blood following chronic environmental exposures suggest approaches to the transfer model, but the finding does not define transfer specifics for individual exposures.

5. Application of Formalized Kinetics

The goal of all of the approaches indicated above is to provide meaningful values for A_h, the second component of the dosimetric calculation. In effect, this is represented by the area under the curve of activity as a function of time after administration.

This approximation is formalized in the MIRD schema through use of the concepts of cumulated activity, $\tilde{A}$, which is the integral of activity as a function of time. It is calculated as:

$$\tilde{A} = \int A(t)\ dt \qquad (13)$$

which gives the sum of all of the nuclear transitions in the source organ during time period t. This concept can be extended to express the average time that the activity remains in the source organ. This is referred to as the residence time, t, and is given by

$$\tau = \tilde{A}/A_o \qquad (14)$$

The equivalent concept, especially when the activity must enter the source organ from another compartment, is determination and integration of the curve of activity. This also must be calculated on the basis of assigned compartment sizes, rate constants, and coefficients.

These values of activity can be calculated graphically, but are usually addressed through computer-assisted programs and modeling languages such as SAAM and STELLA®. These facilitate the ability to establish and solve complex differential equations that yield residence times, the total area, or the series of values that represent area during specific time periods after administration.

C. Specific Modeling Considerations

1. Components of the Model

Biokinetic or time-dependent compartmental models are based on the biological behavior of the material of interest. This behavior serves as the metabolic paradigm for the model and may include extrapolations from a series of measurements. These data also yield relative concentrations while ancillary information may be obtained from the study of the surrogate materials or systems. The input into the models includes general descriptive and quantitative temporal descriptions of radioactivity in the woman as well as transfer coefficients. The basic operational models are developed from the information and models given in several broadly based sources as well as targeted reports referred to in this section. Placental transfer information from which coefficients were estimated was obtained from compendia, textbooks, and comprehensive reviews dealing with the physiology of

pregnancy, of the placenta, and of the fetus as well as from general physiology and radiological protection literature.

Neither the rates nor the fraction absorbed from the gastrointestinal tract or lung has a direct influence on the modeling. Instead, the models are based on activity that is considered to be instantaneously introduced into the woman's transfer compartment. The absorbed fractions of energy become of importance in recommendations concerning practical exposure situations and these values are included in the descriptions of the groups of elements. Because tables relating to regulatory considerations are based primarily n values from ICRP Publication 30, these are the values that will be given but subsequent changes in the values for gastrointestinal absorption, f_1, are noted. No attempt was made to revise the inhalation classes that were assigned in ICRP Publication 30 to reflect current changes in NCRP and ICRP lung models or absorption classes.

2. Biokinetic Evaluations

Descriptions and models for biokinetic behavior will be based on metabolic descriptions given in sources such as ICRP and NCRP and in other reports by contributors to those activities. Placental transfer is driven by quantitative availability of the materials at relatively early times after introduction; this provides good agreement with models for alkaline earths. The interactions may not always be usefully described by such models, however, and reasonable modifications are introduced to yield results that are compatible with reported observations and with known and rational biological and biochemical behaviors and principles.

Shorter-term behaviors are the primary drivers of the transfer model. Release and return to plasma from soft tissue and bone compartments and redistribution may serve to explain observations of increases in fetal radioactivity during the initial days after exposure in rodent experiments. Such cycling is included in the feto-placental biokinetic model only when it makes a detectable impact on the resulting estimates of activity and/or dose.

Estimates of placental transfer and descriptions of disposition in the embryo/fetus are taken directly from literature or derived de novo from composites of information. Thus, the gestational-stage and post-exposure-time-dependent values of radionuclide content of embryo/fetus, both average and localized concentrations, are based on accepted models for the adult woman.

More detailed or longer-term patterns of biological behavior are described for some radionuclides. These descriptions use the most parsimonious model that does not introduce distortions and allows for inclusion of information concerning placental transfer and continuing relationships between the embryo/fetus and the woman. In other instances, only general or generic relations can be stated and the minimal model that will yield reasonable approximations is used.

3. Implementation of the Model

The approach for each radionuclide or radionuclide group thus has been to assemble the information and assumptions. The calculations and procedures were such as to yield stage-related values of radioactivities in the embryo/fetus relative to intake. These employed formal biokinetic models when possible, together with appropriate concentration ratios or relative behaviors. These models were used for calculation of embryo/fetus deposition and retention parameters that provided radiation dose factors and considerations for acute, chronic, and pregestational intakes.

It is to be noted that some soft tissue compartments that are relevant to adult dosimetry pertain to the embryo/fetus only to the extent that activity entering and retained is not otherwise available for transfer. These compart-

ments, together with direct fetal observations or measurements, serve to establish local concentrations and overall demand and retention patterns. To simplify the model when possible, maternal compartments, including subdivisions of bone, are combined and overall sizes and rates are assigned so as to accommodate placental transfer demands. In addition, metabolic uncertainties, which have been kept conservative, do not affect the calculated doses. As will be observed, most of the dose is received by the embryo/fetus soon after injection, when it has higher levels of activity and much higher concentrations.

The accepted models for many groups of radionuclides such as the alkaline earths and the actinides involve substantial movement between soft tissue and bone. Much of the redistribution occurs within and among bone compartments so that the activity is not readily available to the embryo/fetus. Examination of the fractions and coefficients shows that much of the transport of activity between bone and plasma occurs with long half-times so that the process does not have a meaningful impact relative to placental transfer.

Because of its growth, concentrations in the embryo/fetus will decrease when activity remains constant. Even though there might be continuing exchange, in practice and because of compartmental kinetic considerations, it would be expected that there would be little or no net return from the fetus to the woman. Thus, as was observed in Section II for bidirectional arrows in compartmental models, net movement or "apparent" half-times are often used in the models.

4. Dosimetric Modeling

Analysis and modeling provide the value for the A_h term or terms in the equation for dose. These values express the activity in the source organ or organs and, for these purposes, are given relative to stage of gestation and time after exposure. They may be expressed as residence times, as in the original MIRD formulation, or as integrals and a series of incremental values, as in our modification of the MIRD approach.

Thus, a separate calculation was performed for initial exposures at each month of gestation, expressed as 30-day intervals for uniformity. The output of the modeling (as given in the tables of Appendix A, for example) is expressed as the fractional deposition in the embryo/fetus at a time soon after introduction into the transfer compartment (denoted as 0 time) and the retention at subsequent times. These are again tabulated for 30-day intervals after injection although calculations were performed for successive days or more frequently for short-lived isotopes. The individual daily values were those used to calculate dose factors and rates, as in Section III. These calculations lead to the tables of radiation dose factor and dose rates that are given in Appendix B.

D. Factors Influencing Dosimetric Approach

1. Selection of Concentration/Activity Estimators

Detailed examination of compatibility of results derived from various types of calculational approach is restricted to only a few elements. Good agreement was seen, however, in the comparisons that will be made in Sections V and VII. More importantly, some of the data were compatible and could be combined to establish the central values used for descriptions in Section V. As will be evident, these display reasonable agreement when comparisons are restricted to comparable stages of gestation.

Similarly, using alternative extrapolation procedures, approximations of relative concentration and activity values in the conceptus may be made for other elements. These reasonable approximations follow the ICRP approach and result in typical assumptions, such as that rare earth elements for which there is no specific information will behave in a manner similar to cerium.

There are several nuclides for which there is neither information nor a basis to extrapolate. With a few exceptions, the absence of reported studies may be taken as suggesting that intake is unlikely or that there is no special prenatal affinity for such materials. Therefore, the average embryo/fetal concentration could be assumed to be no more than in the woman. There are occasionally reports of a high ratio in specific tissues although the overall concentration ratios are not affected. It should cause minimal impact if concentration ratios of uncommon radionuclides were assumed to be one (1), even when they are probably less, but it is important to avoid gross underestimates.

2. Biokinetic Implications of Localized Deposition

Section II described the impact that removal from participation in a compartment by sequestration in a subcompartment would have on compartmental kinetics. In addition, de novo development and increase in the size or functionality of a fetal structure or tissue would serve as an additional, and often important, compartment in the biokinetic calculation. There are a number of such situations that pertain relative to development of the embryo/fetus and they are found to have marked gestational-stage-dependent impacts on the model. The following will present a few examples in the context of their biokinetic implications.

The gestation-related aspect of many of the biokinetic models is based on the fact that bone is not present in the embryo during early gestation. At times through 2 months of gestation, the embryo/fetus is embedded in the uterine mucosa. The model assumes that soft tissue distribution, which includes the uterus, also represents the concentration of even bone-seeking radionuclides in the embryo/fetus. Skeletal elements begin to develop shape and form early during the fetal period and their growth and mineralization or calcification become increasingly important through later gestation.

Calcium biokinetics during gestation, as in the adult, serves as the template for the behavior of several elements such as strontium, radium, and lead. This concept is based on summaries by Widdowson (see e.g., Widdowson 1968) for total contents and relative concentrations of calcium and other minerals in skeletal elements and other fetal organs. Ossification and calcification of skeleton are modeled as subsequently progressing for purposes of calculations so that fetal bone increasingly participates in the fetal burden.

a. Phosphate

Based on the cited analyses of developmental biochemistry by Widdowson, phosphate concentrations progressively increase throughout gestation in the skeleton and its components, as well as in soft tissues. The simplified situation assumes that the tissues that will evolve into the fetal skeleton would have initial concentrations that are the same as other soft tissue. During skeletal development, however, concentrations in forming bone progressively increase to values that are 10 to 20 times as great as those in fetal soft tissue. In the adult, the bone-to-soft-tissue concentration ratio increases with time after the initial distribution as a consequence of different retention times; this also should apply to the fetus. Also, as with the adult, fetal bone radioactivity should remain without net release during its development, and would draw on soft tissue phosphate stores. These considerations resulted in the partition model given in Section V that considered the composite whole fetus concentrations to be 2.8 times the woman's soft tissue concentration at all times after 3 months of gestation.

b. Strontium

As with calcium, strontium deposition in the skeleton becomes progressively greater as the fetus approaches term. This pattern and its implications for modeling - implications that are especially pertinent in human development - are factors that must be considered in extrapolations. In particular, the extent of bone maturation is

substantially greater in the human fetus than in some common laboratory rodent species, such as the mouse and rat, in which most calcification takes place in the postnatal period.

Biokinetic modeling can be based on identified patterns of skeletal composition and relative mineral behavior. Comparative fetal-to-maternal skeleton deposition leads to gestational-stage-dependent levels of relative concentration. The modeling can consider the stage-dependent changes in the mineral composition of bone relative to stage of gestation and yield values of fractional multipliers to estimate the influence on concentrations and the associated radiation doses.

Percentage activity of strontium in the woman's skeleton following the initial deposition and early redistribution is considered as 25% of the administrative activity. Using gestational-stage-related deposition and retention fractional multiplier values provide the transition from there being no skeletal deposition in the early embryo to fetal skeletal concentrations of strontium that are the same as those of the woman at 6 months of gestation and thereafter. The model gives results that are in accord with reports that strontium concentrations in fetal and maternal bone are similar at later times of gestation.

c. Radium

Similar models, patterns, and values were introduced into the modeling of deposition and retention of radium in the embryo/fetus. The approach again provided a transition from no skeletal deposition in the early embryo to skeletal concentrations that are the same as those of the woman at 6 months of gestation and thereafter. The activity going to the fetal skeleton is modeled by using this factor as a multiplier of the ratio of skeletal masses, which represents the major content of radium. The model gave results that are in accord with reports that radium concentrations in fetal and maternal bone are similar at times long after exposure. This allowed the consideration that a concentration ratio of unity for the fetus/woman pertains both for multiple occupational or continued environmental exposures because bone drives overall concentrations.

c. Actinides

Although the conceptus is embedded in the uterine mucosa during the first 2 months of gestation, evidence from experimental animal studies strongly suggest that there is selective deposition of actinides in the fetal membranes. Because of uncertainties, both quantitative and semantic, neither enhancement nor placental barrier was included in the model. The average concentration in the early embryo was assumed to be identical to that of the uterus, as given by maternal soft tissue. The model assumes gradual transitions during the third month to accommodate changes in fetal metabolism and morphology that influence partition between the pregnant woman and her embryo/fetus. These and other factors also introduce restriction of placental transfer that is assigned a transfer factor of 0.1. Despite quantitative differences, these are analogous to the fractional absorption factor from the gastrointestinal tract.

The masses of bone and liver, as well as of fetal soft tissues, increase concurrently with the processes of skeletal ossification and calcification. As a result, the rate of increase in total radioactivity in the fetus is greater than directly proportional to the rate of increase in total fetal mass or ratio of fetal to maternal mass. Consequently, a transition is modeled for relative concentrations that progressively increase; total activity transferred to the near-term fetus would then increase even more markedly.

3. Dosimetric Implications of Localized Deposition

In addition to the impact of localized deposition on kinetics in various gestational stages, situations may warrant calculating local radiation dose as a basis for estimating risk. This is the case with radioiodine, where dosimetry requires that the fetal thyroid be considered as a source organ for calculating dose to the remainder of the fetus

and for calculating self-dose. As will be shown in Section V, radiation doses to the fetal thyroid may be orders of magnitude greater than doses to the remainder of the fetus or the average fetal doses. Such differences are relevant to evaluating an dose-effect relationships and risk.

It will be noted in the descriptions of phosphate in Section V that, except for absorbed fraction, it makes little difference where in the embryo/fetus the energy is dissipated as long as the activity was not restricted to its surface. Nonuniformity does not necessarily complicate calculations of the average or total body dose to the embryo/fetus, which is the current regulatory limit. The inhomogeneity would become a major consideration, however, when there was reason for concern about dose to specific tissues or organs of the embryo/fetus.

Nonuniform radiation dose may be especially relevant with radiophosphorus because skeleton and bone marrow are major sites of deposition as well as concern relative to effect. Assumptions underlying the prenatal metabolic model are based on the differential disposition in fetal bone, but this localization is not taken into account for calculating beta doses to skeleton as an individual tissue of the embryo/fetus. The magnitude of the differential concentration is gestational-stage dependent, and the relative radiation doses may be greater because of the progressively increasing density of bone.

The deposition pattern of strontium also involves a significant localization factor. As noted, almost all of the strontium content of the late fetus is in bone so that, in one sense, skeletal mass should be used for calculation. Doing so would give a substantially higher average concentration to the target. Because most current recommendations are stated in terms of dose to the embryo/fetus, the total body is the appropriate mass to consider for purposes of the analyses of this report.

V. GENERAL ELEMENTAL RADIOISOTOPES

A. Inputs into Specific Radionuclide Models

This section summarizes relevant information from evaluations of the literature that forms the basis for the biokinetic component of the dose calculation. Quantitative data were supplemented using patterns from qualitative studies and accepted physiologic and metabolic information. Complementary information was integrated from the relative concentration and dynamic approaches to develop the descriptions and the resulting metabolic and dosimetric tables that are presented in the appendices.

The approaches described in the preceding section were implemented using the most parsimonious model that still would allow incorporating all critical elements of the biological behavior. Simplifications or generalizations were used when reasonable to bridge uncertainties. These were employed especially when comparative boundary-setting calculations disclosed that the results were insensitive to choice of coefficient or parameter.

The f_1 values identified in the description of the characteristics and behavior of this section, as well as inhalation classes, are those given in ICRP Publication 30 (1979, 1980, 1981). More recently revised values, such as those given in ICRP Publications 56 (1989) and 67 (1993), will also be indicated. The earlier values, together with those that were revised in ICRP Publication 48 (1986), were used in calculations of dose relative to ALI and are the numbers that are tabulated in Federal Regulatory Guidance No. 11 (Eckerman et al. 1988).

Use of the Stella® modeling language (Peterson and Richmond 1994, Hannon and Ruth 1995) required assignment of quantitative values to relevant compartments of the woman, placenta, and embryo or fetus, fractional movements and feedbacks, and descriptors of rate. Inclusion of the placenta, as shown in Figures 2 and 3 and discussed in Sections II and IV of this report, is unique to intrauterine biokinetic modeling. The placenta usually was considered as a single compartment but it sometimes was appropriate to model it as consisting of two subcompartments: labile and non-labile. The overall placenta, or the labile subcompartment when the model required division, was accepted as being essentially transparent in the dynamic model and was assigned a retention half-time of 0.25 day. As will be described, many radionuclides are sequestered in the placenta and fetal membranes and are retained in the non-labile compartment with half-times that range from several days to infinity.

Reasonable parameters and coefficients for the several compartments, including the placenta, could be identified or derived in most cases. Blanket approximations were assigned when required and default values were used when necessary. The modeling employed the suggestion by Leggett (1992a, 1992b) that net movement could be used to simplify calculation of some bidirectional transfer situations. This simplification also has been incorporated into models given in ICRP publications (1993). Again, following ICRP approaches, default values for rate constant or half-times were selected for quantifying general or imprecise situations. Thus, the models used a biological half-time of 0.01 day for immediate distribution or transport and 0.25 day for rapid biological movements.

B. Output from Specific Radionuclide Models

The following subsection will summarize the relevant information and describe the general models that led to the expanded analyses and dosimetric approaches. Representative examples of the relationships and factors that were used for the biokinetic calculations related to typical forms in which these radionuclides may be found in work environments are provided. These calculations yielded deposition and retention fractions of important isotopes of these materials, which form the basis for dosimetric calculation.

The usual format will be to give separate tables of deposition/retention in the woman and in the embryo/fetus for radionuclides that have penetrating emissions because the maternal activity contributes significantly to the radiation dose to the embryo/fetus. In evaluations of radionuclides that involve only (or predominantly) non-penetrating radiations (alpha or beta particles), tables are given only for the embryo/fetus. Deposition and retention tables were generated and presented for fetal and maternal thyroid glands because both are meaningful source organs for radioiodine exposure.

The tables that describe biological disposition are compiled in Appendix A. The tables of numerical results for dose factors and dose rates are given in Appendix B. Comparable appendices are given separately in association with recommendations concerning other categories such as radiopharmaceuticals (Appendix C) or to provide for the use of reference values such as ALI (Appendix D).

After prenatal exposure to some radionuclides, there are meaningful fractional amounts of residual activity at birth. Where appropriate, these values were extracted from tables in Appendix A and are summarized in Table 4 and discussed in Subsection D of this section. Dosimetric implications of this residual activity are also considered and estimates of their contribution to postnatal radiation doses are given (Table 5). Subsection D also provides further discussion of the prenatal and postnatal dosimetric implications associated with localized depositions of radioactivity in volumes of the feto-placental unit.

C. Information for Selected Radionuclide Groupings

1. Inorganic Hydrogen and Carbon

Hydrogen has two stable isotopes and one radioactive isotope, ^{3}H, which is usually referred to as tritium. Tritium is continuously produced in nature by the reaction of fast neutrons in cosmic rays with atmospheric nitrogen but is likewise formed in fission reactors. It is naturally encountered in many forms, ranging from the gas to inorganic compounds such as tritiated water and to a variety of organic compounds.

Carbon has two stable isotopes and six radioisotopes. The most commonly encountered radioisotope, ^{14}C, is produced by cosmogenic interactions and occurs in nature. Because its half-life is over 5,000 years, it is widely used for carbon-dating of ancient materials. Radiocarbon is also produced in nuclear reactors and ^{14}C is used in procedures such as metabolic tracer studies. Another important radioisotope is the short-lived positron emitter, ^{11}C, which is used in Positron Emission Tomography (PET) imaging studies. Like tritium, radiocarbon can be encountered in many forms, from inorganic gaseous compounds such as CO and CO_2 to a wide range of organic compounds. The distribution kinetics in biological systems depend on the chemical form in which it enters the body.

a. General Characteristics and Biological Behavior

Tritium, either as the gas or incorporated into water molecules, is readily absorbed from the lung or gastrointestinal (GI) tract (ICRP 1979, 1989). The usual assumption is that water vapor and hydrogen gas readily cross the lung capillaries equally in both directions. Most free hydrogen in air forms water, as does some of that which is absorbed, so that little tritium actually enters the body as gas. The behavior of this fraction should not markedly differ from that of water, the same f_1 value of 1 is considered to apply, and a single model is used for both forms.

The atomic weight of tritium is three times that of the most abundant isotope of hydrogen, ^{1}H, so that an 'isotopic' or 'mass' effect may occur in some reactions. In particular, the specific activity of tritium in the water of expired air has been measured as being lower than that in plasma. This phenomenon could lead to higher radiation doses with chronic exposures than would be

calculated from single acute exposures (Robertson 1973). It is not likely that significant effects of this sort would be detected under ordinary conditions involving exposure of the embryo/fetus.

b. Fetoplacental Considerations

The percentage water content of the embryo/fetus tends to be greater than that of the adult, with an inverse age relationship, so that relative tritium concentrations may be greater (Widdowson 1968). The total percentage and time relationships are species-dependent; the uterine mucosa also tends to have a cyclically higher water concentration than average body, and this may be further increased in pregnant women. Diametric micro-dosimetric considerations result from the dilution of biologically relevant molecules in tissue. These theoretical differences are assumed to not have sufficient practical consequence for inclusion in the model. The high diffusibility of water should lead to there being the same concentration in the implanting blastula as in uterine or extracellular fluids and the model assumes uniform distribution throughout the uterine mucosa.

Models for tritiated water are based on the assumption that water freely crosses most membranes, including the placenta, in both directions. Transfer of tritiated water is routinely used as a marker to detect functional deterioration of the biological preparation in studies of placental transport. Tritiated water is assumed to be uniformly distributed throughout the soft tissues of the woman and embryo/fetus and to have the same 10-day biological half-life in the embryo/fetus and in the adult.

Carbon dioxide and carbon monoxide are the most likely inorganic forms in which radiocarbon may be encountered in the environment. A more likely source is the carbon dioxide that is generated in the maternal body, as well as the embryo/fetus, as a result of catabolism of labeled organic compounds. The model considers this as being transferred from fetal to maternal blood and rapidly excreted through her lungs.

c. Biokinetic Models

The biokinetic model assumes that tritiated water is uniformly distributed throughout the adult body, including the uterine mucosa. It is assumed that the tritium is readily available to the early implanting embryo, which will have the same concentration as the mucosa, and that it freely crosses the placenta and most other membranes, in both directions. The model assumes that the concentrations of tritium in the conceptus and throughout the pregnant woman almost immediately become the same, irrespective of stage of gestation, so that the amounts of activity are directly proportional to relative masses. It is also assumed that tritiated water in the embryo/fetus, irrespective of whether it entered by placental transfer or was formed by catabolism of organic molecules, readily exchanges and is excreted in parallel with its loss from the woman's body, with the same biological half-life of 10 days.

The calculated values of deposition and retained fraction in the embryo/fetus are shown in Table A1 (Appendix A) for administration of the inorganic form of ^{3}H, i.e., tritiated water. These are given for successive 30-days intervals, representing the months of gestation.

d. Dosimetric Models

Tritium has a half-life of 12.28 years and emits beta particles with a maximum energy of 18.6 keV and an average energy of 5.7 keV. The carbon isotope of major interest, ^{14}C, has a half-life of 5,730 years, emits beta particles with an average energy of 0.049 MeV, and decays to ^{14}N. All of the energy was assumed to be deposited in the region that contains the ^{3}H or ^{14}C and radiation absorbed doses were calculated with the entire embryo/fetus as target. The resulting dose rates and doses to the embryo/fetus from introduction of unit activity (1 μCi) of tritiated water into the woman's circulation are given in Table B1 (Appendix B).

2. Tritium and Carbon in Organic Compounds

a. General Characteristics and Biological Behavior

The biochemical literature provides extensive information about the behavior of organic compounds that were labeled with tritium and radiocarbon as tracers, but the radiation protection literature provides few evaluations of these tracers per se (Kistner et al. 1987). These compounds have disparate behaviors and a few materials have been selected as 'typical' to provide illustrations. To avoid the need for overly detailed information about the metabolism of the parent compounds, many of which first require digestion, the materials are considered in the form that is present in blood after absorption and thus represents the nominal 1 μCi that is introduced into the blood of the pregnant woman. In general, however, an f_1 value of 1 is assumed for compounds of interest after they have been digested.

b. Fetoplacental Considerations

Generic models and dosimetric examples of the behavior of labeled organic compounds are based on glucose, which typifies hexoses, and leucine, which serves as a prototypic, well-utilized amino acid. These materials usually are ingested in foods that require digestion before gastrointestinal absorption, but they will be considered only in representative forms that are in blood after they have been absorbed and constitute the woman's initial burden. Other hexoses and amino acids may be assumed to have behaviors such that radiation doses to the embryo/fetus are not greater than for the specific examples (Meznarich et al. 1987).

Glucose: Glucose is actively transported from maternal to fetal blood and concentration differences also serve as a major driving force for placental transfer. Fetal glucose provides energy and serves for synthesis and body growth. During late gestation, glucose consumption by the uterus and its contents represents 30% of total maternal utilization and transferred glucose provides roughly one-half of the energy requirement for the fetus (Hay and Meznarich 1989). Glycolysis of tritium-labeled glucose produces tritiated water, which exchanges and distributes throughout the intracellular and extracellular water pools in both maternal and fetal compartments. The small fraction of tritiated water that may become incorporated into lipid via lipogenesis will be ignored in this model. Radiocarbon-labeled glucose is oxidized to $^{14}CO_2$ (ICRP 1981). This does not accumulate in the fetus because it is rapidly transferred to the mother via the placenta, and then exhaled (Meschia 1982).

Amino acids: Most studies of amino acids have been directed at metabolic aspects and there is limited information concerning the relative fetal to maternal tissue radioactivity concentrations for any one amino acid. Amino acids are placed into two main metabolic categories: essential amino acids, which are the most thoroughly studied, and nonessential. The essential amino acid, leucine, is the most commonly used marker for studies of amino acid and protein metabolism during fetal development, and confirmatory data have been provided by the results of studies with other amino acids (Meschia 1982).

Most amino acids are actively transferred across the placenta in both directions and the net flux is from the maternal blood circulation to the fetal circulation. In general, the concentrations of free amino acids in fetal tissues are similar to those in maternal tissues.

Concentrations of total amino acids in fetuses are similar among species at comparable stages of maturation. Amino acid nitrogen accounts for about 80% of total nitrogen in fetuses and the major function is to serve as metabolic components for synthesis of proteins.

Thymidine: Most information concerning thymidine in intact animals has been obtained from injections for labeling of cell populations and for studies of long-term toxic effects, which included developmental stages.

Publications by the ICRP (1981) and NCRP (1979a, 1979b) consider that from 1/10 to 1/5 of available thymidine is absorbed from the gastrointestinal tract in that form. Injected tritiated thymidine is cleared from the peripheral circulation of the adult with a half-time of 2-3 minutes and about 50% is incorporated and the other 50% is catabolized to water and excreted (NCRP 1979b). There are not major differences between the metabolic behaviors of ^{3}H- or ^{14}C-labeled thymidine in intact animals. Both precursors are incorporated into the DNA of proliferating cells, where it remains until the cell divides when it is partitioned between the daughter cells. Moreover, some may be re-utilized when the cell dies so that there is long-term retention of the incorporated thymidine.

c. Biokinetic Models

Glucose: The mass of distribution of both ^{3}H or ^{14}C sugars is assumed to be the body of the woman, exclusive of the skeleton. In early pregnancy, glucose is uniformly distributed throughout the soft tissues, including uterus and uterine mucosa. When placental transfer becomes an important consideration, after the beginning of the fetal period, glucose still is modeled as crossing to the fetus with a half-time of 0.01 day, and the concentration is not considered significantly different from the average in the woman. Fetal concentration of some hexoses may be less, but for broad considerations the generic average may be assumed, recognizing the possibility of overestimation.

The model assumes that one-half of the glucose in the woman and in the embryo/fetus is catabolized for energy with a half-time of 0.25 day. The products are tritiated water, which is retained with the 10-day half-life used above, and carbon dioxide, which is considered to cross the placenta after formation and to leave via the woman's lung. The other one-half of the glucose is assumed to be converted to glycogen or other persistent molecules, and retained with an effective 50-day retention time.

Amino acids: Significant amounts of labeled amino acids are incorporated into protein during organogenesis or the growth phases of gestation. It may be anticipated that there would be a high proportional retention of the activity as compared to the dam. Concentration concurrently would be reduced through dilution by further incorporation of amino acids during progressive growth, so that consistently major deviations from maternal concentration would not be expected.

Amino acids that are not required for protein synthesis are oxidized and provide approximately 25% of the fetal energy requirement (Battaglia and Meschia 1978). Oxidation of ^{3}H-labeled amino acids produces tritiated water; as was indicated for glucose, this exchanges and distributes throughout the intracellular and extracellular water pools in both maternal and fetal compartments. Small amounts of ^{14}C-labeled amino acids may enter carbohydrate pools after oxidation, but the predominant fraction forms $^{14}CO_2$, which is rapidly eliminated as described in the previous section.

The model considers that amino acids display uniform initial distribution at the same concentration as that in the soft tissues of the woman. Thus, when weighted over the fetal period, it is assumed that 50% is synthesized into proteins or other structural materials. These molecules may be retained throughout gestation but internal exchanges lead to an effective retention time considered to be 50 days.

The partition of this activity changes during tissue differentiation. Catabolism of amino acids for energy production might be higher during pregnancy, but there are no reliable data relating metabolism to stage of gestation. For the general case, the model assumes that the other 50% of the amino acids in the embryo/fetus is catabolized to water or CO_2 during the first day; these are retained or excreted as described above, and fetal distribution is considered uniform.

The calculated values of retained fraction in the embryo/fetus after administration of a hexose or amino acid labeled with ^{3}H or ^{14}C are shown in Tables A2 and A3 of Appendix A, respectively, for administration at successive months of gestation.

Thymidine: Based on similarities of ^{3}H- and ^{14}C-labeled thymidine in intact animals, a general scenario assumes a 5-minute half-time in the maternal circulation prior to incorporation of activity into proliferating cells. The wide range of proliferating fractions among tissues primarily affects the value assumed as the mass of distribution for adult dosimetry. The NCRP model in Report No. 63 (1979b) assumes 10% of the total as the mass of distribution for proliferation. This would amount to 5.8 kg in a 58 kg nonpregnant woman; the uterine mucosa, embryo, and extraembryonic tissues could be included in this compartment. Inclusion would not affect mass and this situation could be considered to pertain through 3 months of gestation.

Thus, initial thymidine concentrations in the embryo/fetus are considered as being essentially the same as in the woman. The activity is modeled as being partitioned with equal participation of the uterine contents (placenta and fetus primarily), but the model considers that fractional activity progressively increases with mass through gestation. Retention is considered to be the same in the woman and conceptus because any differences that result from differential division rates should be small. It is also assumed that any preexisting maternal burdens are essentially unavailable for transfer.

A fraction, estimated as about 50%, of activity entering the transfer compartment of the adult is incorporated and remains in the DNA with long-term retention (NCRP 1979b). Most of the remaining 50% is rapidly catabolized to water or carbon dioxide and excreted. The central value, 30 days, is for biological half time in adults and includes re-utilization and/or cells leaving the proliferating pool, and ignores transfer of water or CO_2. Subsequent increases of mass of the pregnant woman are assumed to be mostly water, fat, and uterine contents. Because proliferation is rapid and the proliferating fraction is large, re-utilization should be high in the embryo/fetus; 80% is assumed as the fractional retention through the remainder of gestation. Changes in this fraction with stage of gestation might be expected, but such effects are beyond evaluation because of programmed cell death; details such as isotopic mass effect would further reduce validity.

d. Dosimetric Models

As noted above, tritium has a half-life of 12.28 years and emits weak beta particles with an average energy of 5.7 keV. The carbon isotope of major interest, ^{14}C, has a half-life of 5,730 years and emits beta particles with an average energy of 0.049 MeV. The other isotope of interest, ^{11}C, has a 20.4-minute half-life and decays by emission of a positron with an average energy of 0.39 MeV together with gamma rays.

All of the energy was assumed to be deposited in the region that contains the ^{3}H or ^{14}C. Radiation absorbed doses were calculated with the entire embryo/fetus as target. Dose factors were calculated directly from the deposition and retention values given in Tables A2 and A3. The dose rates and integral doses to the embryo/fetus from introduction into the woman's circulation of unit activity of ^{3}H in an organic compound, such as glucose or an amino acid, are shown in Table B2. Comparable dosimetric values are presented in Table B3 for these organic compounds when they are labeled with ^{14}C.

Thymidine dosimetry illustrates uncertainties that are independent of placental transfer because, irrespective of the label, thymidine is contained almost entirely in the chromosome. Because the path length of the tritium beta particle is so short, the primary dose is to the cell nucleus, but the dose is more uniform throughout the labeled cell with ^{14}C. Irrespective of the specific volume in which the energy is absorbed and depending on the circumstances, it may be averaged over whole cell, tissue, or organ, or the body mass for statements of specific or average dose.

3. Phosphorus

Phosphorus has a single stable isotope, ^{31}P. It has several radioactive isotopes and cyclotron-produced ^{32}P was used for early metabolic studies. This isotope was among the first radioelements detected in effluent waters of production reactors and in the food chain, including fish. Because of these findings, as well as the biological and biochemical importance of phosphate, studies have addressed its metabolism using both the stable element and the radioisotope. Dose factors for an additional radioisotope, ^{33}P, are given in ICRP Publication 53 (1988) relative to its clinical use.

a. General Characteristics and Biological Behavior

Phosphorus is an essential constituent of the human body and is integral to the structure and biochemistry of protein, DNA, and bone. The daily intake of phosphorus in food and fluids is 1.4 g and the body content of Reference Man is given as 780 g, with 50 g in muscle and 700 g in skeleton (ICRP 1975). The fractional uptake of phosphorus from the gastrointestinal tract and lung is considered to be 0.8 for all compounds (ICRP 1979). Most compounds are assigned to inhalation class D but some phosphates are assigned to class W.

Further information about general metabolic models for radiopharmaceutical systematics is presented in ICRP Publication 53 (1988) and reports by the RIDIC (Watson et al. 1992). Modifications are used here to provide a model for estimation of radiation doses to the embryo/fetus from general intake by a pregnant woman. Comments relative to dosimetry after it is administered as a radiopharmaceutical are given in Section VII of this report.

b. Fetoplacental Considerations

The radioisotope, ^{32}P, can be produced in accelerators and, because of the metabolic importance of phosphorus compounds, the earliest mammalian developmental studies preceded its availability from nuclear reactors. One such study in rats found a slow placental transfer of phospholipid but more rapid transfer of phosphate and increasing specific activity with gestational stage (Nielson 1942). A study of transfer and effect of ^{32}P-phosphate on prenatal growth in guinea pigs (Wilde et al. 1947) developed fundamental approaches to analysis of transfer kinetics and demonstrated that the transfer rate per unit placenta weight increased 10-fold between 31 days of gestation and term but that the amount transferred was approximately equal to the total retained in growth. Subsequently, reactor-produced ^{32}P-phosphate was used for transfer studies in sows (Newland et al. 1960), for modeling of transport in the developing eggs of chickens (Epstein and Wolken 1951), and modeling studies with sea urchins that provided a theoretical groundwork (Green and Roth 1955).

Gestational-stage evaluations of anomalous prenatal development after ^{32}P-phosphate administration to pregnant rats during implantation or organogenesis included measurements of placental transfer and prenatal distribution (Sikov and Noonan 1957). Comparative measures were determined as components of studies of postnatal effects of exposure during the fetal period (Sikov and Lofstrom 1957). An overall analysis (Sikov 1961) indicated that relative concentrations in the embryo/fetus, rapidity of reaching maximum amounts of radioactivity, and retention of activity all increased as the ^{32}P was administered at successively later stages of gestation, from pre-implantation to organogenesis through the late fetal period. The differences were sufficiently great that cumulated self-dose (uncorrected for size or absorbed fraction) during the prenatal period was greater after administration during later gestation than at earlier times. Distribution measurement during fetal stages found the highest concentrations in the skeleton, somewhat lower values in the liver, and concentrations that were markedly lower in other tissues including the placenta.

c. Biokinetic Models

Based on descriptions in ICRP Publications 30 and 53, phosphorus that enters the maternal transfer compart-

ment is modeled as having a retention half-time of 0.5 day. During this distribution period, 15% of the activity goes to excretion, 30% to skeleton, and 55% to remaining tissues. The 15% that goes to early excretion is considered to enter directly into the kidney and bladder compartment, from which it is eliminated with a 4-hour retention time.

The 55% of activity that goes to the remaining tissues rapidly partitions through the compartment that constitutes the other 85% of body weight. It is then redistributed between the fraction that is made up by the extracellular fluid (15%) and the remaining tissues (40%). Activity in the fluid is assigned a biological half-life of 2 days; this activity is translocated to the remaining tissue compartment, which has a retention half time of 19 days.

The 30% of the activity assigned to skeleton, which has a reference mass of 15% of body weight including marrow, is considered to be distributed with 15% each to cortical and to cancellous bone. Skeletal radiophosphate is variously assigned either a 1500-day or an infinitely long nominal biological half-time. These approximations do not enter into effective half-life because physical half-lives of phosphorus isotopes are much shorter, being 15 and 25 days for the longest-lived isotopes.

The general model was expanded to include the embryo/fetus by extrapolating patterns from animal experiments and integrating information on phosphate and calcium metabolism during human prenatal development. The model considers the embryo/fetus to be included in the component comprising 70% soft tissues plus skeleton, with masses as given in Table 2, Section II. When administration is made at times prior to major skeletal development, the model assumes that there is free transfer, that steady-state conditions apply, and that concentration in nonspecific tissue of the embryo/fetus are the same as in the general soft tissues of the woman, including uterus, uterine mucosa, and the contents. The model assumes that the steady-state for radioactivity in soft tissue also pertains in the embryo/fetus at subsequent times. Also, the associated biokinetics will lead to soft-tissue concentrations that remain roughly the same as maternal remaining tissue. Consequently, an additional decrease in concentration with growth is not required for the model.

The developing skeleton begins to play an increasingly important role in phosphate biokinetics at these stages. A parsimonious model was adopted because the data were inadequate to justify use of more complex kinetics. In adults, the concentration ratio of bone to soft tissue increases with elapsed time after the initial distribution phase as a consequence of the differences in retention times (ICRP 1979). This relationship also should apply to the fetus. Analyses of the literature have shown that the concentration of phosphate in the fetal skeleton and its components progressively increases throughout normal human gestation (Dickerson 1962, Widowson and Dickerson 1964, Widdowson 1968).

In the simplified situation that is used for the model at early stages, average concentrations of endogenous phosphate throughout the primitive tissues that will develop into the fetal skeleton are considered to be the same as fetal soft tissues. Skeletal concentrations then increase during subsequent gestational stages so that they ultimately reach and are maintained at values that are 10 to 20 times greater than those in general soft tissues of the fetus.

As the fetal bone develops, radioactivity that enters from exogenous sources is modeled as remaining without release, as in the adult model, and as drawing on soft tissue content, which remains in a steady state with the woman. The partition model yields an overall composite that defines the whole fetus concentrations to be the same as the woman's soft tissue concentration during the first two months of gestation. This is followed by a transitional period that provides a progressive rise throughout the third month to attain a relative whole fetus-to-maternal concentration ratio that is 2.8 times the woman's soft tissue concentration at times subsequent to 3 months of gestation. All of the activity in fetal bone is considered to be retained.

The age-dependent deposition and retention model inputs were set using the woman's body and skeletal weights and the fetal growth curve. This gave stage-related values for the initial deposition and retention as ^{32}P, as tabulated in Table A4 of Appendix A.

d. Dosimetric Models

The most important radioisotope, ^{32}P, has a 14.3-day half-life and emits a single beta particle with an average energy of 0.064 MeV. Assumptions underlying the prenatal metabolic model were based on differential disposition in fetal bone but this localization is not taken into account for calculating beta doses to the embryo/fetus. The gestational-stage-dependent dose factors for ^{32}P are given in Table B4, Appendix B.

Inhomogeneous Distribution: Radiophosphorus provides an example of factors that relate to inhomogeneous distribution and that might be included in a complete dosimetric description. As was noted in previous sections, the pattern of nonuniform distribution of radioactivity in the fetus affects biokinetics and the amounts of activity that are deposited and retained. For consideration of the dose limit, as stated, it makes little difference where in the embryo/fetus the energy is dissipated other than as relates to absorbed fraction of emitted particles, with the proviso that the activity was not deposited only on the surface of the embryo/fetus. Thus, nonuniform deposition does not complicate calculations of average or total body radiation absorbed dose to the embryo/fetus.

Inhomogeneities become a consideration, however, when there is interest in radiation dose to specific prenatal tissues. This nonuniform radiation dose could be meaningful to epidemiologic evaluations of radiophosphorus because skeleton and bone marrow are sites of interest for their potential effects. The magnitude of the radiation doses to developing bone or its progenitor tissues as compared to dose to nonspecific soft tissues changes with stage of gestation.

4. Chromium

Chromium has four stable isotopes; ^{52}Cr is most abundant at 83.3%. Among nine radioisotopes, the relevant isotope is ^{51}Cr, a gamma-emitter with a half-life of 27.7 days. This isotope has been used to label blood cells for clinical diagnostic evaluations and this special situation will be considered in Section VII that deals with radiopharmaceuticals.

a. General Characteristics and Biological Behavior

The absorption of chromium chloride and other simple compounds from the gastrointestinal tract is variable but, for purposes of dosimetry, ICRP Publication 30 (1980) identified the absorption fraction, f_1, as 0.01 for trivalent chromium and 0.1 for hexavalent chromium. It also was assumed that chromium entering the gastrointestinal tract following inhalation is in the hexavalent state.

The distribution and retention of chromium in the body also depend on the chemical form and route by which it is administered. Sodium ^{51}Cr-chromate has a marked affinity for erythrocytes, so it has been used for in vitro labeling of erythrocytes to measure their in vivo survival times. The chromate may label circulating erythrocytes in vivo; this radioactivity disappears from the circulation of normal persons with a biological half-time of approximately 30 days. Labeled platelets are retained in the circulation or tissues according to their remaining life. Intravenously injected chromic chloride does not enter the erythrocyte and about one-fourth of the activity is excreted within a day.

b. Fetoplacental Considerations

Deposition in the rat uterus, including placentas and fetuses, was measured at 3 days after intravenous injection of trivalent ^{51}Cr potassium chromate in serum albumin (Wallach and Verch 1984). They found values of 0.73 to 1.02% of the administered activity per fetoplacental unit or 0.17 to 0.26% of the activity per g.

These values were in agreement with their other measurements of about 8% of administered activity per pregnant uterus; this amounted to roughly 30% of the body content being in the uterus. They did not distinguish between placental and fetal deposition, but estimation gives a value of 2% in uterus, 4% in placentas, and 2% in fetuses.

Studies by Mertz et al. (1969) found that intravenous trivalent chromium did not significantly accumulate in the fetuses when given before or at the start of pregnancy. Significant amounts of a natural complex that was fed repeatedly throughout gestation entered and were retained by the embryo/fetus.

Wallenberg et al. (1978) found that ^{51}Cr ions from unbound-activity associated with labeled platelets crosses the placenta of monkeys. Estimates based on total blood and plasma counts suggested that 2% of unbound activity was transferred during a 5-day period and that the initial transfer rate was 0.05% of the administered activity during the first 3 hours. The authors extrapolated these data from the monkey to a human fetus with a weight of 1700 g (about 31 weeks of pregnancy). They estimated that administration of 20 μCi (0.74 MBq) of ^{51}Cr-labeled platelets would give a total radiation dose of 7.4 mrem to the fetus.

c. Biokinetic Models

Intravenously injected chromium chloride (^{51}Cr-III) is considered as the prototypic compound for the behavior of inorganic (ionic) chromium in adults. Chromic chloride is firmly bound by plasma proteins and does not penetrate the erythrocyte membrane so that normal subjects excrete about 25% during the first 24 hours after intravenous injection (ICRP 1988). The model assumes that 5% of chromium in the circulation goes to bone, where it is retained with a biological half-life of 1000 days. Based on scans and compartmental analysis, the assumed fractional distribution is 25% to liver, 2.5% to spleen, and the residual 72.5% is distributed uniformly throughout the remaining tissues. The model for total body retention in the human has three components with half-life values of 8 hours (30%), 10 days (30%), and 160 days (40%).

The concentration of chromium in the embryo is considered to be the same as that in the uterus through the first 60 days of pregnancy. Based on the inferred transfer fraction and retention, the model gives subsequent concentrations in the fetus that are one-half of the concentration of the remaining soft tissue of the woman. These gestational-stage-dependent model inputs were set for ^{51}Cr using the fetal growth curve and the weights of the woman's body and skeleton. This model gave stage-related values of deposition and retention, as tabulated for the maternal body in Table A5a and for the embryo/fetus in Table A5b (Appendix A).

d. Dosimetric Models

The relevant isotope is ^{51}Cr for general and radiopharmaceutical considerations. This has a 27.7-day half-life and decays by electron capture and emission of a 0.32-MeV gamma ray. The gamma energy was assumed to be deposited according to the stage-related phantom and radiation absorbed doses were calculated with embryo/fetus as the target. The gestational-stage-dependent dose factors for radiation dose to the embryo/fetus for maternal injection of ^{51}Cr are given in Table B5 (Appendix B).

The clinical uses involve injection of labeled cells and platelets for measure of their survival. These uses and the associated dosimetry will be considered in SectionVII that deals with radiopharmaceuticals; a table of radiation doses, based on calculations by others, is given as Table 9 in that section.

5. Iron

The most abundant stable isotope of iron is ^{56}Fe (92%); there are three other stable isotopes and several radioactive isotopes. Two radioisotopes, ^{55}Fe and ^{59}Fe, are most relevant to radiological protection evaluations from

the standpoint of reactor contamination. These, together with ^{52}Fe, also have been the most important from their use in nuclear medicine. Results from clinical practice and nutritional evaluations have provided the information about biological behavior in the human that is incorporated into the biokinetic model described below.

a. General Characteristics and Biological Behavior

Iron is a natural body constituent, with a content in Reference Man of 4.2 g, with 3.3 g in soft tissues; daily intakes are 16 mg in food and drink (ICRP 1975). Common models such as MIRD Dose Estimate Report No. 11 (Robertson et al. 1983) and ICRP (1988) consider that the amounts of total-body iron and of storage iron are less in women than in men. Iron plays an critical role in hematopoiesis, being an intrinsic component of the hemoglobin molecule, which contains the major fraction. Smaller fractions are stored as ferritin and hemosiderin and there are lesser amounts in other compartments. The role of iron in hematopoiesis also pertains in the embryo/fetus through most of gestation.

The extent of gastrointestinal absorption of iron is influenced by chemical form, and ferrous salts may be absorbed to a greater extent than ferric salts. Absorption is also affected by the presence of interfering substances, iron content of the diet, and body iron stores, but the fractional absorption from the gastrointestinal tract of all iron compounds, f_1, is considered to be 0.1 in normal individuals. Absorption may be elevated in a pregnant woman and a higher value of 0.5 applies under conditions of iron deficiency (ICRP 1980, 1988). Oxides, hydroxides, and halides of iron are assigned to inhalation class W and all other compounds to inhalation class D.

The metabolic model in ICRP Publication 30 (1980) assumes that 8% of iron leaving the transfer compartment is distributed to liver, 1.3% to spleen, and the remainder is uniformly distributed throughout all other organs and tissues of the body. The model given by MIRD and ICRP Publication 53 for radiopharmaceutical iron essentially considers that the activity is rapidly cleared from the plasma and accumulates in the red marrow, where it is incorporated into and remains in the hemoglobin of erythrocytes.

Based on assumed red cell distribution, MIRD considers that the longer-lived radioisotopes, ^{55}Fe and ^{59}Fe, follow the distribution pattern of circulating RBC: 5% in liver, 5% in spleen, 4% in marrow, 8% in the heart, and 78% in other organs and tissues of the body. The radioiron is not released until after the death of the red blood cell, which has a half-time of 120 days, when the cycle is repeated. This model does not apply to short half-lived radioisotopes, such as ^{52}Fe, which may decay before incorporation into circulating red cells.

b. Fetoplacental Considerations

The placental transfer and biological disposition of ^{59}Fe have been studied extensively and analyses of data have identified two major patterns for transfer to the fetus (Seal et al. 1972). In species with hemochorial placentas, there is a rapid route that involves the release of serum iron from transferrin to the placenta and its movement into the fetal circulation. By two to three hours, 5% or more of the maternally injected ^{59}Fe is transferred to the near-term fetus. Iron does not seem to be transported to the fetus by transferrin although it may act together with other mediators. Iron transport is bidirectional but net transfer is essentially unidirectional in species with hemochorial placentas. In species that have placental types other than hemochorial, the route seems to involve release of maternal hemoglobin from extravasated red cells in phagocytic zones of the chorioallantoic membranes. Transfer of ^{59}Fe amounts to less than 0.1% in periods up to 24 hours after injection (Anghileri et al. 1985).

Iron transport measurements of transfer across of the placenta of rhesus monkeys utilized ^{59}Fe that was injected into the maternal circulation of some of the animals or was injected into the fetal circulation of the others (van Dijk 1977). Data from these experiments were used to develop a compartmental model of iron transport and rate constants were calculated for a five-

compartmental system. As above, transport from mother to fetus seemed more efficient than in the reverse direction and the results of the compartmental analyses agree with the compartmental model of Robertson et al. (1983).

Iron content in human pregnancy was determined by Baglan et al. (1974), who found that concentrations in the maternal and fetal blood were approximately equal but concentration in the placenta was three to four times lower. The mechanisms by which iron traverses the human placenta are not clear, but it is known that in the rat near-term transfer is achieved against a concentration gradient (Fletcher and Suter 1969, Glasser et al. 1969). These data have been interpreted as suggesting that placental transfer of iron involves an active transport mechanism (Galbraith et al. 1980). Transfer is maintained in the presence of inadequate maternal iron stores, even causing iron deficiency in the woman (Beaton 1974).

Hahn et al. (1951) orally administered ^{59}Fe to 819 pregnant women during early pregnancy and found that 1 to 3% of the administered activity was present in fetal blood at birth. The findings led Dyer, Brill, and their colleagues to evaluate these results and obtain further data from measurements in patients undergoing therapeutic abortion and studies in experimental animals (Dyer and Brill 1969, 1972, Dyer et al. 1973). Liver was the major site of fetal deposition, reaching concentrations that were 200 times that of the remainder of the fetal body at times through mid-gestation. Their measurements disclosed that there was a lesser relative difference associated with the liver of sheep. Extrapolation of the comparative data led to assumptions of partition at other stages of the human fetus, e.g., 36-38 weeks of age, beyond those that were measured directly. Partition is considered to be increased at these ages in the younger fetus.

In their evaluations of fetal dose, Dyer and Brill (1969) calculated beta self-dose to fetal liver, liver to fetus gamma dose, overall self-dose, and gamma dose from the maternal activity. The contribution from maternal activity was the most prominent source of radiation dose. They calculated that the total fetal dose for exposure during the period between 9 and 22 weeks of gestation would be about 38 rad/μCi. There were some differences in liver dose through this period, but the values ranged from 331 to 536 rad/μCi. Liver self-dose should be part of dose, but early retention in liver would not pertain over time as it would be released as red cells.

Roedler (1987) combined various data with the MIRD model of iron kinetics (Robertson et al. 1983) to calculate concentration ratios for times between 9 and 22 weeks of gestation. The ratio of the fetal to adult livers was 80. The physical and effective half times of ^{59}Fe were estimated as 45 days in adults but effective half time was 3.2 days in the fetus corrected for growth. In the fetus, 12% of the activity was assumed to be in storage and 88% in erythropoiesis, with effective half-times of 10.7 days and 2.2 days, respectively.

c. Biokinetic Models

Intravenously injected iron is modeled as being distributed to all of the maternal tissue with a 0.25-day half-time, and then translocated so that it is incorporated into erythrocytes that become uniformly distributed and retained indefinitely. It is assumed that red cells do not cross the placenta, and that the rate at which iron from destroyed cells becomes available is low enough not to require inclusion in the model. The early embryo is embedded in the uterine mucosa. The model assumes that the concentration of radioiron in the early embryo is the same as in the uterus and that radioiron-containing erythrocytes are in the surrounding uterine tissue.

The concentration of radioiron in the embryo/fetus after completion of distribution is considered to be greater than that in the woman. The fetus displays increasing avidity in order to fulfill its iron needs for erythropoiesis. Activity is modeled as being three times the ratio of the fetal to maternal masses at 90 days of gestation. This ratio pertains through 150 days of gestation. Because of progressive build-up of iron stores, there is

decreased transfer. Thus, the model considers that the ratio decreases to a factor of two at 180 days and to concentrations that are the same as those in the woman at 210 days and thereafter. The transitional periods are modeled as involving a linear increase between 60 and 90 days of gestation as well as gradual decreases during the times between 150 and 180 days and between 180 and 210 days.

Dyer and Brill (1969) and Roedler (1987) modeled a high concentration ratio of embryo/fetus liver to woman's liver at earlier gestational ages and times after administration. The ratio would progressively be reduced as the masses of the embryo/fetus increased; thus, the value would be too high to be used as the overall concentration ratio. Moreover, when the total mass of the embryo/fetus is used as the basis for dose calculation, liver content per se becomes a less dominant factor.

Deposition and retention values for iron in general elemental form are given in Appendix A. Fractional activities in the maternal body and in the embryo/fetus are shown in Tables A6a and A6b, respectively, for ^{55}Fe. The corresponding activity values for ^{59}Fe are given in Tables A7a and A7b.

d. Dosimetric Models

An important radioisotope of iron from the standpoint of reactor contamination is ^{55}Fe; this has a half-life of 2.7 years and decays to stable manganese by electron capture. Another radioisotope, ^{59}Fe, emits several beta particles (0.116-MeV average energy) and gamma rays; it decays to stable cobalt with a half-life of 44.5 days. Calculations of dose factors for these isotopes of iron in their usual elemental form were based on the above deposition and retention values. The resulting dose rates and doses to the embryo/fetus are given for ^{55}Fe in Table B6 and for ^{59}Fe in Table B7.

Although not substantively different from these elemental forms, dosimetry of these isotopes of iron as radiopharmaceuticals has been evaluated by others. These calculations will be considered in Section VII, which deals with radiopharmaceuticals.

6. Cobalt

Cobalt has a single stable isotope, ^{59}Co. Several radioisotopes are produced by incidental as well as purposeful activation in nuclear reactors. The most commonly encountered isotope, ^{60}Co, is produced by neutron bombardment of stable ^{59}Co; it has a half-life of 5.27 years so that it is persistent in reactor piping and hardware. Sealed sources containing ^{60}Co are used in medical radiation therapy devices and in industrial radiography. Radiocobalt sources are used in thickness gauges and calibration devices and are thus relevant to numerous other occupational and environmental situations.

Also of importance are ^{57}Co and ^{58}Co that are used to label vitamin B-12 for diagnosis of pernicious anemia and determination of vitamin absorption and turnover rates in patients. These uses will be considered in Section VII, which deals with radiopharmaceuticals.

a. General Characteristics and Biological Behavior

Cobalt is a natural constituent of the human body, with a content in Reference Man of 1.5 mg, with 0.11 mg in the liver (ICRP 1975). Water and many foods contain low concentrations of inorganic cobalt; it may be bound to organic molecules, particularly proteins. Cobalt is an intrinsic component of the vitamin B-12 molecule, which is present in many foods of animal origin.

Cobalt is assumed to enter blood as the chloride, and its fractional absorption value, f_1, was taken as 0.1 in ICRP Publication 67 (1993). Absorption of dietary cobalt tends to be even greater. The ICRP in Publication 30 chose 0.3 as the absorption fraction for nonspecific organically complexed compounds. Absorption of cobalt oxides from the gastrointestinal tract is minimal and f_1 is taken as 0.05 for oxides and hydroxides (ICRP 1979). Oxides, hydroxides, halides, and nitrates are assigned to

inhalation class Y and all other compounds to inhalation class W.

The fraction of vitamin B-12 that is absorbed from the GI tract of normal individuals is taken as 70%. Absorption and biological disposition of the radiopharmaceutical relates to clinical state and conditions associated with the administration, as will be considered in Section VII.

b. Fetoplacental Considerations

Zylicz et al. (1975a, 1976) studied the distribution of intravenously injected $^{60}CoCl_2$ in pregnant rats as a function of gestational age. They found no significant differences between retention at 24 hours compared to rats that were not pregnant. The radioactivity in the fetoplacental unit increased with time and the concentration of ^{60}Co in the blood of the fetus after injection on the 20th day of gestation was about four times greater than in the blood of the mother. Concentration in the fetal liver was about 1.5 times that in the kidney, but both were lower than that in the liver and kidney of the mother.

Autoradiographic studies detected the highest concentrations of $^{60}CoCl_2$ in cartilaginous structures, liver, kidneys, and pancreas of pregnant mice (Flodh 1968). The placenta accumulated moderate amounts of radiocobalt throughout the study, with a slight increase during the first 24 hours after administration. The total fetal accumulation of ^{60}Co at all intervals studied was lower than that of the mother, but there was selective accumulation in the fetal skeleton during the first days after administration. Except for the liver, which showed a fairly high concentrations at 4 days after injection, low concentrations were observed in the soft tissues of the fetuses, and the fetuses had no noticeable radioactivity after 16 days.

Baglan et al. (1974) measured the cobalt content of human placentas, maternal blood, and fetal blood. All concentrations were low but the concentration in the placenta was about 10 times higher than in blood; concentrations were approximately equal in maternal and fetal blood.

Autoradiography after injection of pregnant mice with vitamin B-12 indicated that concentrations in blood were lower than in most tissues at 15 minutes and almost undetectable at 4 hours (Ullberg et al. 1967). Placental activity was the highest of all tissues, reaching a peak concentration at about 1 hour. This activity was slowly translocated to the fetuses through 24 hours, reaching higher concentrations than the maternal tissues. Fetal uptake was dose-dependent; fetal concentrations were 130 times those in maternal tissues at low vitamin dosages and 95% was retained at 24 hours. With larger dosages, the fetuses had concentrations that were only 5.5 times higher than maternal tissues, and 11% of the activity was retained at 24 hours.

At 1 hour after administration of ^{57}Co-labeled vitamin B-12 to pregnant rabbits, the concentration in the placenta was 0.35 of that in maternal blood but 110 times that in the fetus (Mahon et al. 1973). At that time, the blood contained 90% of the administered activity, liver 6%, kidneys 2%, and marrow 10% but placenta plus fetus compartment had less than 1%.

Luhby et al. (1958, 1959) administered single, small tracer doses of ^{58}Co-labeled vitamin B-12 to pregnant women to determine the range and kinetics of placental transfer. Transfer to the fetus ranged from 0.3% to 28% of the amount administered. More than 90% of the activity was present in tissue, rather than in placental blood, for several hours. Substantial amounts were not transferred until 24 hours after administration and maximum transfer occurred within 15 to 21 days. The range of deposition of ^{58}Co vitamin B-12 after maximum placental transfer occurred was 1.5% to 2.0%.

c. Biokinetic Models

As indicated above, cobalt metabolism, including its retention, placental transfer, and fetoplacental distribution, depends on the chemical form, which is different

for vitamin B-12 than for inorganic or nonspecific organic compounds. Placental transfer information is generally consistent for categories of compound. It is assumed that nonspecific organic forms are absorbed as cobalt chloride and these are the biokinetics that are modeled. Basic metabolic and kinetic models are based on descriptions given in ICRP Publications 30 (1979) and 67 (1993). The basic model for vitamin B-12 is that presented in ICRP Publication 53 (1988).

Inorganic Cobalt: One-half of the inorganic cobalt entering blood is assumed to be excreted with a half-life of 0.5-day; the other one-half is transferred to the woman's tissues and the transparent placenta with the same 0.5-day half-time. Essentially all activity is cleared from blood by 24 hours after injection and is distributed among several organs and tissues. The elevated concentrations in liver do not affect the present placental transfer biokinetic model, which treats maternal tissue as a single compartment. Of cobalt translocated from the transfer compartment, 60%, 20%, and 20% are assumed to be retained with biological half-times of 6, 60, and 800 days, respectively (ICRP 1979).

Cobalt transfer to the embryo/fetus is such that the stage-dependent fraction of activity is proportional to corresponding relative weights. Transfer rate coefficients are set to accommodate the slight build-up in the placenta, with all concentrations becoming equal at 1 day. Concentration in the embryo/fetus, which could be decreased by growth, remains in a steady-state with the woman so that concentrations are modeled as remaining the same. Moreover, if hepatic concentrations are assumed to be four times those in the remainder of the body, this would also pertain to the fetus so that average concentrations also would remain the same.

The initial deposition and retained fractions of cobalt chloride were calculated for the radioactive isotopes most likely to be encountered. To provide for the recommended approach to calculation, stage-related values in relevant source compartments were calculated for ^{57}Co. These values are shown as the fraction of activity deposited and retained in the maternal body in Table A8a, the maternal liver in Table A8b, and the embryo/fetus in Table A8c. The same format is used to present fractional activity values in the three compartments for ^{58}Co (Table A9) and ^{60}Co (Table A10).

Vitamin B-12: The behavior of carrier-free vitamin B-12 in normal persons is derived from the biokinetic models described by the ICRP for radiopharmaceuticals in Publication 53 (1988). The small fraction that is excreted is ignored. For modeling purposes, all is considered to be distributed with a 0.25 day half-life. The liver takes up 60%; this is retained with a half-time of 500 days. The remaining 40% is distributed throughout the rest of the body and eliminated with half-times of 1.0 day (25%) and 500 days (75%).

The model considers that there is an initial deposition of vitamin B-12 in placenta, followed by a slow transfer to the fetus. By the day after administration, distribution in soft tissues of the fetus has become similar to that in the mother and the model considers this to be all tissues. For this purpose, the model leads to there being the same average concentration in fetal total body as in the mother.

The deposition of ^{57}Co-labeled vitamin B-12 and its retention in the maternal body are given in Table A11a; values for the maternal liver are in Table A11b and for the embryo/fetus are in Table A11c. The same format is used to present fractional activity values of vitamin B-12 in the three compartments for ^{58}Co (Table A12) and ^{60}Co (Table A13).

d. Dosimetric Modelss

Inorganic Cobalt: Dose calculations were performed for injection of simple inorganic compounds of these three radioisotopes of cobalt. The ^{57}Co decays by electron capture and gamma emission with a half-life of 271.8 days. The predominant decay of ^{58}Co is by electron capture and positron emission with a half-life of 70.9 days, and ^{60}Co decays by beta (0.094 MeV) and gamma emission with a half-life of 5.27 years. The gestational-stage-dependent dose rates and doses to the

embryo/fetus corresponding to the above distributions are presented in Tables B8, B9, and B10 for ^{57}Co, ^{58}Co, and ^{60}Co, respectively.

Vitamin B-12: Biokinetic models were developed by the ICRP (1988) for four combinations of clinical state and administration conditions associated with the use of radiocobalt-labeled Vitamin B-12 in nuclear medicine. Only the basic situation was used above for deriving the generic biokinetic model. The deposition and retention values corresponding to this generic model were used to calculate vitamin B-12 dose factors for the embryo/fetus in a normal woman. These values are tabulated in Tables C1, C2, and C3 of Appendix C. Some results that specifically relate to nuclear medicine are provided in Table 11 of Section VII.

7. Zinc

Zinc has five stable isotopes, but ^{64}Zn accounts for about one-half of the total. Among its almost 20 radioactive isotopes, ^{65}Zn is most frequently encountered. This isotope was among the earliest radionuclides detected in reactor effluent waters. Radiozinc enters into the food chain, which makes it of relevance for exposure of populations and dosimetry of the embryo/fetus. Another isotope, ^{72}Zn, is of secondary interest.

a. General Characteristics and Biological Behavior

Zinc is important for protein synthesis; it is essential for growth, sexual maturity, and wound healing; and it plays critical roles in prenatal development. The zinc content of Reference Man is 2.3 g with 1.8 g in soft tissues (ICRP 1975). Reported values of the uptake of orally administered zinc from the gastrointestinal tract vary widely, depending on daily intake and diet. The ICRP (1980, 1993) considers 0.5 as the fractional absorption of all compounds of zinc. All commonly occurring compounds were assigned to inhalation class Y.

b. Fetoplacental Considerations

Placental transfer of ^{65}Zn has been studied in several species of experimental animals, and agreement is adequate to broadly generalize the pattern across studies. Feaster et al. (1955) found that movement across the rat placenta to the fetuses was relatively free at all stages of gestation. Radiozinc concentration in organs paralleled total zinc values in maternal tissues; the highest concentration was in kidney, followed in order by liver, pancreas, and femur. Fetal content of zinc increased throughout gestation and reached a maximum at term.

During the first few hours after injection during earlier gestation, the greatest fraction of activity in the products of conception tended to be in placental tissues. However, activity in the embryo/fetus soon approaches the placental activity. After administration at subsequent times of gestation, the relative fetal activity progressively increases and placental activity decreases. Sharp upsurges of radiozinc uptake have been observed during intermediate periods of gestation of some species, similar to but slower than those found with radioiron. Other studies found that the transfer of radiozinc became more rapid with advancing pregnancy, indicating more efficient mechanisms of placental transport (Terry 1960, Matsusaka 1977, Schulert et al. 1969, Ferm and Hanlon, 1974 and Zylicz et al. 1975b).

Hansard et al. (1969) compared the fetoplacental distribution of ^{65}Zn in large animal species during the third trimester of pregnancy. The placentas and the fetuses each contained roughly one-half of the activity recovered in the products of conception in the gilts. In the ewes and heifers, the placenta contained about 40% and the fetuses about 60%. In gilts, the percent of injected activity in the maternal liver decreased by one-half in the period between 12 and 168 hours after injection. However, the activity in the liver of the fetuses increased almost 30-fold over this time period, while the activity in

the heart, kidney, and spleen remained approximately the same.

Zinc concentrations were found to be highest in the liver of human fetuses at 22 to 43 weeks gestation and then decreased with gestational age (Casey and Robinson 1978). Levels in skeletal muscle increased with age. There were no tissues that appeared to store zinc, indicating that all zinc available to the fetus would be utilized.

Baglan et al. (1974) found that 1) zinc concentrations in fetal blood were less than one-half those in maternal blood but that 2) concentrations in placentas were about four times those in fetal blood. Measurements of zinc concentrations in venous blood from 15 normal mothers and from the umbilical cords of their babies found that absolute levels of free zinc in the pregnant woman at term remained unchanged from the nonpregnant state (Henkin et al. 1971). However, they found that levels of total zinc were lowered in maternal serum at term primarily because of significant decreases in zinc-binding proteins. Mean fetal serum zinc concentrations, both bound and free, were not significantly different from levels in nonpregnant women.

Zinc concentrations in human embryos increased about seven-fold in the period of rapid growth from 31 to 36 days, during which mass doubled (Chaube et al. 1973). Little difference was seen among ages between 36 to 78 days of gestation There were no pronounced trends related to age, sex, or stage of development in zinc concentrations in the liver, brain, and kidney of fetuses from the second trimester.

c. Biokinetic Models

Whole-body retention of orally administered radiozinc has two components and is more tenaciously retained in the skeleton than in other tissues. The ICRP 30 model considers that 20% of zinc leaving the transfer compartment is translocated to the skeleton and retained with a biological half-time of 400 days. The remainder of the zinc in the transfer compartment is considered as uniformly distributed in all other organs and tissues. Thirty percent of this zinc (24% of total) is retained with a biological half-time of 20 days and 70% (56% of total) with a biological half-time of 400 days.

The model considers that activity in the transfer compartment is immediately distributed to the woman's skeleton and soft tissue, with distribution and retention functions as indicated in the preceding paragraph. This initial partition does not differ markedly from uniform and the model assumes that the embryo/fetus participates equally in this distribution with a fractional activity given by the ratio of its mass to that of the woman. This pattern is assumed to pertain at all stages of gestation. Average concentration would initially be the same as remaining tissues of the woman, and thereafter it would remain at the same concentration as the woman, with bidirectional transfer.

The gestational-stage-dependent values of deposition and retention in the woman are given in Table A14a of Appendix A. The corresponding values in the embryo/fetus are presented in Table A14b.

d. Dosimetric Models

Decay of ^{65}Zn is by electron capture and positron emission, with a half-life of 243.8 days. The gestational-stage-dependent dose factors for the embryo/fetus that were derived from the above retention values are given in Table B11.

8. Gallium

Gallium has two stable isotopes, ^{69}Ga (60%) and ^{71}Ga (40%). Four of the more than 20 radioisotopes are of particular interest because of their use in nuclear medicine. This section describes the background information for the biological behavior and placental transfer of gallium and develops biokinetic models. Deposition and retention in the embryo/fetus are generically exemplified

by ^{67}Ga , which has a 3.26-day half-life. Considerations specific to nuclear medicine will be given in Section VIII, Radiopharmaceuticals, and the dose factors are tabulated in Appendix C.

a. General Characteristics and Biological Behavior

Metabolic data for gallium are not given for Reference Man (ICRP 1975). The ICRP (1981) adopted a fractional gastrointestinal absorption value of 10^{-3} for all gallium compounds. Oxides, hydroxides, carbides, halides, and nitrates were assigned to inhalation class W and all other compounds to inhalation class D.

Studies on distribution and retention in various species and routes of administration show that the distribution and retention of radioactive gallium in the body is influenced by the amount of stable or carrier gallium that is administered (ICRP 1981). Intravenously injected gallium with carrier concentrates in bone, but carrier-free radiogallium as the citrate is more diffusely distributed.

b. Fetoplacental Considerations

Because of its use for placental localization, several studies have examined the disposition of gallium in pregnant animals. The reports include that of Mahon et al. (1973), who compared distribution of 15 different agents at 1 hour after injection in near-term rabbits. They found that the fetal activity of ^{67}Ga was among the lowest of the agents while placental activity was among the highest. This resulted in an individual placenta to individual fetus activity ratio of 34, with a corresponding activity concentration ratio of 200. Wegst (1981, 1992) measured distribution in rabbits at sequential times after administration at several stages of gestation. Total activities increased with gestational time, reflecting increases in tissue masses. In general, however, the activity in the placenta was 10 times that in the fetus at 24 hours.

Lathrop et al. (1992) obtained a closely spaced series of comparative measurements of gallium and indium clearance and distribution after intravenous injection in nonpregnant mice and mice on the day before expected delivery, or a few days earlier for more extended studies. The fraction of injected activity in the placenta rose rapidly and remained high subsequently but the fraction in the fetus continued to increase during the first day and was roughly constant at a higher level at times from 2 to 5 days. The placenta-to-fetus concentration ratio of gallium was about 6 at 15 minutes and increased to reach a value of about 9 during the 3-to 6-hour period. The ratio progressively decreased to a value of 2.6 at 24 hours and the fetus and placenta were the same at 48 hours.

In reviewing this literature, Roedler (1987) noted that the fetal-to-maternal concentration ratios of gallium ranged from 0.2 to 4. On the basis of MIRD Dose Estimate No. 2 (Cloutier et al. 1973), together with a combination of data from these reports, Watson (1992c) developed a biokinetic model of gallium that she used for calculating residence times.

The results derived from this model indicate that the placental activity can be considered to be about 10 times the fetal activity with little decrease occurring after uptake. The ratio of the concentration of gallium in the fetus at term to the concentration in the maternal total body immediately after injection as derived from this model would be about 0.85. The residence time from this model, together with mathematical models of the pregnant woman (Watson 1992a), were used to calculate radiation doses at the end of the first, second, and third trimesters. These reports and calculations are considered in Section VIII, Radiopharmaceuticals.

c. Biokinetic Models

The description in ICRP Publication 30 (1981) for carrier-free gallium was used as the basis for the biokinetic model. This model was adjusted on the basis of information in MIRD (Cloutier et al. 1973), ICRP (1988), and the evaluations of Watson (1992c).

Gallium is modeled as leaving the transfer compartment with the default half-time of 0.25 day, with initial depositions of 30% in mineral bone, 9% in liver, and 1% in spleen. The remaining gallium that leaves the transfer compartment is assumed to be distributed uniformly throughout all other organs and tissues of the body, including the transparent placenta. Of gallium deposited in any maternal organ or tissue, 17% is assumed to be retained with a biological half-time of 30 hours and 83% with a half-time of 613 hours.

Transfer of activity to the fetus is modeled by considering the placenta as consisting of two subcompartments, as was described in Subsection A. The radiogallium is retained with a 0.25 day half-time in the labile component. Activity that enters the non-labile subcompartment is retained more tenaciously, and a slower half-time of 5 days is assigned. These accommodate the high relative placental concentration levels that are considered as being twice those of maternal liver, 8-times those in her other soft tissues, and 10 times the fetus at early times. There is then a shift such that fetal concentration increases to become the same as the general soft tissues of the woman by 2 1/2 days. The model is simplified by considering than once activity is deposited, there is no clearance or cross-over from the fetus and ignores any additional deposition from gallium being cleared by the woman so that radiodecay controls subsequent activity.

The deposition and retention of ^{67}Ga in the woman and in the embryo/fetus relative to stage of gestation are given in Tables A15a and A15b, respectively.

d. Dosimetric Models

The values given in ICRP Publication 53 (1988), which is based on the MIRD dosimetry (Cloutier et al. 1973), provide estimates of the radiation dose to the uterus of a nongravid woman. This value is appropriate for an approximation of the radiation dose for the embryo/fetus from conception through times of two to three months of gestation.

Doses at these and later times were derived from the above tables of ^{67}Ga deposition and retention. Primary interest is relative to the use of gallium in nuclear medicine, which is discussed in Section VII. Therefore, the corresponding dose factor tables for ^{67}Ga in the embryo/fetus will be given in Table C5 of Appendix C, which corresponds to that section. Dose factors are presented for ^{66}Ga and for ^{72}Ga in Tables C4 and C6, respectively. A comparison of approach and doses obtained on the basis of residence times is presented in Table 12 and discussed in Section VIII.

9. Krypton

Krypton has six stable isotopes of which ^{84}Kr (57%) is most abundant. Several radioactive isotopes of krypton are produced in nuclear reactors, but the 10.7-year half-lived beta-emitter ^{85}Kr is of primary interest in radiological protection of the embryo/fetus.

The inert gas krypton is not a natural constituent of the human body and ICRP Publication 30 did not give a metabolic model. However, it was stated for xenon (ICRP 1980) that the internal radiation dose from an inert gas absorbed in tissue or contained in the lungs could be considered as negligible in comparison with the radiation from an external cloud. There are special considerations relating to potential exposure of pregnant women and the embryo/fetus to noble gas. The basis for the models and parameters relating to such exposures are developed in Section VI and dose factors are given in association with those descriptions.

10. Rubidium

Rubidium has two stable isotopes, ^{85}Rb and ^{87}Rb, with relative abundances of 72% and 28%, respectively. Among more than 20 radioisotopes and isomers, ^{86}Rb is of greatest interest for general radiological protection and is modeled in this section. As will be described in Section VII, different considerations pertain to the two isotopes of clinical relevance - the short half-lived ^{81}Rb (4.6 hours) and ultrashort ^{82}Rb (1.3 minutes).

a. General Characteristics and Biological Behavior

Rubidium is a natural constituent in the human body and the content of Reference Man is given as 0.68 g with 0.47 g in soft tissue (ICRP 1975). Rubidium is considered to be uniformly distributed among the organs and tissues of the body, except for mineral bone, which has a greater concentration than the average (ICRP 1975). The transport mechanisms are assumed to be similar to those for potassium, and rubidium is often used as a tracer for potassium in physiological studies (Dancis et al. 1983).

Rubidium is almost completely absorbed from the gastrointestinal tract and the f_1 value is considered as 1 (ICRP 1980). All compounds are assigned to inhalation class D.

b. Fetoplacental Considerations

Saperstein (1958) found that intravenously injected ^{86}Rb is nearly 100% extracted after 20 seconds in every organ except for the lung, liver, and brain. This rapid distribution provided the basis for a study of blood flow with ^{86}Rb (Boda et al. 1971). They found that, with the exception of the parenchymal organs, significant changes occur in the blood distribution of the individual organs in the fetus and in the normal living and hypoxic newborn.

There was a rapid uptake of ^{86}Rb by incubated fragments of human term placental fragments (Dancis et al. 1983). This led to high intracellular concentrations that had not reached equilibrium at the end of the study. They concluded that the rubidium diffuses passively through the same channels that are used by other small water-soluble molecules, such as urea, sodium, and chloride.

These results are in accord with the measurements of rubidium content in human placentas, maternal blood, and fetal blood by Baglan et al. (1974). These investigators found that the concentrations in the maternal and fetal blood were approximately equal but the concentration in the placenta was about 50% higher.

c. Biokinetic Models

The ICRP (1980) assumed that 25% of the rubidium leaving the transfer compartment is deposited in the skeleton and the remainder is distributed uniformly throughout all other organs and tissues. All rubidium translocated to tissues of the body is assumed by ICRP 30 to be retained there with a biological half-time of 44 days. This corresponds to the estimates in ICRP Publication 53, made on the basis of human data, that 5% has a 5-day half-time and 95% has a 60-day half-time.

Rubidium is modeled as leaving the transfer compartment with a half-time of 0.25 day and becoming uniformly distributed throughout all tissues of the woman. Placental transfer biokinetics are modeled on the basis of participation in this distribution, with continuing free bidirectional exchange, so that the same concentrations are soon reached in all compartments.

The model assumes equilibrium so that growth of the embryo/fetus and clearance are compensated by transfer from woman and concentrations remain the same. Thus, activity in the embryo/fetus is given by the ratio of its mass to the mass of the woman. The concentration in the early embryo is considered to be the same as that of the woman's uterus and to receive the same radiation dose.

Gestational-stage-dependent initial deposition and retention with time were evaluated on the basis of this model. The values for ^{86}Rb are given in Tables A16a and A16b of Appendix A for the woman and the embryo/fetus, respectively.

d. Dosimetric Models

The half-life of ^{86}Rb is 18.7 days and it decays to stable ^{86}Sr by the emission of two beta particles, with average energies of 0.233 MeV and 0.709 MeV and a 1.077 MeV gamma ray. The dose factors for ^{86}Rb, corresponding to the model, are given in Table B12.

11. Strontium and Yttrium

Among the four stable isotopes of strontium, ^{88}Sr (83%) is most abundant; the only stable isotope of yttrium is ^{89}Y. Strontium has several nuclear fission-related radioisotopes, but ^{89}Sr and ^{90}Sr have received the greatest attention in the fields of radiological protection and generalized environmental contamination.

Two radioisotopes, ^{85}Sr and ^{89}Sr, are used in clinical medicine and are considered in ICRP Publication 53 (1988). Yttrium has several radioisotopes but the one of primary interest is ^{90}Y, which is a decay product of ^{90}Sr; the two are found in equilibrium.

a. General Characteristics and Biological Behavior

As given in Reference Man (ICRP 1975), the strontium content is 0.32 g; almost all is in skeleton; soft tissues contain only 3.3 mg. Total body content or normal daily intake of yttrium is not given, but total liver content is given as 1.6 mg and the total trabecular bone content as less than 4.5 mg. In Publication 30, the ICRP assumed the f_1 value to be 0.3 for soluble salts absorbed from the GI tract and lung. This GI absorption value was endorsed by an NEA expert group and adopted in ICRP Publications 56 and 67 (1989, 1993). A greater value of 0.6 was adopted for infants and 0.4 for children. For radiation protection purposes, ICRP assigned soluble compounds of strontium to inhalation class D and $SrTiO_3$ to inhalation class Y. The ICRP (1980) chose 0.0001 as the fractional absorption of yttrium from the gastrointestinal tract, but this has been raised to 0.001. Oxides and hydroxides of yttrium were assigned to inhalation class Y and all other compounds to inhalation class W.

As with other alkaline earths, many aspects of the metabolic behavior of strontium are similar to those of calcium. There are quantitative differences between transfer of the two elements between metabolic compartments, however, which are often evaluated in terms of observed ratio (OR) values.

According to the ICRP (1980), 25% of the yttrium that leaves the transfer compartment goes directly to excreta, 50% is translocated to the skeleton, 15% is translocated to the liver, and 10% is uniformly distributed throughout all other organs and tissues. The yttrium that is not immediately excreted is assumed to be retained indefinitely in the body. The Task Group on alkaline earth metabolism developed a comprehensive model for the retention of strontium in adults (ICRP Publication 20, 1973). This model has undergone several revisions and expansions; the most recent is presented in ICRP Publications 56 and 67 (1989, 1993) and forms the basis for the model used here.

b. Fetoplacental Considerations

Strontium is among the most thoroughly studied radionuclides and there is reasonable agreement regarding its placental transfer and fetoplacental disposition. Part of the calcium and strontium previously fixed in the skeleton of pregnant mice migrated to the fetus during the last days of pregnancy, but the amount of calcium in the fetuses was much greater than the amount of strontium (Pecher and Pecher 1941). Subsequently, Finkel (1947), found that ^{89}Sr administered to mice during pregnancy passed to the fetuses and the total amount in the neonates varied directly with their weights and inversely with the length of time between exposure and birth when that time exceeded three days. The ratio of strontium concentrations in the fetus to that in the mother also depended on time between injection and delivery.

When rabbits were injected with a mixture of ^{90}Sr and ^{90}Y, the two radionuclides were approximately in radioactive equilibrium in the fetuses and in the mothers' bones (Kidman et al. 1951). When injection was 24 hours before delivery, fetal concentrations of strontium were four to eight times greater than those in the mothers. For animals injected nine days before delivery, the mean ratio of concentrations was 0.76 and was about 0.03 for animals injected 38 to 50 days before delivery. Findings reported by Ruhmann et al. (1963) and by

Stather et al. (1987) were consistent with these results. Strontium transfer to the fetus and retention in the placenta depend on chemical characteristics as well as period of pregnancy (Moskalev et al. 1969); this also pertains to the behavior of yttrium (Kriegel and Weber 1961).

According to Holmberg et al. (1960), the ability of the mouse fetus to take up ^{90}Sr appeared after the 14th day of gestation, and the uptake continued for more than four hours after injection of the mother. The placental transfer of strontium in rats, rabbits, sheep, and cows increased twentyfold between midterm and the end of pregnancy. Twardock (1967) found a decrease in placental discrimination of the guinea pig against strontium during gestation. The gradual decrease occurred throughout gestation and there was no abrupt change associated with loss of any placental tissue layers. Placental discrimination in the rabbit was somewhat greater than that in the rat, but in both the placental transfer of strontium from dam to fetus is about one-half that of calcium (Wassermann et al. 1957).

Schulert et al. (1969) found that the rat placenta contained about 25% less strontium than calcium at 14 days of gestation but retained about 22% more strontium than calcium at 20 days. The concentration of strontium in the fetus increased through gestation as above. Studies with mice that were administered ^{89}Sr on day 17 of gestation and killed on day 20 (Jacobsen 1978) found the following fetal-to-maternal concentrations ratios: liver 4.9, kidney 12, heart 1.1, brain 1.5, calvarium 1.6, and long bones 5.0. Taylor and Bligh (1992) measured transfer of alkaline earth metals in rats and found that the transfer ratios for passage across the placenta do not differ significantly from those for gastrointestinal transfer; the ratios for strontium ranged from about 0.3 to 0.4. Placental turnover of yttrium occurred during the last quarter of the gestation period. At this later stage of pregnancy, the ratio of the concentration in the placenta to that in the fetus was approximately 30 (Kriegel and Weber 1961).

In a study using pregnant monkeys, ^{85}Sr was injected into the fetal circulation and ^{90}Sr into a maternal vein (MacDonald et al. 1962). There was twice as much ^{85}Sr in the mother's body as in the fetus when the nuclide was administered to the fetus. The fetus and placenta contained 43% of the ^{85}Sr and 12% of the ^{90}Sr. The strontium concentration in fetal bone was greater than in maternal bone; the concentration ratio for fetal/maternal bone was about 20:1 with ^{85}Sr and 3:1 with ^{90}Sr. The pattern of strontium accumulation in bone tissue was the same for both radionuclides. MacDonald et al. (1962) showed that the transport of radiostrontium across the primate placenta was bidirectional, but, as Griessl (1987) pointed out, the net flux is mainly unidirectional.

Griessl (1987) drew several other conclusions from her review of literature on strontium metabolism in pregnancy. Strontium intakes before pregnancy are not available to any great extent for transfer to the fetus. The total amount of strontium in the developing skeleton increases about twentyfold during pregnancy. During the last four weeks before birth, the fetal skeleton accretes the same amount of strontium as during all preceding months of pregnancy. In the sixth month of pregnancy about 6% to 10% of ingested strontium is transferred to the placenta. In the final month, this value reaches 10% to 17%. Strontium follows calcium pathways in the body but metabolic processes discriminate against strontium in favor of calcium. However, the ability of placental membranes to discriminate against strontium decreases during pregnancy. By the end of pregnancy, this discrimination has almost disappeared and strontium is passed on to the fetus at nearly the same Sr/Ca ratio as that present in the maternal circulation.

c. Biokinetic Models

The model assumes that 3% of the strontium in the transfer compartment goes to early excretion and 15% goes to bone surfaces enroute to deeper deposition. Most of the administered activity (82%) is distributed to soft tissue

with 80% of this lost with a 2-day retention half-time, going to excretion and to bone. Although most of the remaining soft tissue content is retained with a 30-day retention half-time, a small fraction is retained tenaciously.

The gestation-related aspect of the model is based on the fact that bone is not present in the embryo during early gestation. At times through 2 months of gestation, the embryo/fetus is embedded in the uterine mucosa. The model assumes that soft tissue distribution, which includes the uterus, also represents the concentration of strontium in the embryo/fetus.

Skeletal elements develop their shape and form early during the fetal period. Their growth and calcification become increasingly prominent through the remainder of gestation. As with calcium, strontium deposition in the skeleton becomes progressively greater as the fetus approaches term. As noted in Section IV, the biokinetic modeling is based on patterns of skeletal composition and relative mineral behavior. This utilizes the resulting gestational-stage-dependent comparative models of fetal-to-maternal skeletal deposition and estimated values of fractional multipliers that describe the influence on concentrations and the associated radiation doses.

Percentage activity of strontium in the woman's skeleton from the initial deposition and early redistribution is taken as a total of 25%. These concentrations were used to calculate gestational-stage-related deposition and retention of strontium in the skeleton of the embryo/fetus through the use of the fractional multiplier values. This approach provides a transition from no skeletal deposition in the early embryo to skeletal concentrations that are the same as those of the woman at 6 months of gestation and thereafter. Even when activity is assumed to remain constant in the embryo/fetus because of bone deposition, strontium concentrations decrease because of the growth of the conceptus.

The model gives results that are in accord with reports that strontium concentrations in fetal and maternal bone are similar at later times. This pattern accounts for many of the reports that present divergent values of OR and should pertain to multiple occupational or continued environmental exposures. The behavior of the ^{90}Y in the fetus and in the mother's bones is considered to be the same as that of the ^{90}Sr. Initially deposited and retained fractions in the maternal body and the embryo/fetus are shown for ^{89}Sr in Tables A17a and A17b and for ^{90}Sr-^{90}Y in Tables 18a and A18b.

d. Dosimetric Models

The half-life of ^{89}Sr is 50.5 days. It emits a beta particle with an average energy of 0.583 MeV and a gamma ray. The other isotope of importance, ^{90}Sr, has a 29-year half-life and emits a beta particle with 0.20-MeV average energy. It does not have a gamma ray. It decays to 64-hour ^{90}Y, which is also a beta-emitter (0.93-MeV average energy).

All soft tissue has the same nominal concentration. The radiation dose to the uterus or uterine contents serves as an estimate of the radiation dose to the embryo/fetus during the first two months of gestation. Fetal bone contains significant and stage-related amounts of strontium after deposition. This is explicitly accounted for in the calculational approach for ^{89}Sr. The results are in Table B13.

The radiation doses corresponding to fractional retention of the ^{90}Sr activity, as shown above, depend on the physical factors associated with the ^{90}Y. Allowance has been made for the impact of radioactive equilibrium. The corresponding dose rates and doses for ^{90}Sr-^{90}Y are presented in Table B14.

Roedler (1987) summarized fallout measurements and other data from the literature to estimate radiation doses to the fetus from ^{90}Sr. He calculated that for maternal intakes at six months of pregnancy, the fetal dose was 0.22 Gy/MBq (0.81 rad/μCi), while for intake at nine months, the fetal dose was 0.67 Gy/MBq (2.48 rad/μCi). The ratio of bone doses in fetus to those in the adult was 0.1 for intake at six months and 0.3 for intake at nine months. Stather et al. (1992) used human data and a

Ca:Sr discrimination ratio of 1:0.5 as the basis for estimating radiation doses to the woman and the fetus from chronic ingestion of strontium.

Localized Deposition: Strontium also illustrates the impact of localized deposition on the fetoplacental kinetics. As noted, almost all of the strontium content of the late fetus is in bone. In the sense that skeletal mass could be used for calculation, it would give a substantially higher average dose to the target. Because current recommendations are stated in terms of dose to the embryo/fetus, the total body is the mass considered in our analyses.

12. Technetium

Technetium has about 20 radioisotopes but there are no stable isotopes. The isotopes ^{95}Tc, ^{96}Tc, and ^{97}Tc, with half-lives of 61, 4.3, and 90 days, respectively, may be of general interest for radiological protection.

The most frequently encountered isotope from the standpoint of medical and associated occupational exposures is ^{99m}Tc, which is eluted from molybdenum-technetium generators as the pertechnetate. It is employed directly and is also used to label other compounds that are prepared as diagnostic radiopharmaceuticals. These clinical applications and the associated dosimetry will be considered in Section VII of this report.

a. General Characteristics and Biological Behavior

Data for technetium are not given in Reference Man (ICRP 1975). The absorption of pertechnetate from oral intakes is variable in timing and extent. The recommendation given in ICRP Publication 30 (1980) of 0.8 as fractional absorption for inorganic compounds of technetium for radiation protection purposes is specifically applicable to pertechnetate. An f_1 value of 0.5 was adopted in ICRP Publication 67 (1993) for technetium incorporated in foods because it is less readily absorbed in this form. Oxides, hydroxides, halides and nitrate of technetium were assigned to inhalation class W and all other compounds to inhalation class D.

Pertechnetate is the most frequently encountered compound of technetium and serves as the general form that is considered in this section A simple model is given in ICRP Publication 30 (1980) for pertechnetate distribution and retention following intravenous administration although it does not describe its initial disposition. For modeling and calculating radiopharmaceutical uses, MIRD used a multicompartmental model that described distribution in adults at early times after intravenous administration (Hays and Berman 1977).

This degree of detail is not required for evaluation of placental transfer and radiation dose to the embryo/fetus because of uncertainties in fetoplacental factors. Thus, the information assembled in ICRP Publication 67, which is an expansion of Publication 30, provides an adequate but simpler description of the distribution and retention of pertechnetate in the adult. When combined with extrapolations from the biokinetic model for radioiodine, this description provides for modeling of placental transfer and deposition of pertechnetate in the embryo/fetus and its thyroid gland.

There is a wide variety of other radiopharmaceuticals that are labeled with ^{99m}Tc and used for clinical diagnosis; the model given here for pertechnetate is not directed to these other compounds. Models for ^{99m}Tc-labeled radiopharmaceuticals are described in ICRP Publication 53 (ICRP 1988) and in reports by several investigators. Biological behavior during pregnancy and the associated dosimetry of some widely used agents will be summarized in Section VII. As appropriate, these will include published extrapolations that estimate radiation dose to the human embryo/fetus from information in the reported study. With few exceptions, however, pertechnetate that is not bound or is released from the radiopharmaceutical will represent the primary activity that reaches the embryo/fetus.

b. Fetoplacental Considerations

Data are available concerning the placental transfer and disposition of ^{99m}Tc-labeled pertechnetate in pregnant animals. At one hour after intravenous injection in third-trimester rabbits, the ratio of ^{99m}Tc-labeled pertechnetate concentration in the placenta to concentration in blood was 4.34. The concentration ratio of placenta to fetus was 1.23 and the total activity in a single placenta to that in a single fetus was 0.22 (Mahon et al. 1973).

Lathrop et al. (1976) studied the effect of perchlorate on the quantitative distribution patterns of intravenously injected sodium ^{99m}Tc-pertechnetate in the adult and its fetus. At 1.5 hours after administration, the concentration ratio of technetium in the placenta to that in the blood was 2.1, and this ratio was reduced by a factor of four by perchlorate administration.

Wegst et al. (1983) estimated cumulated activity for ^{99m}Tc-pertechnetate biodistribution data from nonpregnant and pregnant rats at 13, 15, 17, 19, and 21 days of gestation. They found that the fetal activities per unit weight of tissue and cumulated activities were not constant over the gestational ages studied. The maximum values were determined after injection on the 13th day of gestation; it fell by a factor of 2.5 at midterm and rose again at term. The placental tissue cumulated activities were several-fold higher and remained essentially constant over time.

Roedler (1987) compiled data for determination of concentration ratios for ^{99m}Tc-pertechnetate in maternal and fetal tissues. A variety of species, gestational times, and conditions were used to calculate the ratios of concentration in fetal to maternal tissues Thus, his results showed wide ranges: total body, 0.04 to 4.8; femur, 1.7 to 7.1; stomach, 0.64 to 1.56; spleen 0 to 18.6; and thyroid, 0.06 to 0.62.

c. Biokinetic Models

The biological half-time in the transfer compartment is considered to be 0.02 day. It was assumed that 4% of technetium that leaves the transfer compartment is translocated to the thyroid, where it is retained with a biological half-time of 0.5 day; 10% is assumed to be translocated to the stomach wall and 3% to the liver. The remaining technetium leaving the transfer compartment is assumed to be uniformly distributed throughout all other organs, where 75% is retained with a biological half-time of 1.6 days, 20% with a biological half-time of 3.7 days, and 5% with a biological half-time of 22 days.

Because some aspects of technetium biodistribution resemble those of iodine, the model for fetoplacental disposition of iodide was used as the point of departure. The iodine model does not have a tissue component, and it has early excretion. Extrapolations made from the histogram in MIRD Report No. 8 (Lathrop et al. 1976) yields further contrast. As noted, the technetium model assumes that 96% of the administered pertechnetate activity goes to general tissues plus plasma and extracellular fluid. This occurs instantaneously from the distribution compartment. Because of the high fluid content of the embryo/fetus, the 96% biodistribution can be assumed to be uniformly distributed to all tissues.

ICRP Publication 67 states that of pertechnetate translocated to organs and tissues other than the thyroid, 75% is assumed to be retained with a biological half-time of 1.6 days, 20% with a biological half-time of 3.7 days, and 5% with a biological half-time of 22 days. The model used here considers this as a single biological retention half-time value of 2 days. It also assumes that the 4% of technetium translocated to thyroid is not incorporated into organic molecules; it is retained with the biological half-time of 0.5 day suggested in ICRP Publication 67.

The resulting values of deposition and retention of ^{99m}Tc as pertechnetate are shown in the multiple parts of Table A19 of Appendix A: the values are shown in Tables A19a for the woman's total body, in A19b for her thyroid, in A19c for the embryo/fetus, and A19d for the fetal thyroid gland.

d. Dosimetric Models

The relevant isotope, ^{99m}Tc, decays to long-lived ^{99}Tc by internal transition with a half-life of 6.02 hours. The primary emission is a 0.141-MeV gamma ray (88.9%). The radiation dose and dose rate to the embryo/fetus that corresponds to the above values of deposition and retention are shown in Table B15a. The dose factors for the fetal thyroid are given in Table B15b. These are repeated as Tables C7a and C7b of Appendix C because of the particular relevance to radiopharmaceutical dosimetry.

13. Ruthenium

Ruthenium is among the most abundant fission products in waste effluent from reprocessing of nuclear fuels (Nishimura et al. 1988). Among several radioactive isotopes, ^{103}Ru and ^{106}Ru have half-lives and abundances that make them of interest for radiological protection. The daughter, ^{106}Rh, emits a high-energy beta particle and is of importance in ruthenium dosimetry.

a. General Characteristics and Biological Behavior

No data are given for ruthenium in Reference Man (ICRP 1975). Affirming ICRP Publication 30 (1980), ICRP Publication 56 (1988) gives the fractional gastrointestinal absorption of ruthenium from food, the f_1 value, as 0.05 for adults and children and 0.1 for infants. Oxides and hydroxides of ruthenium were assigned to inhalation class Y, halides to class W, and all other compounds to inhalation class D.

Ruthenium that enters the transfer compartment is assumed to be retained with a biological half-time of 0.3 day. The assumption is that 15% of the activity leaving the transfer compartment goes directly to excretion. The remainder is distributed throughout all organs and tissues of the body uniformily and with no selective skeletal deposition. Of the total, 35% is retained with a biological half-time of 8 days, 30% with a biological half-time of 35 days, and 20% with a biological half-time of 1000 days. The daughter, ^{106}Rh, is of importance in the dosimetry because it emits a high-energy beta particle, but its distribution pattern may be ignored because of its short half-life.

b. Fetoplacental Considerations

An early whole-body autoradiographic study detected a marked deposition of ruthenium in the fetal membranes, as well as in maternal kidney and connective tissue (Nelson et al. 1963). There was a lesser concentration in the placenta which seemed to follow blood clearance. Therefore, rhuthenium seemed to be one of the few elements, other than actinides and some of the other heavy metals, that localized in the yolk sac; this phenomenon is of interest because it may have relevance for induction of postnatal effects.

This localization was confirmed in subsequent studies that measured the biokinetics of ^{106}Ru in rats (Nishimura et al. 1988). Biological disposition varied with animal age and the chemical form in which the ruthenium was administered, but the percentage of the injected activity transferred across the placenta in rats consistently increased with gestational age after intravenous injection of $^{106}RuCl_3$. For example, approximately 0.4% of the activity was transferred to the totality of the fetuses at 20 days of gestation, which may be calculated as being equivalent to an average concentration less than 5% that in the dam. Markedly high concentrations were found in the fetal membranes, and this study quantitatively confirmed that the concentrations in the placenta and fetal membrane are higher than those in the fetus. Some of this behavior may relate to early findings in which ruthenium was used as a poorly absorbed tracer for study of gastrointestinal passage rates by age, and elevated absorption was detected in neonatal rats compared to adults.

Subsequent experiments by Levak (1994) found concentration ratios as high as 0.1 following administration to rats at various stages of gestation. Values of 0.2 were

measured at 7 days after administration to near-term guinea pigs. Again in these studies, markedly elevated concentrations were detected in the yolk sac and placenta.

Studies of fetal-to-maternal concentration ratios with ^{106}Ru in rats have shown that the fetal concentration is much lower than that of the mother. The ratio is larger when administration is made in late pregnancy (Stather et al. 1992). For administration to the early fetus, uptake of ruthenium in fetal and maternal tissues, expressed as percent of administered activity at birth, was 51.9 and 0.023, respectively, and for late gestation was 64.4 and 0.082. These yielded concentration ratios of 0.015 and 0.051 for the two times of administration.

These limited experimental results in animals suggest that average ruthenium concentrations in the embryo or fetus might be considered as high as 10% of those in the pregnant woman. The behavior of the daughter ^{106}Rh can be considered as identical to ^{106}Ru because of its short physical half-life.

The concentration of radioactivity in the rodent placenta is several-fold that in the fetus and is similar to that of many maternal tissues, possibly reflecting blood content. The reasons are not known but there is marked and persistent location in the yolk sac. Assessment of the significance of the resulting extraembryonic radiation doses are discussed elsewhere in this report. The morphologic differences between the size and location of the yolk sac in rodents and in humans or other primates would be expected to influence the dosimetric significance and potential for effects produced by this activity.

c. Biokinetic Models

The evaluation accepts that only small fractions are absorbed from the GI tract and are available to enter blood. Of activity introduced directly into the transfer compartment, 15% is excreted with a half-life of 0.5 day. The other 85% is modeled as being uniformly distributed in all tissues including uterus and mucosa. Of the 85% that is retained, biological retention half-times are as follows: 35% for 8 days, 30% for 35 days, and 20% for 1000 days. Because it is embedded in the uterine mucosa, concentration in the embryo/fetus during the first 2 months of gestation is considered to be the same as that in the average soft tissue. This is greater than pertains at later times for the fetus.

Concentrations in placenta are considered as the same as that in the woman's tissues and are modeled as being a maternal tissue. A relative transfer coefficient for the model is taken as being 0.1 without any clearance from the fetus. This gives initial average fetal concentrations that are 10% of the average concentration in the pregnant woman, with increased values for stage-adjusted activity. Thus, relative fetal-to-maternal concentrations may rise with time, but the radioactivity content does not.

The deposited and retained fractions of ^{106}Ru (in equilibrium with ^{106}Rh) in the embryo/fetus are presented in Table A20.

d. Dosimetry Models

As noted above, the decay product of ^{106}Ru, ^{106}Rh, is radioactive and decays by emission of a high-energy beta particle with an average energy of 1.415 MeV. The contribution of ^{106}Rh to the embryo/ fetus dose must be included in any calculations. The dose rates and doses corresponding to the above deposition and retention are shown in Table B16.

14. Indium

Indium has over 30 radioisotopes. Two of its short-lived radioisotopes are routinely used in nuclear medicine. Information about ^{111}In, with a 2.8-day half-life will be used in this section to derive a general biokinetic model. Because is is mainly encountered as a radiopharmaceutical, the corresponding dosimetry will be given in Section VII. The 1.7-hour half-life ^{113m}In, which is also used for some types of clinical studies, will also be considered in that section.

a. General Characteristics and Biological Behavior

The absorption of indium from the gastrointestinal tract was considered to have an f_1 value of 0.02 (ICRP 1980). Oxides, hydroxides, halides, and nitrates of indium were assigned to inhalation class W and all other compounds to inhalation class D.

After intravenous injection of carrier-free ionic indium, it rapidly binds to transferrin like protein in plasma. This binding and transport influence indium deposition in normal adults and pregnant women, especially behavior in the placenta. The ICRP (1980, 1987) assumes that of indium leaving the transfer compartment, 30% goes to red marrow, 20% to liver, 7% to kidneys, and 1% to spleen. The remaining 42% is assumed to be uniformly distributed throughout all other organs and tissues of the body. Total body retention half-times are considered to be 2 days for 30% of the activity and 70 days for the other 70%. Indium is excreted in both urine and feces.

b. Fetoplacental Considerations

Lathrop et al. (1992) compared localization and retention of radiogallium and radioindium in pregnant and nonpregnant mice; limited studies were also performed in guinea pigs and a monkey. Linear compartmental models with associated rate constants were constructed and fitted to the data points for nonpregnant and pregnant animals. They found that the transfer of indium to the intestine was bidirectional but that no fecal excretion occurred. The patterns from this paper are incorporated as a major basis for the models described below.

Carrier-free ^{113m}In binds specifically to transferrin after intravenous injection. The radioactive indium that reaches the placenta during pregnancy is released from transferrin and accumulates in the placenta, but significant activity does not cross into the fetal circulation (Wochner et al. 1970). A similar finding was obtained in studies by Graber et al. (1970), who found that virtually no indium crossed to the fetus of rats but large amounts accumulated in the placenta.

Limited transfer information was obtained from a study that was performed to obtain baseline data for estimating doses to the human fetus during placental scanning. A near-term dog was intravenously injected with ^{113m}In and cesarean section samples were obtained at 45 minutes and analyzed (Niehoff et al. 1970). They found 2.5% of the remaining activity in the placenta but only 0.0097% in amniotic fluid and 0.0044% in the pup. They concluded that ^{113m}In does not cross the placenta to any extent during the time before radioactive decay.

Sastry et al. (1976) calculated from these results that 0.8% of administered activity crosses the placenta at 30 weeks of pregnancy in the human and has an effective half-time equal to the physical half-life of ^{113m}In. They estimated that the placental content of ^{113m}In would be 4.8% of the administered activity and the uterine wall content would be 1.8%. The presence of very small amounts of carrier indium significantly lowers the placental concentration of indium without much change in the blood levels or fetal concentration.

Measurements in third-trimester rabbits found that the activity concentration of carrier-free ^{113m}In in the placenta at one hour after administration was 3.8 times that in the blood but more than 800 times that in the fetus (Mahon et al. 1973). The ratio of activity in an individual placenta to an individual fetus was about 70.

c. Biokinetic Models

Initial binding to transferrin is considered as essentially instantaneous and a partition time of 0.25-day is assumed. Radioactive indium reaching the placenta is released from transferrin and large amounts accumulate in the placenta with the same 0.25 day partition time. The model incorporates the estimates that 0.8% of administered ^{113m}In activity crosses the human placenta with an effective half-time equal to the physical half-life and that the placental content would be 4.8% of the administered activity. Small amounts of carrier indium significantly lower the placental concentration without much change in the blood levels or fetal concentration.

Indium does not rapidly cross into the fetal circulation, but the conclusions of cited experiments with short-lived ^{113m}In are not quantitatively applicable to ^{111}In with its physical half-life of 2.8 days. The fetoplacental component of behavior for biological disposition of the longer-lived ^{111}In is similar to that of 3.26-day ^{67}Ga, both of which are routinely used in nuclear medicine and the model for gallium and can be used with change in parameters to accommodate quantitative differences. Placental deposition and transfer to the embryo/fetus involve an initial placental deposition that is 20 times that in the embryo/fetus and 10 times that in general soft tissues of the woman. This then results in biological retention half-times of 0.25 day in the labile compartment of the placenta and 5 days in the non-labile component of the placenta. All concentrations are considered to have become the same by 2.5 days.

Values of gestational-stage-dependent fractional deposition and retention were calculated for ^{111}In, the longer-lived radioisotope. These values are given in Table A21a for the maternal body and in Table A21b for the embryo/fetus (Appendix A).

d. Dosimetric Models

Primary interest in exposure to radioindium is related to its clinical use. Dosimetry corresponding to the above pattern of deposition and retention will be considered in Section VII that deals with radiopharmaceutical compounds. The corresponding dose factors are given in Table C8 (Appendix C).

15. Iodine

Iodine has a single stable isotope, ^{127}I, and over 20 radioactive isotopes with a wide range of half-lives and decay schemes. There are numerous routes and circumstances through which members of the population, including pregnant women, have been exposed to radioiodines. The sources are isotopes that enter into the occupational or general environment from nuclear detonations or reactor releases and into the food chain.

Iodine is a highly reactive halogen and readily labels a wide range of organic compounds. Radioisotopes of iodine, both as iodides and as labeled compounds, have been routinely used for diagnosis and treatment of thyroid disorders and for a variety of other diagnostic evaluations. Accordingly, persons can be exposed via deliberate administration for medical procedures or occupational intake of materials being prepared or administered as radiopharmaceuticals.

a. General Characteristics and Biological Behavior

Iodine is an essential element that is required for normal function of the thyroid gland and the control of body metabolism by thyroid hormones. Its availability is usually in the form of iodides, which are rapidly absorbed from the gastrointestinal tract, lung, and other sites. The f_1 value for inorganic iodide is considered to be 1, and all iodide that is ingested or inhaled is assumed to reach the transfer compartment. The biological behavior of iodine differs when it is associated with molecules, such as iodinated tracers used as radiopharmaceuticals for nuclear medicine procedures, or is otherwise bound to organic molecules. These compounds may release inorganic iodine as the iodide.

The approximate range of deposition in the thyroid gland of a normal person is considered to be between 15% and 35% of ingested or inhaled iodide. Some typical models, such as that in ICRP Publication 53 (1988), utilize a range of uptakes by the thyroid gland and consider the remainder of the activity as going directly to excretion. The iodine metabolized by the gland is stored as colloid in the lumen of the thyroid follicles and retained with a biological half-life of 120 days. In normal adults, the thyroid gland and kidneys are the primary organs that compete for iodide and remove it from the plasma although concentrations may be elevated in salivary and mammary glands.

Under pituitary control, the iodine is incorporated into the three thyroid hormones that are involved in control of body metabolism: diiodiothyronine (T2), triiodothyronine (T3), and thyroxine (T4). Thyroid hormones that

are released into the blood are modeled as uniformly distributed throughout the body and retained with a 12-day biological half-time before they are catabolized. This breakdown releases inorganic iodine: 10% is considered to be excreted directly and the other 90% is assumed to re-enter the transfer compartment.

b. Fetoplacental Considerations

Detailed descriptions of the morphological development of the thyroid gland in the human embryo and fetus are given by Shepard (1967) and Sugiyama (1971). Shepard also provided parallel information about development of thyroid function, but gestational-stage-related iodine kinetics in the human fetus are still incompletely defined. There have been several reports that attempted to model these kinetics with the goal of calculating radiation doses to the human fetal thyroid gland from specific isotopes under varied exposure conditions. In contrast, little attention has been directed to the calculation of average doses to the whole embryo or fetus.

The literature on the dosimetry and effects of radioiodine during pregnancy includes reports of studies that investigated the time-course of the development of the thyroid function in experimental animals. Some of these were performed as part of studies of effect that also measured iodine uptake and retention by the embryo/fetus following single, multiple, or chronic exposures of experimental animal species ranging from mice to sheep.

Among studies in the human, Hodges et al. (1955) measured the incorporation of ^{131}I into the thyroid of nine fetuses from therapeutic abortions. The concentrations of radioiodines in fetal thyroid progressively increased and were highest during the period between five and six months of pregnancy. Because of the greater mass of the gland, total thyroid uptakes were highest at term (Evans et al. 1967). The trends in uptake values found by Aboul-Khair et al. (1966) were similar through the sixth month of gestation but they did not report values at later stages. They concluded that iodine metabolism by fetal thyroid gland is markedly different from that of the adult gland and estimated maximum biological half-times of 28 hours in fetal thyroid.

The general pattern derived from these studies is that iodide readily crosses the placenta and is accessible to the embryo or fetus. Iodine crosses the placenta less freely when it is incorporated into thyroid hormone. The prenatal thyroid gland requires substantial morphologic and physiologic development before it has the capacity to trap iodide and must undergo further development before it can metabolize it into hormone. Iodine is generally distributed throughout the embryo and does not localize; tissue concentrations of iodide are assumed to approximate those in the uterus and other maternal soft tissue during this period.

Thyroid development follows and is dependent on the development of pituitary function, especially the secretion of thyroid stimulating hormone. In the human embryo/fetus, incorporation of administered radioiodine into the thyroid may be detected after maternal administration at about 10 to 11 weeks of gestation although active synthesis into hormone does not become evident until about 13 weeks, well into the fetal period. These functions of the thyroid gland-iodine trapping, hormone synthesis, and storage and release-continue to increase with progressive development so that specific details will change throughout gestation.

The differing time course for development of the several morphologic and functional measures may account for differences among the parameters selected for the various analyses that will be reviewed below. In addition, as was noted in the introduction, there are two conventions for stating gestational times (time after fertilization and after last menses); the two-week timing difference may further explain differences among quantitative descriptions.

The relative concentration of radioiodine in the fetal-to-maternal thyroid, which is a gross value that gives the composite of interacting functions, is sometimes stated as being greatest shortly before parturition. This pattern

may overemphasize results obtained after chronic exposures and patterns extrapolated from animal studies. Other reasonable analyses argue that the ratio is greatest at about the end of the second trimester of human gestation.

Prenatal Models and Parameters: Some of the researchers cited above, as well as others, utilized these results and patterns to model iodine metabolism in the pregnant woman and the embryo/fetus and to estimate parameters of the biokinetic models. The general goal was to calculate radiation doses to the fetal thyroid. The biokinetic models that were used, however, range from simple empirical ratios of fetal-to-maternal thyroid concentration at one extreme to recycling multi-compartmental models that have time-dependent transfer coefficients at the other extreme (Aboul-Khair 1966, Dyer and Brill 1969, 1972, Johnson 1982, and Roedler 1987, Book and Goldman 1975).

Perhaps the most comprehensive biokinetic model for radioiodide in the pregnant woman is that developed by Johnson (1982, 1987). An extension by Zanzonico and Becker (1991) included a slow exchange of organic iodine between the maternal and fetal circulations. Using this model, they also calculated absorbed doses for the fetus of mothers suffering from hyperthyroidism and determined the effect of thyroid blocking on the fetal thyroid dose. Watson (1992b) also introduced modifications to Johnson's model, especially inclusion of a "double" hormone and organic compartment for the woman. She used the SAAM (Simulation, Analysis, and Modeling) software to calculate transfer rate constants and residence times for iodide in the pregnant woman with normal thyroid function. The S values for the fetal thyroid (Watson 1992b) were derived from the mathematical model described by Johnson (1982).

Beyond differences in the models, there is little agreement among authors concerning the parameters and coefficients, which leads to further differences among dosimetric results. Book and Goldman (1975) extrapolated results from animal and human studies to estimate the ratio of fetal thyroid concentration to the maternal thyroid concentration. The thyroid concentrations in the last months of pregnancy were estimated to be three- to nine-fold greater in the fetus as compared to the adult. Their descriptions demonstrate that the value depended on the decay scheme and half-life of the radioisotope and route of intake and whether exposure is chronic or acute. Thus, in addition to the stage of gestation, the time course and magnitude of iodine concentrations in the embryo/fetus and its thyroid, the relative degree of localization, retention, and the biological consequences will depend on the specific isotope and its half-life. They obtained ratios of about 1.2 at three months, 1.8 during the second trimester, and 7.5 in the third trimester.

Stieve (1985) suggested that the thyroid uptake of iodine is higher in pregnant than in nonpregnant women, that the biological half-time of iodine in the mother's thyroid is between 80 and 120 days, and that the biological half-time in the fetus is about 4 to 13 days. Johnson (1982) estimated an indeterminately long half-time for iodine in the fetal thyroid at 90 days of fetal age the time that he considered that the fetal thyroid starts to concentrate iodine. The half-times used in his model decreased to about 1300 days at 100 days of gestation, 120 days at 200 days, and 70 days at 270 days of gestation (term).

Roedler (1987) questioned the validity of these long half-times on the basis of the data of Aboul-Khair et al. (1966) and the fact that the measured half-time in newborn thyroid is about 15 days. Roedler suggested a biological half-time of 15 hours for weeks 13-15, 61 hours for weeks 15-19, and a linear increase to 15 days at term. Variations among the retention times in the fetal thyroid result in large differences among the estimates of radiation absorbed dose received by the fetal thyroid.

As examples of the impact of differing models and parameters, dose estimates calculated from the model of Watson (1992b) are smaller than those of Johnson, but are larger than those of Roedler (1987). Calculations of the concentration of iodide in the fetal thyroid using the parameters of Book (1978) and Johnson (1982) yield

similar results at 3 and 5 months of gestation, but differ by nearly a factor of 5 at 8 months.

c. Biokinetic Models

It is clear that these analyses did not provide consensus concerning details of the most appropriate model and parameters. Moreover, none of the models were completely appropriate to the needs of this project. Accordingly, relevant aspects from these evaluations were combined to provide a dynamic model that could address gestational-stage-dependent doses to the embryo/fetus as well as dose to the fetal thyroid gland.

The model that was used for this project is similar to the biokinetic model of Johnson (1982) but integrates some of the refinements suggested by others. It contains elements of the modifications by Zanzonico and Becker (1991) and Watson (1992b) but her 'double' hormone/organic compartment for the woman is not used. Consistent with most models, the fetal thyroid is considered to be a single compartment and re-entry is adjusted by constants. A blended rate constant handles formation and release of organic iodine and the modeling involves simplifications of transfer rate constants and coefficients among metabolic compartments. In addition, it incorporates refined values for parameters and coefficients derived from the compilation and conclusions of Book (1978).

In essence, the model was reduced to a single inorganic compartment that serves to distribute activity to excretion and to maternal thyroid. Any possible pregnancy-stage-related differences in maternal thyroid functions and rates are not included in the model. The fraction going to excretion during the first day is considered to be twice that to the thyroid gland. The fetal thyroid competes in this distribution, with gestational-stage-related rates that result in the gross thyroid concentration ratios following a continuous relationship, which will be described in paragraphs below.

Because there is no specific localization during the embryonic period, prior to active fetal thyroid function, generalized distribution of circulating iodides may be expected. The concentrations throughout the embryo are the same as those in general maternal soft tissues, especially the uterus, which is representative of the embryo. As localization in the fetal thyroid begins, it continues to increase as its function progresses.

Modified factors, parameters, and coefficients in compilations by Book (1978) served as an initial basis for refinement of the values that were debated by Johnson (1987) and Roedler (1987). On this comparative basis, many of the ratios stated by Book (1978) seem too high given the available human data. In particular, these values used animal data to extend human data and, because of discrepancies in times of thyroid development relative to gestational stages and fractions, extrapolation may yield distortion.

Accordingly, data were selected from which to construct an overall smooth age-related curve of fetal-maternal concentration ratios of ^{131}I as a function of stage of gestation. This does not pertain to short half-lives and, the impact is illustrated by the tables for the ^{132}I and ^{135}I isotopes. As noted, these lead to such low values for deposited and retained fractions that it was appropriate to tabulated residence times rather than fractional deposition.

The deposited and retained fractions of several isotopes of iodine in maternal body and thyroid, as well as the deposited and retained fractions of the activity in fetal thyroid and in the embryo/fetus exclusive of its thyroid, are shown in Tables A22 through A26.

d. Dosimetric Models

The radiation absorbed dose to the embryo/fetus is a combination of energy from radioactivity in the woman's thyroid and throughout the remainder of her body, emissions from iodine in the fetal thyroid, and radioiodine

distributed throughout the embryo/fetus. The radiation doses to the fetus and fetal thyroid are affected by the half-lives and emissions of the individual isotopes in addition to stage-dependent influences of anatomical relationships and tissue concentrations. Because of its localization in the fetal thyroid and relationship to the prenatal development pattern, dose rates and radiation doses from sodium iodide for the embryo/fetus and for its thyroid are provided separately.

Before the fetal thyroid begins to function, the thyroidal dose is not meaningful. As indicated, the embryo receives the same as the uterine dose during these first several weeks. Gestational-stage related values of fractional deposition and retention of several radioisotopes of iodine were developed and tabulated in the preceding paragraphs. The corresponding dose rates and doses to the embryo/fetus and the fetal thyroid for several isotopes are presented in Appendix B, Tables B17 through B21.

16. Xenon

Xenon has nine stable isotopes and almost 30 radioisotopes. Neutron irradiation of air in air-cooled nuclear reactors results in the production of radioxenon, especially ^{133}Xe and ^{135}Xe. The most frequently encountered isotope is ^{133}Xe, which is commonly used in nuclear medicine diagnostic studies for imaging lungs after inhalation or cerebral blood flow after injection.

Xenon is an inert gas that is not a natural constituent of the human body. A metabolic model was not given in ICRP Publication 30 because it was considered that the internal radiation dose from an inert gas absorbed in tissue or contained in the lungs would be negligible in comparison with the radiation from an external cloud.

The MIRD Committee developed biological parameters and a model for the distribution of ^{133}Xe under the conditions used for clinical evaluations in human patients (Atkins et al. 1980). According to this model, when ^{133}Xe is breathed from a spirometer under ordinary study conditions, the concentration in the lungs rapidly approximates that in the spirometer, but body equilibrium would require up to 30 hours of rebreathing. Fatty tissues constitute the compartments with the slowest turnover rate constants.

Based on the ICRP assumption that inert gases (including krypton, xenon, and radon) have similar biological behavior in the body, this would serve to provide a general model. The noble gases differ in their biological dispositions in the woman and the embryo/fetus, however, because of their individual partition coefficients, which interact with the temporal factors associated with the conditions of exposure. These conditions and results form the basis for the general models and for the individual parameters and tables of dose factors that are developed in Section VI.

17. Cesium

Cesium has a single stable isotope, ^{133}Cs, but almost 40 radioactive isotopes are formed by nuclear fission. Fallout radiocesium on vegetation may enter the food chain through grazing by livestock and concentrate in meat or be secreted in milk. The radioisotopes of special interest are those with atomic weights of 134 and 137. The latter isotope, ^{137}Cs, is incorporated into long-lived radioactive sources that are used for sterilization of packaged materials, radiography in commercial facilities, and brachytherapy sources for cancer treatment.

a. General Characteristics and Biological Behavior

The cesium content of Reference Man is 1.5 mg, of which 0.57 mg is in muscle and 0.16 mg in bone. Absorption from the gastrointestional tract is rapid and complete; the fractional absorption value, f_1, is given as 1 in ICRP Publications 30 and 67 (1979, 1993). Cesium is chemically related to potassium, and its behavior is similar. As would be expected from these similarities, cesium has a generalized distribution, with approximately uniform concentrations among soft tissues of adults, both human and animals.

Retention is sometimes given in terms of two biological retention half-times for cesium entering any tissue: 10% for 2 days and 90% for 110 days (ICRP 1980, 1989). A single overall value of 84 days is usually used for adult women. It is often considered that turnover rates are increased in pregnant women (NCRP 1977a; ICRP 1975, 1979).

b. Fetoplacental Considerations

There does not appear to be placental discrimination against cesium relative to potassium, and relative specific activities of ^{137}Cs and ^{40}K in fetal soft tissues or bone are not significantly different from activities found in adults (Kaul et al. 1966). They found also that concentrations were similar in the muscles of the mother and fetus and in the placenta. Others also have found that concentrations in the fetus were similar to those in the mother and were essentially independent of time of gestation, including early stages (Wilson and Spiers 1967). Analyses of the bone and muscle tissue concentrations in human samples collected during periods of fallout in the 1960s found the ratio to be 1:15.

The most common finding is that the biological half-time in woman is shorter during pregnancy than that in the nonpregnant woman. Zundel et al. (1969) studied women during and immediately after their pregnancy and found that the mean half-time of cesium was 47 days during pregnancy and 71 days after pregnancy ended (see also Bengtsson et al. 1964, Rundo 1992, Bertelli 1992).

c. Biokinetic Models

Cesium leaving the transfer compartment is modeled as immediately becoming uniformly distributed throughout the entire soft tissue body mass, which is considered as a single metabolic component (ICRP 1993, NCRP 1977a). In this report, the woman's mass is modeled as 53 kg at conception (0 months), with increasing soft tissue masses at subsequent times (Table 2). Differences among concentrations in soft tissues on the day following injection are not sufficient to require special consideration, and the concentrations are assumed to be uniform.

For general purposes, NCRP (1977a) considered the biological half-life of longer-lived cesium isotopes to be 84 days in normal women with a decrease during pregnancy. The biokinetic model here considers that the biological half-life decreases to 50 days in pregnant women, but that this change does not occur until 6 months of gestation. The biological half-times were assumed to follow a regular transition with values of 84 days during months 0 through 5, 70 days at 6 months, and 50 days at times greater than 6 months.

Because cesium readily crosses the placenta after intravenous injection, the initial concentrations are assumed to be the same in the embryo/fetus and the woman so that the equilibrium concentration ratio is 1. Concentrations throughout the embryo/fetus are modeled as uniform and as essentially the same in soft tissues of the pregnant woman. The half-times would be the same, and the embryo in early gestation is reasonably approximated by the uterus.

All soft tissues are considered to be a single metabolic compartment. Activity in the embryo/fetus is calculated from the ratio of its stage-related mass to that of the woman. The gestational-stage-related fractions of the cesium initially deposited and remaining at subsequent times in the pregnant woman and in the embryo/fetus are presented in Tables A27a and A27b, respectively, for ^{134}Cs and in Tables A28a and A28b for ^{137}Cs.

d. Dosimetric Models

The radiation dose to the embryo/fetus was assumed to consist of the sum of the dose due to photons emitted in the woman's body plus the self-dose from betas and photons emitted by the radiocesium (and barium) in the embryo/fetus. The corresponding radiation dose rates and doses to the embryo/fetus are presented in Tables B22 and B23.

18. Cerium

Cerium has four naturally occurring stable isotopes, predominantly ^{140}Ce (88.5%), and is used in manufacturing, largely as a catalyst. Of the approximately 20 radioactive isotopes and isomers, ^{141}Ce and ^{144}Ce are of greatest radiological interest. Both are beta-emitting radioisotopes produced by neutron activation of stable cerium and may be found as contaminants in nuclear plants. Cerium is probably the most important fission product of the rare earth series, and ^{144}Ce is an abundant by-product of atomic bomb detonations, constituting a predominant isotope in fallout. This lanthanide element serves as the prototype for the biological disposition of elements of this series.

a. General Characteristics and Biological Behavior

The biological behavior of radioactive cerium has been extensively examined by animal experimentation and ^{144}Ce is among the radionuclides evaluated by analysis of human tissue samples. Consequently, information about cerium, supplemented by the limited data on other elements of the series, has been used to establish the prototypic descriptions of rare earth metabolism. The gastrointestinal absorption fraction was taken to be 3×10^{-4} for all compounds of cerium in ICRP Publication 30 (1979). More recent values (NEA 1988, ICRP 1989) consider the fraction as 1×10^{-3} for adults and as 1×10^{-2} for infants through 1 year of age.

The excretion pattern of cerium in mice is biphasic, with biological half-times of 10 days and 7.5 years. On the day after injection into female mice, 55% of the body burden was in liver and 33% in bone, but after 220 days 3% of the retained activity was in liver and 95% in bone (Naharin 1969).

The model in ICRP Publication 30 assumed that 60% of the cerium entering the transfer compartment was translocated to liver, 5% to spleen, 2% to bone, and 15% to all other tissues. The retention half-time in all tissues is taken to be 3500 days (ICRP 1979, 1989). The same retention was used for adults and infants, but the partition fractions between liver and skeleton were reversed.

b. Fetoplacental Considerations

Mahlum and Sikov (1968) found that concentrations in various fetal structures on the day after intravenous injection of $^{144}CeCl$ in pregnant rats at 15 or 19 days of gestation were independent of age. In the 20-day fetuses, 22% of the total fetal body burden was in the liver, 47% in the skeleton, and the remaining 30% was distributed in the soft tissues. In contrast, 75% of the body content of the adult rats on the day after injection was in liver, 13% in skeleton, 2% in the kidneys, and the remaining 10% was distributed throughout the remaining soft tissues. This pattern of strong age-related concentration differences of cerium is in good agreement with the description for the infant in ICRP Publication 56 (1989).

Cerium, as demonstrated with ^{144}Ce, localizes in the chorioallantoic placentas and yolk sacs of rats at concentrations that are one to two orders of magnitude greater than the fetuses (Zylicz 1975a). Injected cerium in pregnant mice accumulated in the placenta, but not in evident disturbance of placental function (Marciniak et al. 1988). D'Agostino et al. (1982) found that exposure of pregnant or lactating mice to cerium led to reduced neonatal weight, but this may relate to maternal toxicity rather than to a developmental effect. Injection of a salt of stable cerium in chick eggs did not produce congenital anomalies (Ridgway and Karnofsky 1952).

Injection of ^{144}Ce as citrate in pregnant mice that littered at 48-72 hours after injection resulted in uptakes of 2.3% of the mother's body burden per pup (Naharin 1969). The fraction of the body burden in the litters fell as the time was increased between mating and administration of the isotope. By contrast, each fetus contained only 0.06% if delivered by Caesarian section at 24 hours after injection. When the babies were allowed to nurse, the body burden increased until the 11th day and then decreased, exhibiting a two-phase excretion pattern slightly shorter than that of adults.

The data demonstrate that the amount of cerium circulating in maternal blood and available to the fetuses determines deposition in the fetus and that little is available for transport after deposition in the maternal skeleton. Thus, a single maternal intake would result in a small fraction entering the fetus; about one-half of the initial fetal content would be in soft tissue and the other half in bone, shifting with time to nearly 100% in bone. The fraction of a pre-existing maternal burden that enters fetal tissue would decrease as the time between the intake and pregnancy increased.

c. Biokinetic Models

The biokinetic model is based on the distribution pattern from ICRP Publications 56 and 67 and use of the skeleton, rather than bone, as a compartment. As stated, the overall half-time is 3500 days, with 50% in liver, 30% in skeleton, and 20% in other tissues. The corresponding percentages in the newborn model of ICRP Publication 56 are 10, 70, and 20, respectively, with the same 3500-day half-time.

Distribution from the circulation takes place with a 0.25-day half-time. A small fraction of the activity sequestered in the placental compartment is considered nonlabile and has an initial concentration equivalent to 0.04 times the average in the whole woman. This compartment, which is not included in the model, is considered to be part of the woman's body. The inhomogeneous distribution in the woman does not contribute to the modeling and is ignored, other than for the uterine involvement in the compartment denoted as "other tissue."

Placental transfer gives an initial or a 1-day fetal concentration that is 0.02 times the average concentration in the woman. The mass ratio is given as fetal mass divided by nonskeletal maternal mass. The net flow in the model is unidirectional and does not include clearance from the fetus. The subsequent decrease in concentration is attributable to growth only.

The gestational-stage-related fractions of the cerium initially deposited and remaining at subsequent times in the pregnant woman and in the embryo/fetus are presented in Tables A29a and A29b, respectively, for ^{141}Ce and in Tables A30a and A30b for ^{144}Ce.

d. Dosimetric Models

The dose to the embryo/fetus was assumed to consist of the sum of the dose due to photons emitted by the radiocerium in the woman's body plus the self-dose from betas and photons emitted by radiocerium in the embryo/fetus. The radiation dose rates and doses to the embryo/fetus are given in Table B24 for ^{141}Ce and B25 for ^{144}Ce.

19. Platinum Series (Osmium, Iridium, and Platinum)

The so-called platinum series includes osmium and iridium in addition to platinum. Members of the series display generally similar chemical and biological behaviors although the ICRP 30 models differ. Osmium has seven stable isotopes and numerous radioisotopes. Only one radioisotope, ^{191}Os, which is used in generators to produce ^{191m}Ir for medical imaging, is relevant for evaluation of radiation dosimetry of the embryo/fetus.

Iridium, the second member of the series, has two stable isotopes and several radioactive isotopes. Based on physical properties, ^{192}Ir was used as the isotope for evaluation of biokinetics and dose factors. The 4.96-second half-life ^{191m}Ir is used in clinical medicine for radionuclide angiography. The time before decay, however, would be inadequate for significant placental transfer and self-dose dose to the embryo/fetus.

Platinum has six stable isotopes and numerous radioactive isotopes. It is not of particular interest for evaluations relative to radiation dose factors for the embryo/fetus. In the absence of information on placental transfer

of osmium and iridium, however, and because its behavior was considered by ICRP in its description of the metabolic models for these elements, data on platinum provides a basis for biokinetic models of these elements. Moreover, metabolic and toxicologic information have been obtained concerning metallic platinum and its salts, which are commonly used in the fabrication of jewelry, as catalysts in manufacturing, and (in platinum-containing organic compounds) as antineoplastic drugs.

a. General Characteristics and Biological Behavior

Although, osmium, iridium, and platinum display similar chemical and biological behaviors, there are notable differences in the fractions of the deposited activity with short and long retention times. These differences are seen in the models for osmium and iridium in Part 1 of ICRP Publication 30 (1979) as compared to platinum in Part II (1980). Because of the later year of publication, the platinum parameters will be assumed to be most valid and will be used for all three elements, together with available inferences regarding placental transfer.

Data from direct measurements were not available for osmium so that th ICRP inferred its absorption and metabolism from experimentally determined information concerning iridium. Neither element is listed as a normal constituent of the human body, and no information for body content or intake is given for Reference Man (ICRP 1975). The ICRP considers the fractional absorption values, f_1, of all compounds of osmium and iridium to be 0.01. The oxides and hydroxides are assigned to inhalation class Y, the metals and their halides and nitrates to class W, and all other compounds to class D.

Elevated concentrations of platinum in kidney compared to that in the total body, were found after intravenous injection in rats. Concentrations increased to a lesser extent in liver, spleen, and adrenal (Moore et al. 1975a). After inhalation of the metal, rats have relativly elevated concentrations in kidney and bone (Moore et al. 1975b). Yoakum et al. (1975) found renal deposition after oral exposure to diets supplemented with stable platinum sulfate.

b. Fetoplacental Considerations

In the absence of direct data, placental transfer and fetoplacental disposition of osmium and iridium are extrapolated from information concerning platinum. Observations regarding developmental toxicity provide inferential evidence for the placental transfer of platinum although reported effects could have been mediated through maternal effects (D'Agostino et al. 1984). This study found that administration of platinum salts to pregnant mice resulted in altered postnatal development, but neither placental transfer nor platinum content of the fetuses and offspring was measured. Administration of the sulfate led to decreased body weight of offspring in the postpartum period from 8 to 45 days. Administration of sodium hexachloroplatinate led to decreased levels of physical activity of the offspring.

Other inferential evidence comes from experimental evaluations of metallic platinum as an intrauterine contraceptive device in rats and rabbits (Chang et al. 1970, Tobert and Davies 1977). Insertion before copulation led to a decrease of blastocyst implantation that is presumed to be attributable to a mechanical phenomenon. A metallic platinum wire inserted in the rat uterus after implantation had occurred, which does not expose the conceptus to platinum ions, did not decrease fetal survival. Studies involving mechanical contraception should not be interpreted as providing direct evidence regarding placental transfer.

The studies of Moore et al. (1975a, 1975b) involved extensive measurements of absorption, excretion, retention, and distribution after intratracheal, oral, and intravenous administration of ^{191}Pt in saline to male rats. An additional group of pregnant rats at 18 days of gestation were given 25 μCi intravenously and killed 24 hours later. Excretion (19%) was about the same as in adult males during the first day after injection. Most tissue concentrations in the females were slightly less than in males but the value of 0.35% administered activity/g in maternal blood was only about one-third of that in adult males at this same time; it was not until 2 weeks that the males reached this retention level.

Other maternal tissue concentrations were 0.3%/g in bone, 0.6%/g in lung, 1.44%/g in liver, and 4.22%/g in kidney. The corresponding placental concentration was 0.92 %/g, and the average fetus and fetal liver concentrations were 0.01%/g and 0.05%/g, a five-fold ratio. The average fetal concentration at that time was 0.01%/g body weight while the fetal liver had a concentration of 0.05%/g, a five-fold ratio. This elevated concentration in a relatively small mass does not affect totals. However, most of the activity is retained by the placenta, and only a small amount of injected platinum in rats enters the embryo/fetus.

The total activity in the fetal/placental mass may amount to nearly 10% of the injected activity. This would include an indeterminate (but potentially large) fraction in the yolk sac and other membranes. This could account for the quantitative differences between the adult male and pregnant rat but would be unimportant for dose to the adult human or for dose to the embryo/fetus. The placental concentration was higher than for maternal organs other than liver and kidneys; the difference was not enough to require consideration separately as a gamma source and should not be an important source organ in the human.
However, initial deposition and retention in embryo will be the same as the uterus during the first months, before there is meaningful placental deposition.

c. Biokinetic Models

After intraperitoneal or intravenous administration to rats, osmium and iridium concentrations in liver, kidney, and spleen are 10 times those in the average whole body (ICRP 1980). There is no evidence to suggest specificity for bone deposition, and osmium and iridium are considered to have relatively uniform body distribution (other than as indicated).

In normal adults, 20% of the osmium or iridium radioactivity is considered to leave the transfer compartment and enter excreta with a half-time of 0.03 day. No animal data indicates specific bone deposition, so these radionuclides are considered to have relatively uniform body disposition. Partition in the normal adult is taken as 20% to liver, 4% to kidney, and 2% to spleen, while the other 54% is uniformly distributed throughout the other organs and tissues. ICRP Publication 30 gives two biological retention half-times for osmium or iridium entering any tissue: 20% for 8 days and 80% for 200 days.

The gestational-stage-related fractions of ^{191}Os initially deposited and remaining at subsequent times in the pregnant woman and in the embryo/fetus are presented in Tables A31a and A31b, respectively. The corresponding fractions for ^{192}Ir are shown in Tables A32a and A32b.

d. Dosimetric Models

Based on physical properties and potential for exposure, ^{191}Os and ^{192}Ir have been evaluated for this report. The osmium isotope, ^{191}Os, is a beta-gamma-emitter with a 16-day half-life, which is used in generators to produce ^{191m}Ir for medical imaging (angiography) and is relevant to nuclear medicine. Based on physical properties, ^{192}Ir si a beta-gamma-emitter with a 74-day half-life, which was considered as most relevant general radioisotope for assessment of embryo/fetus exposure and calculations. There would not be adequate time for placental transfer or internal dose to the embryo/fetus from the 4.96-second half-life isotope, ^{191m}Ir.

The dose to the embryo/fetus was assumed to consist of the sum of the dose due to photons emitted by the ^{191}Os or the ^{192}Ir in the woman's body plus the self-dose from betas and photons emitted by radioisotopes in the embryo/fetus. The radiation dose rates and doses to the embryo/fetus are given in Table B26 for ^{191}Os and Table B27 for ^{192}Ir.

20. Thallium

Thallium has two stable isotopes, with atomic weights of 203 and 205, and about 20 radioactive isotopes. Stable

thallium is used in industry, some of its salts are used as rat poisons, and it is recognized as a trace environmental toxic pollutant. Radiothallium is used in nuclear medicine imaging for determination of cardiac perfusion.

a. General Characteristics and Biological Behavior

Thallium is a normal trace constituent of the human body. The soft tissue content of Reference Man is not given, but daily intakes are stated as 1.5 mg (ICRP 1975). As a consequence of its uses and recognized toxicity, the biological disposition of intravenously injected thallium has been evaluated in man, as well as in experimental animal species, with good agreement among reports.

Thallium sulfate and nitrate are readily absorbed from the gastrointestinal tract and f_1 is taken as 1 for all compounds. ICRP Publication 30 (1981) assigns all thallium compounds to inhalation class D. Thallium is uniformly distributed throughout the body except for kidneys, which contain about 3% of the activity.

b. Fetoplacental Considerations

Studies in rats and mice demonstrated placental transfer of thallium and its salts and have provided limited quantitative data on deposition in the placenta and in fetal organs. Ziskoven et al. (1983) fed ionic thallium to pregnant rodents and then measured placental transfer. There was a rapid rise in concentrations in fetal tissues; the rate was the same as for the maternal kidney but the concentration levels were only about one-tenth as great. Fetal concentrations were similar to those eventually reached in the maternal brain.

Gibson and Becker (1970) compared thallium effect and placental transfer in normal and potassium-deficient pregnant rats. Both potassium deficiency and thallium sulfate were teratogenic when administered alone and the overall combined teratogenic effect was not more severe. They also studied intravenous infusion of ^{204}Th for 1 hour into control and potassium-deficient near-term rats. Fetal and maternal blood samples obtained at intervals during infusion showed that potassium deficiency did not affect thallium levels in maternal blood and did not enhance placental transfer; both continued to increase with time. Maternal plasma concentrations were 10-fold those in the fetus under all infusion conditions, leading to a conclusion that there was restricted placental transfer. In both groups, maternal blood plasma concentrations were approximately one-half of those in the erythrocytes (Gibson and Becker 1970).

Rade et al. (1982) injected midgestation rats with ^{201}Tl with carrier and obtained samples for analysis at 4 hours through 8 days. The average effective half-time was 64.2 hours and 90% of the activity was excreted within 3 days. There was slower entry of activity into maternal brain and muscle than into other tissues; the peak was followed by an exponential decrease with a half-life of 136 hours in brain and 95 hours in muscle, which accounted for a large fraction of activity retained at 8 days. The placenta and whole fetus declined at the same rate as most maternal tissues. Fetal brain and liver activity peaked at 4 hours; concentration ratios for brain were 0.9 at 4 hours and fell to 0.14 at 8 days; the ratios for liver were 0.19 at 4 hours and 0.14-0.15 thereafter.

Whole body autoradiography after intraperitoneal injection of ^{204}Tl in the mouse demonstrated fetal activity by 15 minutes, with maximum accumulation at 2 to 4 hours. There was greater deposition in placenta and in fetal membranes than in the embryo or fetus throughout gestation (Olsen and Jonsen 1982).

Studies in the human include that of Johnson (1960) who evaluated a baby born to a woman who had ingested rat poison several weeks previously. The report indicated that there was no detectable thallium in the placenta or in cord blood. The woman's urine contained a small amount of thallium at term but none was detected in the baby's urine. The baby's scalp had patches of alopecia (deficient amounts of hair), which indicated that the thallium had crossed the placenta. This was included among more than 20 cases in a review of ingestion by pregnant women, mostly attempts at suicide or to induce abortion (Barlow and Sullivan 1982). Reports of con-

trolled studies on human thallium exposure during pregnancy have not been identified, but based on symptomology such as the characteristic alopecia, it clear that thallium crosses the human placenta.

c. Biokinetic Models

The ICRP Publication 30 model assumes that the element is instantaneously translocated from blood. Except for kidneys, which contain about 3% of the activity, the remaining 97% is uniformly distributed throughout all organs and tissues. Thallium is considered to be lost from all tissues with a biological half-life of 10 days (ICRP 1981).

Based on the uniform distribution, the embryo is considered to be at the same concentration as the uterus during the first 2 months of gestation. After administration at later stages, the average fetal concentration is considered to be at an initial level that is one-half of the woman's concentration. The activity is then lost with the same biological half-life of 10 days as given for the woman.

The gestational-stage-dependent values of deposition and retention of ^{201}Th are shown in Table A33a for the pregnant woman and in Table A33b for the embryo/fetus.

d. Dosimetric Models

The most important thallium radioisotope for evaluating exposure of the embryo/fetus is ^{201}Th, as modeled above. This accelerator-produced isotope, which is used clinically as the chloride, decays by electron capture with a half-life of 73 hours. The gestational-stage-dependent dose factors for the embryo/fetus are shown in Table B28.

21. Lead

Lead has about 40 isotopes and isomers; the most abundant are stable but more than 20 are radioactive. There are long-standing health concerns about both stable and radioactive lead. Some of the radioisotopes are encountered in relation to the radium and radon series and may be formed in situ by decay of polonium or bismuth. The most relevant isotope for evaluating placental transfer and exposure of the embryo/fetus is ^{210}Pb, a beta-gamma-emitter with a 22-year half-life. This isotope has also been used as the predominant tracer for biological studies.

a. General Characteristics and Biological Behavior

Lead is a trace constituent of the human body although it is not of normal metabolic or biochemical relevance. Lead content of the skeleton and total body of Reference Man are 110 mg and 120 mg, respectively, and daily intakes in food and water are given as 0.44 mg (ICRP 1975).

The absorption of many lead compounds is greater than the absorption of metallic lead although it is more variable. In Publication 67, ICRP again adopted the ICRP Publication 30 recommended f_1 value of 0.2 for ingestion. Based on greater absorption in the infant, the value is given as 0.6 for the 3-month infant and 0.4 for children of 1-15 years of age. All common lead compounds are assigned to inhalation class D.

Lead is readily bound to circulating red blood cells, a pattern that is included in the model of ICRP Publication 67 (1993). This has been shown to be important in studies of fetoplacental disposition, as described below, and is incorporated in the biokinetic models.

b. Fetal and Placental Information

Data from both human and animal studies agree that lead can be readily, but slowly, transferred across the placenta to the fetus (Barltrop 1969, McClain and Becker 1975). After intravenous injection of rats at 17 days of gestation with lead nitrate, maternal blood and plasma concentrations declined exponentially with time (McClain and Becker 1975). This was paralleled by a decrease in placental concentration; fetal lead concentra-

tion increased through the 24-hour study, however, and reached a final concentration that was about 60% of that in placentas. A lead-chelate complex crossed the placenta more readily than did lead nitrate but was excreted from the pregnant rat more rapidly, so that fetal content was not increased (McClain and Becker 1972).

Hackett and Kelman (1983) reported that lead metabolism (blood clearance, tissue distribution, fetoplacental concentrations) and toxicity were affected by dosage level and route of administration in pregnant rats exposed by gavage, inhalation, or intravenous injection. Using this same range of intravenous dosages (5 and 25 mg/kg lead nitrate or carrier-free ^{210}Pb), Hackett et al. (1982a, 1982b) also found that distribution among fetoplacental component varied with stage of gestation and were dose-dependent. After injection during early organogenesis, the relationship between administered carrier-dosage and the lead content of the egg cylinder (a composite structure of developing fetoplacental elements) was especially complex. When allowance is made for dependence on mass administered, these results also were in general accord with those reported by McClain and his colleagues (McClain and Becker 1972, McLain and Siekierka 1975) for the same stage of gestation.

Clearance from maternal to fetal circulation, as directly measured in a perfused guinea pig placental preparation, was among the lowest of several elements evaluated by Kelman and Walter (1980). They also demonstrated that the high concentration of circulating lead affected maternal blood flow to the placenta, and that the true clearance value may have been higher. We note that for lead (and for essentially all radionuclides/elements considered here), the carrier-free form is relevant to the models and to the practical situations.

Carpenter et al. (1973) reported patterns of diffuse activity in the fetus and found substantial amounts of autoradiographic activity associated with the placenta and membranes after injection of hamsters with ^{210}Pb during early organogenesis. Hackett et al. (1982b) found lesser intensities of autoradiographic activity associated with embryonic structures, yolk sac, and placental tissue at early times after injection at comparable stages of gestation in the rat. By one day after injection early in the fetal period, the placenta, Reichert's membrane, and visceral yolk sac contained radioactivity; activity in the fetal liver and chondrogenic areas increased with time. This study also demonstrated that the pattern found by Carpenter was attributable to the presence of ^{210}Pb in the injection medium.

Human studies yielded data that indicate that lead can be readily transferred across the human placenta to the fetus and that this transfer can be monitored as early as the 12th week of gestation (Barltrop 1969). Gershanik et al. (1974) measured lead levels in maternal and neonatal blood samples. The mean concentrations in maternal blood were significantly higher in women from urban than from rural environments, but were not related to stage of gestation. Overall mean concentrations in neonatal cord blood (9.4 μg Pb/100 ml) were similar to those in maternal blood (10.5 μg Pb/100 ml). In a subgroup of 98 cases of paired samples, there was a high correlation of lead levels in mothers and corresponding infants.

Roels et al. (1978) likewise found a highly significant correlation between lead concentrations in cord and maternal blood, and also detected a weaker, but statistically significant correlation with the concentration in the placenta. Their value (8.4 μg Pb/100 ml) was similar to those of many other workers, although some groups had reported up to a four-fold greater placental concentration.

c. Biokinetic Models

The initial deposition site of intravenously injected ^{210}Pb is considered to be the red blood cell mass, which is modeled as containing 55% of the activity at day 1 with the remainder in the liver, soft tissue compartments, and skeleton. The red cell activity is released to plasma with a 20-day half-time, following a pattern such that 30% of the activity is excreted during the first 20 days. Lead leaving the plasma is distributed to the liver and soft tissue compartments and progressively to the skeletal compartments, which effectively contain about 20% of

activity during this time period. Lead can be substituted in the calcium positions of apatite and rapidly distributes throughout the volume of mineral bone. Assumptions about partition or translocation between bone surface and matrix are not needed for the placental transfer or embryo/fetus model. However, net retention half-times of 7 days, 30 days, and infinity are used for skeleton, but there is tenacious retention only in mineral bone.

There is only nominal prenatal deposition during the earliest stages of gestation, and there is no significant localization prior to ossification. Concentration in the embryo/fetus is modeled as being the same as the uterus or generalized soft tissue, which largely ignores red cell activity. A similar relationship for initial concentration for soft tissue of the embryo/fetus is modeled as applying through gestation. The growth of soft tissue mass leads to increasing relative percentages of administered activity relative to gestational age.

For net kinetics, the model assumes that activity does not return to woman from fetus and that decreased concentration comes from growth. These assumptions yield patterns that are in accord with and account for findings suggesting that lead concentrations in fetal and maternal blood and bone are similar after continuing exposure to environmental sources.

Progressive changes in bone composition relative to stage of gestation influence initial deposition and subsequent concentrations. As was described in Section IV, known patterns of skeletal composition and relative mineral behavior allow derivation of gestational-stage-dependent comparative models of fetal-maternal skeleton deposition. The values from this model were introduced into the modeling of deposition and retention of lead in the embryo/fetus. This provides a transition from the situation in which there is no skeletal deposition in the early embryo to a condition where concentrations are the same as those of the woman at 6 months of gestation and thereafter. The activity going to the fetal skeleton is modeled by using this factor as a multiplier of the ratio of skeletal masses, which are the maternal and fetal that represent the major content of lead.

The gestational-stage-dependent values of deposition and retention of ^{210}Pb are shown in Table A34a for the pregnant woman and in Table A34b for the embryo/fetus.

d. Dosimetric Models

Based on physical characteristics and potential for entry or formation in the body of the woman or the embryo/fetus, the most relevant isotope for evaluating placental transfer and exposure of the embryo/fetus is ^{210}Pb, as modeled above. This isotope decays with a half-life of 22 years by beta-gamma emission to 5-day ^{210}Bi and then to ^{210}Po. The biokinetic behaviors of these decay products in the sites of formation are markedly gestational-stage-dependent and, based on the model given in ICRP Publication 67 (1993), would not follow the lead model except toward term. Accordingly, dose from these radionuclides was not included in the present calculations and should be evaluated separately, based on the radionuclides' individual behaviors. The gestational-stage-dependent dose factors for the embryo/fetus from photons in the woman's body plus self-dose from betas and gammas in the embryo/fetus are presented in Table B29.

22. Bismuth

Natural bismuth has a single stable isotope, ^{209}Bi, but it has a multitude of radioisotopes. Only one radioisotope, ^{210}Bi, an important member of the uranium series that is encountered following decay of radon, is of primary relevance to exposure of the embryo/fetus.

a. General Characteristics and Biological Behavior

Bismuth is a trace constituent of the human body; its content in soft tissues is given as less than 0.23 mg for Reference Man, with a normal daily intake of 20 μg (ICRP 1975). Gastrointestinal absorption of stable bismuth salts have been of interest because of the possibility

of exposure during pregnancy though the oral use of nonprescription agents containing bismuth subsalicylate, e.g., "Pepto Bismol," for relief of indigestion. ICRP Publication 30 takes the value of f_1 as 0.05 for ingestion; bismuth nitrate is assigned to inhalation class D and all other compounds to class W.

Bismuth is rapidly cleared from blood and ICRP Publication 30 states clearance from the transfer compartment as "directly" for all compounds. The greatest deposition of bismuth translocated from the transfer compartment is in kidney; concentrations in spleen, liver lung, and bone are an order of magnitude lower.

b. Fetal and Placental Information

Bio-available bismuth has been shown to be concentrated in the placenta but is readily transferred to the fetus (Thompson 1941). Autoradiographic evaluations of human placentas at term and from terminated pregnancies also have detected its presence. It may bind to numerous tissues, especially growth fronts of bone (Reynolds 1982, Stemmer 1976) initial concentrations may be assumed to be the same as general soft tissue of the woman, but bismuth tends to be retained.

c. Biokinetic Models

The model assumes that 30% of bismuth leaving the transfer compartment goes to excreta with a default half-time of 0.25 day and 40% goes to kidney. The embryo/fetus is not considered to participate in these pools but receives a proportionate fraction of the other 30% of the activity, which is uniformly distributed throughout all other tissues. Of this distributed activity, 60% is assumed to be retained with a biological half-time of 0.6 day and 40% with a half-time of 5 days.

The mass of the embryo/fetus is assumed to participate equally as a site for the 30% of activity that is initially distributed to other tissues. The model, however, considers that the embryo/fetus does not receive any of the activity that is subsequently excreted by the woman but that all radioactivity in the embryo is retained, being diluted by growth to reduce concentration.

The gestational-stage-dependent values of deposition and retention of ^{210}Bi in the embryo/fetus are shown in Table A35.

d. Dosimetric Models

The radioisotope, ^{210}Bi, an important parent and daughter associated with decay of radon, is of primary relevance to exposure of the embryo/fetus. The dose factors for the embryo/fetus associated with this beta-emitter with a 5-day half-life are presented in Table B30.

23. Polonium

Polonium does not have any stable isotopes, but there are over 30 naturally occurring radioisotopes, with half-lives ranging from a fraction of a second to a thousand years. Most polonium isotopes are disintegration products of radon. Perhaps the most important isotope for exposure of the embryo/fetus is ^{210}Po, a 138-day alpha-emitter that decays to ^{206}Pb.

a. General Characteristics and Biological Behavior

Traces of polonium are found in the human body but no values are given for Reference Man; the reference daily intake is given as 0.1 Bq. The value for the absorbed fraction, f_1, given in ICRP Publication 30 has been raised by successive expert groups and the most recent is the 0.5 for adults given in ICRP Publication 67 (1993). In the absence of specific data, the same value was adopted for children, and a larger value of 1.0 was adopted for infants.

Based on measurements of ^{210}Po in tissues, ICRP Publication 30 considered the total content of the body as 40 Bq, with about 60% in mineral bone. This was considered to result primarily from in situ production from ^{210}Pb and only minimally to represent distribution of ingested or inhaled polonium.

Polonium, as a decay product of radon, is especially encountered as deposited on particulates or in tissue after in situ decay of radon. It has been reported to deposit in lung after inhalation of cigarette smoke. Oxides, hydroxides and nitrates of polonium were assigned to inhalation class W and all others to class D in ICRP Publication 30.

b. Fetal and Placental Information

The pattern seen in animal studies, which found that minimal fractions of polonium salts pass into fetal tissues, are in accord with results of human measurements. Lacassagne and Lattes (1924) reported that salts of polonium deposited in the syncytial cells of the placental chorioric epithelium. It appeared that detectable amounts of polonium did not pass into the fetal connective tissue or the fetal endothelium.

Subsequent experimental studies provide inferential evidence that confirms the placental deposition and the absence of appreciable transfer of injected ^{210}Po. Studies using injection of rats with an equilibrium mixture of ^{210}Pb and ^{210}Po resulted in intense autoradiographic labeling of the placenta, Reichert's membrane, and visceral yolk sac (Hackett et al. 1982b). The intensity of the labeling was much less when freshly separated ^{210}Pb was injected, indicating that the greatest fraction of the autoradiographic label was derived from the polonium component. This result suggested an alternative explanation for findings of Carpenter et al. (1973), who had found high levels of activity in these same structures in their experiments that used an equilibrium mixture of lead. Reinterpretation suggests that the labeling was attributable to the ^{210}Po rather than to the ^{210}Pb.

Radioanalyses of specimens of Arctic lichens and grass, reindeer and caribou, and postpartum placentas found elevated levels of radionuclides, especially ^{210}Po and ^{210}Pb (Holtzman 1966). This activity results from natural fallout and concentration by the slow-growing grasses and the animals. These results are compatible with other observations of human tissues, where elevated concentrations have been measured in placentas from populations who consumed reindeer and caribou meat (Hill 1966). This again represented natural fallout radioactivity resulting from ^{222}Rn. There was excellent correlation with levels of ^{137}Cs in the environment and illustrates the role of the food chain.

Analyses of autopsy specimens have detected polonium isotopes in a variety of tissues, including the fetus. These results are compatible with other observations in human tissues, where elevated concentrations have been measured in placentas from populations who consumed reindeer and caribou meat during the period when fallout radioactivity was of particular importance.

c. Biokinetic Models

Following the description in ICRP Publication 67 (1993), the model considers that intravenously injected polonium is deposited mainly in soft tissue and that skeletal content is related to marrow. A total of 35% is assumed to be deposited in liver, kidney, and spleen, another 10% in red bone marrow, and the other 45% to all other tissues. All of this activity is retained with a biological half-time of 50 days.

The uterus participates equally in this distribution and, during the first 2 months of gestation, the embryo is considered to be at this same concentration. As the placenta evolves, it may be assumed that there would be minimal transfer. However, to be conservative, the embryo/fetus is considered to participate in the distribution. The model assumes that the initial concentration in the fetus is 10% of the woman's soft tissue concentration, there is no return to the woman, and there is a linear transition period between concentrations at 60 and 90 days of gestation. The kinetics described by the model would allow the placenta and membranes to receive deposition of material in the circulation.

Polonium also could be formed within the conceptus by decay of radon and its progeny, for which different excretion kinetics are assumed by the ICRP. This possi-

bility is mainly applicable to chronic environmental exposure and has little relevance to acute introduction of activity. Deposition and retention values of ^{210}Po in the embryo/fetus after acute injection at representative stage of gestation are given in Table A36.

d. Dosimetric Models

Among several polonium isotopes, ^{210}Po, an alpha-emitter with a 138-day half-life, is considered to be of primary relevance to embryo/fetus exposure. The gestational-stage-related dose factors for the embryo/fetus corresponding to the above model are presented in Table B31.

Localized Deposition: It appears that there would be a minimal average radiation dose to the embryo or fetus from ^{210}Po (or other isotopes) in the body of the pregnant woman and that most might be localized to the bone marrow. The placenta and membranes might also receive radiation doses from the retained radioactivity; these would be low on an average basis but could be locally high.

Harrison et al. (1991a, 1992) have reviewed available data and, in particular, determined concentrations in hematopoietic tissues. In addition to confirmation of deposition in placenta and fetal membranes, deposition in the embryo/fetus was determined. These values were used for dose calculations, including hematopoietic dose, that extended earlier estimates by Stather (1984).

24. Radon

Radon is a radioactive gas that is generated by decay of radium in the natural series. Half-lives of the natural isotopes range from a small fraction of a second to the 3.8-day alpha-emitting ^{222}Rn, which is considered to be the isotope of particular dosimetric importance for exposure of the embryo/fetus.

Radon is an inert gas that is not a natural constituent of the human body and shares some of the characteristics mentioned for krypton and xenon. Its biokinetic and dosimetric models differs from these other inert gases in that the internal radiation dose from activity contained in the lungs or present in tissue predominates and there is no meaningful radiation from the external cloud.

The conditions and biokinetics form the basis for models and parameters that are developed in Section VI for noble gases and associated tables of dose factors. As will be noted, there are meaningful differences among the noble gases in their biological dispositions in the woman and embryo/fetus because of individual partition coefficients and temporal factors associated with the conditions of exposure. With radon in particular, the radiation dose from decay products is of particular concern. Exposures from deposited daughters in feto-placental sites would be evaluated for the specific physical and biological behavior of these radionuclides.

25. Radium

Radium is a naturally occurring alkaline earth metal that includes more than 20 radioisotopes, but fewer than 10 are of significant radiological concern. All of the isotopes are radioactive; most emit alpha particles although some are beta-emitters. The most abundant in the environment is ^{226}Ra, an alpha-emitter with a 1600-year half-life that spontaneously decays to ^{222}Rn. Also of interest for dosimetry of the embryo/fetus is ^{224}Ra, a 3.7-day alpha-emitter that has been used clinically.

a. General Characteristics and Biological Behavior

The radium content of Reference Man is given as 31×10^{-12} g, of which 27×10^{-12} g are in the skeleton. Daily intake in food and fluids is given as 2.3×10^{-12} g. The value of f_1 was taken to be 0.2 for all compounds of radium in ICRP 30; this value was adopted by the NEA Expert Group (1988b) and in ICRP Publication 67 (1993). The fractional absorption value was taken as 0.6 for infants and 0.3 for children. Commonly occurring compounds were assigned to inhalation class W.

The ICRP task groups and independent groups of investigators have extensively modeled the behavior of radium and its decay products in soft tissue and bone as well as the resulting radiation doses in adults and, more recently, in children (see ICRP Publication 67). To a first approximation, radon formed in soft tissue or bone surface is lost without decay, all thorium and actinium are retained, and others behave as does the parent.

The dosimetric model derived from the ICRP (1973) assumed that radium isotopes with half-lives greater than 15 days are internalized into bone while shorter-lived isotopes are considered to be distributed over bone surfaces at all times following skeletal deposition. The retention functions given in that report are considered in ICRP Publications 56 and 67, but the assumptions are not needed for the placental transfer model.

b. Fetal and Placental Information

Most information about the age-related biological disposition of radium was obtained from experience with ^{224}Ra and ^{226}Ra. Animal data derive from the study of Wilkinson and Hoecker (1953), who dissolved $^{226}RaCl_2$ in saline and allowed the solution to reach equilibrium. Rats were intraperitoneally injected with the material at 15 days and killed for evaluation at 20 days of gestation. No radioactivity was detected in the placentas or fetuses, but it is not clear whether and to what extent the nuclide was absorbed into the maternal blood from this route of administration and available for placental transfer. These findings in animals of no transfer do not corroborate studies of human materials, which vary quantitatively among themselves but uniformly find fetal burdens of radium.

Human studies include those by Martland and Martland (1950); they evaluated 17 children from 10 mothers who had been employed as radium dial painters. The radium burdens were sufficiently great in some of the women that they subsequently became symptomatic. Burdens of less than 10^{-8} g radium were measured in the children, which the investigators considered to be in the normal range for an unexposed population. This result may be interpreted as indicating that there is little or no recruitment of pregestational bone burden.

Measurements of the ^{226}Ra content of bones and soft tissue of approximately 200 human fetuses at various stages of gestation, as well as 40 additional placentas, have been reported (Muth et al. 1960, Rajewsky et al. 1965). The specific activity of bone ash (10^{-14} Ci/g) was independent of the stage of gestation and was the same as that measured in adult bone. Concentrations (10^{-16} Ci/g) were similar in fetal soft tissues and the placentas. These did not change during gestation although increasing fetal mass led to a concomitant increase in the total content of the fetuses.

Analyses on the skeletal remains of a former radium dial painter who had died from complications of pregnancy and her 7-month fetus were reported by Schlenker and Keane (1987). They estimated that about 0.12% of the radium in the mother had been transferred to the fetus during the 7-months of gestation, as compared to an anticipated excretion of 9% to 22% during this period. They performed several calculations that combined factors from ICRP models, measurements that gave concentration ratios of radium to calcium in maternal and fetal bone, and estimates of relative concentrations in maternal and fetal plasma and then extrapolated levels of activity in plasma at the time of pregnancy. From these, they concluded that the placental transfer of radium was similar to or perhaps slightly greater than that of calcium. From published data, they also calculated that fetal to adult specific activities of natural ^{226}Ra (expressed as mBq per g calcium) would be essentially the same.

c. Biokinetic Models

Aside from physical half-life, the characteristics of the radium are the major factor in placental transfer, biokinetics, and deposition/retention. Time to decay affects the contribution of daughter radionuclides to radiation dose, but their behavior is not included in the present

biokinetic or dosimetric models and should be considered specifically. Biokinetics in the pregnant woman use a parsimonious model that is based on the description given in ICRP Publication 67. Distribution patterns during the first post-injection days are used to emphasize aspects related to the embryo/fetus, as given in Section IV of the present report.

The model considers that 32% of the administered radium goes to early excretion following intravenous injection. As noted for lead, only nominal prenatal deposition is associated with the earliest stages of gestation, and localization within the embryo/fetus is not notable prior to the beginning of ossification. Concentration in embryo is considered to be same as that of the uterus, which is given as generalized soft tissue. Also, analogous values are modeled as applicable to initial concentrations in soft tissues of the embryo/fetus through gestation. However, an increased soft tissue mass results in a larger relative percentage of administered activity with increasing gestational age. The model is based on net movement and assumes that activity does not return from fetus to woman although decreased concentrations will result from growth.

The initial deposition in the woman's skeleton is taken as 25%. Infinite skeletal retention is assumed for purposes of modeling placental transfer. This same 25% concentration is used in establishing gestational-stage-related deposition in the skeleton of the embryo/fetus. The model considers the continuing changes in the mineral composition of bone for the stages of gestation, which will influence concentrations and the associated radiation doses.

As was indicated for lead, Section IV describes an approach to biokinetic modeling that was based on reported patterns of skeletal composition and relative mineral behavior. These patterns provided the bases from which gestational-stage-dependent comparative models of fetal: maternal skeleton deposition were developed. The values from this model were introduced into the modeling of deposition and retention of radium in the embryo/fetus. This approach provides a transition from there being no skeletal deposition in the early embryo to skeletal concentrations that are the same as those of the woman at 6 months of gestation and thereafter. The gestational-stage-dependent amounts of activity going to the fetus are modeled by using the corresponding concentrations as a multiplier of the ratio of fetal and maternal skeletal masses, which represent the major content of radium.

The model gives results that are in accord with reports that radium concentrations in fetal and maternal bone are similar at times long after exposure. It also allows for the possibility that the fetus/woman concentration ratio of 1 pertains both to multiple occupational or continued environmental exposures because bone drives the overall concentration levels.

The gestational-stage-related fractions of ^{224}Ra and ^{226}Ra initially deposited and remaining at subsequent times in the embryo/fetus are shown in Table A37 and Table A38, respectively.

d. Dosimetric Models

Because of its clinical uses, ^{224}Ra, which as a 3.7-day half-life, is of importance relative to dosimetry of the embryo/fetus. Radiation dose rates and doses to the embryo/fetus from this isotope are given in Table B32. Also of dosimetric importance is the environmentally ubiquitous isotope, ^{226}Ra, an alpha-emitter with a 1600-year half-life, that spontaneously disintegrates into ^{222}Rn. Dosimetry for this isotope is of epidemiologic relevance for dosimetry of the embryo/fetus because it was involved in exposure of the radium dial painters. Dose factors are presented in Table B33.

26. Thorium

Thorium isotopes are found in all of the heavy radioelement series. The initial member of the thorium series is ^{232}Th, a 1.4 x 10^{10} year alpha-emitter with essentially 100% natural abundance. There are 11 additional isotopes, with half-lives ranging from a fraction of a second

to 8 x 10^4 years (^{230}Th). Also of interest for evaluation are the alpha-emitters ^{227}Th, ^{230}Th and ^{234} Th, a beta-gamma emitter.

a. General Characteristics and Biological Behavior

Daily intake of thorium in food and fluids is given as 3 μg; body content is not given in Reference Man but studies indicate that mineral bone contains about 30 μg. Based on experimental data, ICRP Publication 30 (1979) selected an f_1 value of 2 x 10^{-4} for all compounds of thorium. Oxides and hydroxides are assigned to inhalation class Y and all other compounds to class W. A greater fractional absorption value of 0.001 was suggested by a NEA Expert Group (1988) and value of 5 x10^{-4} has been adopted by ICRP for thorium absorption from food in adults and children but 5 x10^{-3} in infants (1993).

b. Fetal and Placental Information

Studies reported by Maurer et al. (1950) and Engels et al. (1950) evaluated thorium disposition in pregnant rats at stages through the fetal period. The rats were intravenously injected with 4 μg of natural thorium plus about 5 μCi ^{234}Th and killed 30 minutes to 5 days later. Following rapid blood clearance, placental content rose rapidly to about 0.3% of the injected activity and remained constant thereafter. Specific activities in the embryo or fetus also were independent of the sampling interval at times beyond 3 hours. Fetal concentrations were dependent on stage of gestation at exposure, decreasing from 0.001% administered activity per g after injection at an early fetal stage to about 0.0001%/g after injection towards term. The authors stated that these values were 10^3 to 10^6 times greater than for Thorotrast, a preparation of ^{232}Th that was used as a radiographic contrast agent. They used the data to calculate descriptors of the ability of the placenta to transfer thorium; these values displayed a similar stage-dependent pattern.

Weiner et al. (1985) determined the levels of environmental thorium in human fetoplacental tissues obtained from legal abortions and compared the measurements with data on concentrations in normal adult females. The samples were categorized as first trimester (10-14 weeks post conception), second trimester (22-24 weeks), and early third trimester (26 weeks). There were detectable amounts in five of the seven first-trimester samples, and the highest measured fetal concentration was 39 dpm/kg, with a corresponding placental concentration of only 4.4 dpm/kg. They did not report detectable thorium levels in older fetuses.

c. Biokinetic Models

Based on ICRP descriptions, the model assumes that thorium is cleared from the transfer compartment with a 0.25-day biological half-life. Ten percent of the thorium leaving the transfer compartment is considered to be excreted. Another 70% is deposited on surfaces of bone and then slowly distributed throughout the bone volume, with a biological retention half-life that can be considered infinitely long for purposes of the embryo/fetus. Five percent is assumed to be deposited in liver compartments, and 15% distributed uniformly among all other organs and tissues with a 700-day biological retention half-time.

During the first 2 months of gestation, when the embryo/fetus is embedded in the uterine mucosa, the model assumes that it is at the same general soft tissue concentration. As the placenta develops, transfer to the embryo/fetus becomes restricted. At 90 days of gestation and thereafter, a conservative estimate considers that the concentration of thorium in the embryo/fetus is 5% of that in the woman's soft tissue. Activity in the embryo/fetus is calculated by multiplying this percentage by the stage-related ratio of fetal mass to the woman's soft tissue mass. A linear transition between 60 and 90 days is assumed.

The gestational-stage-related fractions of the ^{227}Th initially deposited and remaining at subsequent times in the embryo/fetus are presented in Table A39. The corresponding values for ^{230}Th and ^{232}Th are given in Table

A40. Fractions of ^{234}Th in the pregnant woman and in the embryo/fetus are presented in Tables A41a and A41b, respectively.

d. Dosimetric Models

Radiation dose rates and doses to the embryo/fetus from alpha particles are given in Table B34 for ^{227}Th, Table B35 for ^{230}Th, and Table B36 for ^{232}Th. The dose to the embryo/fetus from ^{234}Th was assumed to consist of the sum of the dose due to photons emitted by the thorium in the woman's body plus the self-dose from betas and photons emitted by thorium in the embryo/fetus. The resulting gestational-stage-related dose factors are given in Table B37.

27. Uranium

Uranium has 15 radioisotopes but three are most commonly encountered. One is the initial isotope in the uranium series, the 4.5 x 10^9 year ^{238}U. The other two are naturally occurring alpha-emitters that are used in nuclear reactions: ^{234}U (2.4 x 10^5 years) and ^{235}U (7 x 10^8 years). These isotopes, together with ^{233}U (1.6 x 10^5 years), which is often used as prototype for experimental studies and forms the basis for the present modeling, are of greatest interest for exposure of the embryo/fetus.

a. General Characteristics and Biological Behavior

The daily intake in food and fluids is considered to be 1.5 μg for Reference Man and the uranium content of the body is 90 μg, with 59 μg in skeleton and 7μg in the kidneys (ICRP 1975). Uranium compounds have been used for a variety of industrial applications and the metabolism and toxicity of its compounds have been extensively studied in adults of various species. Metabolic models are based on data from occupationally exposed persons, assays of people after ingestion at normal dietary levels, and post-injection for terminal patients.

The ICRP has taken fractional absorption to be 0.05 for water-soluble inorganic compounds (hexavalent uranium) and 0.002 for relatively insoluble compounds. The various compounds are assigned to all three of the inhalation classes. The ICRP assumption is that almost two-thirds of uranium entering the transfer compartment is rapidly excreted; the remaining activity is partitioned between bone, kidney, and other soft tissue.

b. Fetal and Placental Information

Despite extensive information about the behavior of uranium in adult animals, there is relatively little data concerning its placental transfer or disposition in the embryo/fetus. Sikov and Mahlum (1968) analyzed maternal and fetoplacental tissues from rats that had been intravenously injected with ^{233}U citrate at 15 or 19 days of gestation (dg) and killed 24 hours later. Concentrations in the fetuses were on the order of 0.01% and 0.03% administered activity per g for the two times, respectively, as compared to 0.3%/g in the dam. After injection at 19 dg, fetal liver and kidney concentrations were higher than the average concentration in the whole fetus and concentration in the fetal femur was even more markedly elevated.

In a subsequent study, distribution and effects were determined in rats that received intravenous exposure to a range of doses of citrated ^{233}U at 9, 15, or 19 dg (Sikov and Rommereim 1986). Exposure at either of the two earlier times produced a dose-dependent increase in prenatal mortality, a decrease of fetal and placental weights, and an increase in incidence of malformations. With exposure during organogenesis (9 dg), fetoplacental concentration (0.066%/g), represented by the egg cylinder, was highest on the day after exposure. Concentrations in the embryo or fetus and the placenta progressively decreased thereafter, but the concentration in the fetal membranes remained relatively constant. The concentrations in the fetuses at 1 day after injection at 15 or 19 dg (0.004%/g and 0.009%/g) were slightly lower than in the previous experiment, but there was again selective deposition in some fetal organs. The placental concentrations were 0.024%/g and 0.036%/g on the day after injection at the two times, respectively, and the corre-

sponding values for fetal membranes were 0.18%/g and 0.39%/g.

Studies in the human consist of determinations of environmental actinides in human abortuses by Weiner et al. (1985). Significant concentrations of ^{234}U were found in three of seven first-trimester samples. The concentrations were similar in the fetal and placental tissue, and the highest concentration was for ^{234}U. Twelve of 16 second-trimester samples were positive for ^{234}U. The sums of all uranium isotopes for samples that were positive were represented by ranges of 0.097-0.32, 0.31-0.52, and 3.5-3.8 dpm/kg in the fetuses, placentas, and umbilical cords, respectively. The concentration in their reference adult was 2.1 dpm/kg, and they concluded that the fetus did not selectively concentrate uranium.

c. Biokinetic Models

The general biokinetic models for the actinides, which will be described in following sections, provide the framework for the uranium model. These models are based on extensions of the description in ICRP Publication 30, modified by factors modeled in Publications 56 and 67. The model includes only the essential elements of the complex patterns of adult deposition/retention and prenatal disposition. It incorporates the same sorts of stage-dependent changes in degree and patterns of deposition within the fetoplacental unit including metabolism relative to that of the pregnant woman as well as deposition considerations for bone.

Following entry of uranium into the transfer compartment, 14.2% is translocated to bone and 11.8% is deposited in kidney; these activities are modeled as permanently retained while 63.8% is considered as being rapidly excreted. A total of 10.2% is considered as going to the soft tissue compartments, which includes activity transferred to the embryo/fetus. During the first 2 months of gestation, when the embryo is embedded in the uterine mucosa, selective deposition in the embryo/fetal membranes is not included in the model and it is considered that a placental barrier does not exist. Thus, the average concentration is assumed to be identical to that of the uterus and other maternal soft tissue. Concentration in the embryo/fetus is modeled as being the same as that in maternal soft tissue compartments throughout the first 8 weeks of gestation. Ossification and calcification of skeleton are modeled as subsequently progressing. For calculations, fetal bone increasingly participates in the skeletal distribution as explained under plutonium, below.

The placental transfer factor (0.2) reduces entry into the embryo/fetus so that the model predicts a transitional period during which concentration in the embryo/fetus drops to 73% of the "other" maternal tissues at 9 weeks of gestation. The model assumes continued transitions during the third month as developing fetal metabolism and morphology influence partition between the pregnant woman and her embryo/fetus. The mass and calcification of bone increase so that there is a greater than proportionate rate of increase in total radioactivity in the fetus. A smooth transition evolves from the model that predicts average concentrations to be 85% of the woman's soft tissue at 13 weeks, the same at 16 weeks, and more than twice at 30 weeks and thereafter. Thus, total activity transferred to the near-term fetus would amount to about 1.8% of the total injected in the woman. Following transfer into the embryo/fetus, all activity is assumed to remain, without excretion.

The gestational-stage-related values of initial deposition and retained activities in the embryo/fetus derived from this model are presented in Table A42 of Appendix A.

d. Dosimetric Models

Based on the fractional values in Table A41, dose factors for the embryo/fetus were calculated and are given in Appendix B for the three most commonly encountered isotopes of uranium. The values are given in Tables B38, B39, and B40 for ^{234}U, ^{235}U, and ^{238}U, respectively.

28. Neptunium

Neptunium is an activation and decay product that is associated with the nuclear fuel cycle and does not occur in nature. Several of its radioisotopes result from decay of fuel extraction products so that neptunium is primarily encountered as reactor waste, which creates a need for its secure storage. The long-lived alpha-emitter, ^{237}Np is considered the prototypic isotope and is of potential interest for exposure of the embryo/fetus.

a. General Characteristics and Biological Behavior

No information concerning neptunium is given in Reference Man. In ICRP Publication 30, f_1 was taken to be 0.01 for all compounds, but was revised to 0.001 in ICRP Publications 48 and 56 (1986, 1989). Based on experimental data from rodents, which indicated that neptunium is cleared from the lung more rapidly than is plutonium, and by analogy with americium, all compounds were assigned to inhalation class W.

As reviewed in ICRP Publication 67 (1993), most data indicate that the metabolic behavior of neptunium is similar to that of americium and plutonium. This behavior pattern was used for their modeling.

b. Fetal and Placental Information

Rats were intravenously injected after 14 or 19 days of gestation (dg) with ^{237}Np in citrate; tissues for radioanalysis were collected 24 hours later (Sikov and Mahlum 1968). The fetuses had average concentrations on the order of 0.01% and 0.02% administered activity per gram, respectively, at the two times of injection. The highest concentrations in the 20-dg fetuses were in the femurs and kidneys, 0.41%/g and 0.23%/g, respectively. As a basis for comparison, concentrations in the corresponding organs of their dams were 1.9%/g and 3.6%/g. The placental concentrations were 0.04%/g and 0.18%/g at 24 hours after injection at the two times, but the corresponding concentrations in fetal membranes were substantially higher: 0.81%/g and 1.24%/g.

In conjunction with a fetal toxicity study, rats were intravenously injected at 13, 16, or 19 days of gestation with ^{237}Np in nitrate solutions (Moskelev et al. 1969). Measurements two days later found that the neptunium content of the fetuses did not vary uniformly with stage of gestation although fractions in the placentas tended to increase. Calculations, based on assumed weights and litter sizes, suggest that the corresponding concentrations in the fetuses were 0.006%, 0.001%, and 0.003% of the administered activity per gram with injection at the three times, while placental concentrations were substantially higher: 0.4%/g, 0.2%/g, and 0.5%/g, respectively.

c. Biokinetic Models

The biokinetic model for neptunium parallels the model that will be presented for plutonium. It includes the essential elements of the deposition and retention patterns for the adult together with the patterns as inferred for the embryo/fetus. Analogous stage-dependent changes in degree and patterns of deposition within the fetoplacental unit, with known and presumed quantitative differences, and metabolism compared to that of the pregnant woman are included, as well as localization in developing skeletal, liver, and deposition considerations for bone.

Based on the description given in ICRP Publications 56 and 67 (1989, 1993), neptunium introduced into the transfer compartment of the pregnant woman is assumed to be distributed with a 0.25-day half-time. This includes 32% of the activity leaving the transfer compartment that is assumed to be directly excreted. Of the tissue distribution, 45% goes to mineral bone and 10% to the liver compartments. This activity is retained with biological half-times that are long, relative to gestation. Most of the remaining activity goes to soft tissue compartments, which exclude liver and gonad.

The total considered as going to the soft tissue compartments includes activity transferred to the embryo and its adnexa (developing placental structures), all of which are embedded in the uterine mucosa during the first 2 months of gestation. Neither selective deposition in membranes of the embryo/fetus nor the developing pla-

cental barrier is included in the model for these stages. Thus, the average concentration is assumed to be identical to that of the uterus, which is given by maternal soft tissue.

Ossification and calcification of skeleton subsequently progress so that fetal bone is modeled as increasingly participating in the skeletal distribution. The model assumes gradual transitions during the third month because of the developing placenta. The same value as for plutonium, 0.1, is assigned as the relative transfer factor. The influence of fetal metabolism and morphology on partition between the pregnant woman and her embryo/fetus leads to a discontinuity during the transitional period, during which concentration in the embryo/fetus drops to 57% of that in the general maternal tissue compartment at 9 weeks of gestation.

Subsequently, the masses of bone and liver, as well as of fetal soft tissues, increase so that there is a greater than proportionate rate of increase in total radioactivity in the fetus. The transition evolves from the model that predicts average concentrations to be 73% of the woman's soft tissue at 13 weeks, increasing to be the same at about 18 weeks, and more than twice at 25 weeks and thereafter. Thus, total activity transferred to the near-term fetus would amount to about 1.9% of the total injected in the woman. Following transfer into the embryo/fetus, all activity is assumed to remain without excretion.

The gestational-stage-dependent values of deposition and retention in the embryo/fetus are given in Table A43.

d. Dosimetric Models

Of primary interest relative to exposure of the embryo/fetus is ^{237}Np, a 2.1 x 10^6 year alpha-emitter. Dose factors corresponding to the above model are tabulated in Table B41 of Appendix B.

29. Plutonium

Plutonium has about 15 isotopes, all of which are radioactive with half-lives ranging from fractions of a second to the 8 x 10^7 year alpha-emitting ^{244}Pu. Based on their likelihood of being encountered and their usefulness for comparative purposes, two alpha-emitters, ^{238}Pu (87.7 years) and ^{239}Pu (24,000 years), are of primary interest.

a. General Characteristics and Biological Behavior

Reference Man does not give data concerning plutonium; however, weapons testing has led to there being measurable quantities in food and human tissues, and there have been occupational exposures. Plutonium is probably the most thoroughly documented actinide, especially as relates to its behavior during pregnancy, and this behavior is taken as being generally representative of the group. These patterns (including fetoplacental) are reviewed in several publications (ICRP 1981, 1987, 1993; Sikov 1987; NEA 1988; Stather 1992). Considering variations among physicochemical states and exposure conditions, data from human exposures and from studies in experimental animals are consistent.

There is little absorption of the most common chemical forms of plutonium from the GI tract or lung. The value of f_1 in ICRP Publication 30 was taken as 10^{-5} for oxides and hydroxides and 10^{-4} for all other commonly occurring compounds. Plutonium oxides were assigned to inhalation class Y and all other common compounds to class W. The value for commonly occurring compounds was increased to 10^{-3} in ICRP Publication 48 (1986), and ICRP Publication 67 adopted the value of 5 x 10^{-4} for unknown forms in adults, including food, of neptunium, plutonium, and americium. The absorption fraction for infants of less than 1 year of age was increased by a factor of 10, to 5 x 10^{-3}.

Following entry into the transfer compartment, plutonium is assumed to be distributed according to the description given in ICRP Publications 56 and 67. Specifically, 80% is translocated to bone surface and liver; there are age-related partition differences, however, of 50% and 30%, respectively, for adults, but 70% and 10% for infants.

b. Fetoplacental Information

Perhaps the earliest of several animal studies was that of Finkel (1947), who analyzed newborn offspring from viable litters of mice that had been injected with ^{239}Pu before mating or during the last 5 days of gestation. The newborns contained small percentages of the administered dosage and the percentage tended to decrease with increasing dosage and with decreased time between injection and measurement. This and essentially all other animal studies demonstrate that the extent of placental transfer is less than that of alkaline earth, bone-seeking elements, such as strontium.

Subsequent investigations have confirmed that plutonium crosses the placenta, there are quantitative differences in initial deposition relative to stage of gestation, and activity can be transferred to offspring via lactation. Although plutonium is embryotoxic to rats when injected during organogenesis, several-fold greater dosages during the fetal period did not affect prenatal development. Parallel series of experiments, reports, and analytic reviews by PNNL in the U.S. and NRPB in the U.K. provide representative and typical findings and illustrative patterns (Stather et al. 1984, Sikov 1987, Harrison et al. 1991, Morgan et al. 1992).

Most reported quantitative values for biological behavior following injection in pregnant animals fall into a relatively narrow range. Stage-related patterns are generally consistent, and most differences have been defined by exposure conditions. As a general overview, there is continued accumulation of plutonium activity after injection during embryonic stages, but concentration decreases because of continued growth. The pattern of deposition for exposure during the fetal period is similar to that at earlier stages. However, there are quantitative differences among fetoplacental tissue concentrations at differing stages of gestation at injection. The initial placental concentrations are higher and do not display as great a decrease. Concentrations in the fetal membranes are even higher and do not significantly decrease with time.

Autoradiographic studies from several laboratories have shown that the highest fetoplacental concentrations of plutonium were in the fetal membranes during these periods of gestation (Ullberg et al. 1962). The placenta had lower concentrations, and the embryo or fetus even less. Activity was particularly high over the developing yolk sac; this concentration appears to be as much as 10 to 100 times greater than measured overall concentrations in the fetal membranes because the yolk sac represents only a small portion of the total mass. The villous yolk sac is a persistent and functional structure in rodent embryos, but has a transient nutritional function in other mammals. Autoradiographic studies have consistently found that most of the activity in the embryo/fetal membranes is contained within this structure.

To determine if yolk sac deposition also occurs during early gestation of non-human primates, Andrew et al. (1979) and Levack et al. (1994) injected pregnant baboons with plutonium at representative stages of gestation. Radioanalysis and autoradiography of fetoplacental samples obtained 24 hours later found concentration ratios that were similar to those found in the rodent. The autoradiographic localization of activity was also similar in the two species when allowance was made for morphologic differences. The yolk sac, which could be visualized in embryos, had a marked autoradiographic label.

Studies to compare the gestation-stage-dependent partition of ^{239}Pu found differences in distribution among species (Sikov and Kelman 1989). The concentrations in the placentas and fetal membranes were not as high as those found in rodents. The ratio of concentrations between these two structures, compared to the embryo/fetus, was not as high in rats and mice. Guinea pigs,

which have greater maturity near term, were injected at 60 days of gestation and killed on the following day. Measured concentrations were lower than in other species although the pattern of partition was similar (Sikov and Kelman 1989). Studies by Morgan et al. (1991) are in agreement relative to the species differences.

Kelman and Sikov (1981) directly measured placental transfer using in situ perfusion of the near-term guinea pig placenta after injection of citrated ^{239}Pu into the maternal circulation. Transfer, expressed in terms of the calculated clearance value, was found to be the lowest clearance value that had been measured with this system. Clearance of a monitor quantity of tritiated water also was reduced at the highest doses of plutonium, indicating reduced maternal blood supply to the placenta. The threshold for this effect was about 5 μCi/kg body weight and clearance was several-fold greater after adjustment for the decreased blood flow.

A role of physicochemical state and total mass administered has been demonstrated in several comparative studies but is not relevant to normal exposure situations. Hackett et al. (1976) and Green et al. (1979) injected animals with ^{239}Pu, as the citrate, mated them 1 day later, and analyzed the offspring at birth. Each neonate contained about a small fraction of the administered dose and the amount transferred decreased throughout subsequent pregnancies.

Relative fetal concentration values for plutonium, as calculated from data of numerous studies in various animal species, differ from ratios reported after limited numbers of radioanalyses of prenatal human tissues that were obtained for chronic exposures at environmental levels (Bradley and Prosser 1993). Determinations that compared measurements on tissues from abortuses, products of conception, and unrelated adults were not able to detect significant amounts of plutonium isotopes in first-trimester specimens (Weiner et al. 1985). There were measurable amounts of ^{239}Pu in six of the second-trimester samples, with concentrations ranging from 0.11 to 2.06 dpm/kg. Summation of total plutonium from assays in one fetus gave a value of 0.08 dpm, with a concentration of 0.23 dpm/kg. Corresponding values were 4.4 dpm and 0.07 dpm/kg in an average adult female, and the comparisons were taken as suggesting a three-fold concentration factor. The maximal ratio of concentration in umbilical cord to fetus was about 10, but placental concentrations apparently were not greater than those in the fetuses.

c. Biokinetic Models

The biokinetic model incorporates only essential elements of the complex prenatal disposition pattern of plutonium. It generally includes the stage-dependent changes in degree and patterns of fetoplacental deposition, localization in developing skeleton and liver, and metabolism relative to that of the pregnant woman. Plutonium primarily deposits on bone surfaces of adults, in contrast to calcium, strontium, and radium, which are incorporated into the matrix of the bone. Bone remodeling leads to relatively rapid burial in compact bone matrix after prenatal or neonatal exposure of laboratory rodents to plutonium (and other actinides).

Plutonium introduced into the transfer compartment of the pregnant woman is assumed to be distributed according to the above ICRP description. Five percent of the plutonium goes to early excretion; 50% is distributed to skeletal surfaces and 30% to liver. Roughly 15% is considered as going to soft tissue compartments, which here includes that distributed to the embryo and the early fetus.

During the first 2 months of gestation, when the embryo is embedded in the uterine mucosa, there may be selective deposition in the fetal membranes, as discussed above for other actinides. Neither enhanced deposition nor placental barrier is included in the model for these times, and average concentration is assumed to be identical to that of uterus and other maternal soft tissues. The model assumes gradual transitions during the third month to accommodate changes in the placenta and in the morphology and metabolism of the fetus that influence parti-

tion between the pregnant woman and the fetus. These and other factors also introduce restrictions, and the placental transfer factor is assigned a value of 0.1.

Ossification and calcification of skeleton are modeled as subsequently progressing. For the purpose of calculations, fetal bone is considered to increasingly participate in control of the fetal burden. This concept, based on summaries such as Widdowson (1968) for calcium and other minerals, considers total contents and relative concentrations in skeletal elements or other fetal organs. The underlying derivation of the model is outlined and explained elsewhere for calcium metabolism (see Section IV).

These factors, together with concurrent increases in the masses of bone and liver, are such that the increases in total amounts of radioactivity in the fetus are greater than proportional to the increase in total fetal mass or the ratio of fetal-to-maternal mass. The model allows for the needed increase from the situation during the first weeks of gestation, when concentration in the embryo/fetus is the same as in maternal soft tissue compartments. The smoothed transition is used that considers relative concentrations to be 1-1/2 times as great as maternal soft tissues at 13 weeks, twice as great at 22 weeks, and three times at 32 weeks and thereafter. Thus, total activity transferred to the near-term fetus amounts to about 3% of that injected in the woman. Following transfer into the embryo/fetus, all activity is assumed to remain, without excretion.

Table A44 shows the activity calculated from the above assumptions enters the embryo/fetus after administration at successive stages of pregnancy.

d. Dosimetric Models

The alpha particles emitted by ^{238}Pu and ^{239}Pu are the major contributors to the radiation dose received by the embryo/fetus when the activity is contained within the embryo/fetus. The S-value for photons is about five orders of magnitude less than that for alpha particles. The radiation doses for activity contained in the embryo/fetus are presented in Tables B42 and B43 for ^{238}Pu and ^{239}Pu, respectively.

Localized Deposition: Plutonium concentrations and radiation absorbed doses to the embryo itself during embryonic stages are relatively homogeneous, and are similar to those in the uterus or uterine mucosa. These are a small fraction of average concentrations and doses in tissues of deposition in the woman, such as bone and liver. There will be high localized concentrations in the developing placental structures and membranes that may result in radiation doses that are as great as or greater than those to any maternal tissues. Because of their short path lengths, alpha particles from these extraembryonic areas would not reach the embryo. As discussed elsewhere, however, it is during the embryonic stages that deposition in the yolk sac has the greatest potential for producing deleterious effects on stem cells. Exposure of these cells might, in theory, be included in dose received by the embryo or lifetime hematopoietic dose (Harrison et al. 1991) but the magnitude is sufficiently small that it can be ignored in practice.

Reported differences among concentration ratios relate to species-specific gestational stages and to the chronicity of exposure, but maternal metabolic differences remain an important factor. Ongoing efforts are attempting to provide relative concentrations as a function of chronological time and stage of gestation, to allow application to either acute or chronic exposures, and to partially reconcile interspecies differences (Sikov 1987, Sikov and Kelman 1989, Stather et al. 1992).

30. Americium

Americium has 14 major radioisotopes and isomers, with half-lives ranging from a fraction of a minute to thousands of years. Based on the likelihood of being encountered under conditions relevant to exposure of the embryo/fetus, ^{241}Am, an alpha-emitter with a half-life of 432.4 years, is of primary interest.

a. General Characteristics and Biological Behavior

Weapons testing and occupational exposures have resulted in measurable quantities of americium in human tissues although Reference Man does not give data. These human tissue measurements have been reported, and the literature contains substantial data from studies in experimental animals.

Americium absorption is generally taken as being representative of the actinide group of elements. The value of f_1 in ICRP Publication 30 was taken as 10^{-5} for oxides and hydroxides, 10^{-4} for all other commonly occurring compounds. All compounds of americium were assigned to inhalation class W. The f_1 value was increased to 10^{-3} in ICRP Publication 48 (1986); ICRP Publication 67 (1993) adopted a value of 5×10^{-4} for unknown forms, including food, in adults. This was considered to apply to neptunium, plutonium, and americium. The value was increased by a factor of 10, to 5×10^{-3}, for infants of less than 1 year of age.

b. Fetoplacental Considerations

Transfer data were obtained in a fetal toxicity evaluation (Moskelev et al. 1969) of rats that were intravenously injected with ^{241}Am citrate solutions and killed 2 days later. Americium content of the fetuses and placentas varied with stage at injection so that average maternal-to-fetal concentrations ranged from 6:1 to 2:1. Consistent with results reported by others, the fraction of the administered americium that entered the conceptus or fetoplacental unit was less than with plutonium and there was proportionately less selective deposition in the placentas and membranes.

Limited radioanalytic data obtained by Hisamatsu and Takizawa (1983) as part of an autoradiographic investigation are also consistent with these results. Concentration data for the fetal membranes were not presented, but it was evident that they contained relatively increased levels of the administered activity. These relationships of less deposition in the membranes than with plutonium pertained irrespective of whether it was considered on an atomic or percentage basis (Mahlum et al. 1978, Weiss and Walburg 1980).

Because all comparisons had been inferential, Rommereim and Sikov (1986) contemporaneously measured transfer and deposition patterns of the two elements. These confirmed the differences between them, as well as previous suggestions that the prenatal effects of americium were similar to those of plutonium, and included prenatal mortality and rib malformations but not reduced weight of the embryo/fetus. Radiation doses were uniformly less than with the same dosage of plutonium. The effects of americium were quantitatively less than with plutonium when based on administered dosage. However, there was better correspondence between the effects as radiation doses to components of the fetoplacental unit, especially yolk sac.

This study confirmed preliminary reports that, after injection at 9 days of gestation (dg), concentrations in the embryo had decreased to one-tenth of the 12-dg value by 20-dg. The concentrations in the placenta and membranes were 10- to 15-fold higher than in the embryo at 12-dg, but decreased only by a factor of 2 to 3 after 20 days. Fetal concentrations were higher at both 1 and 5 days after injection at 15 days of gestation and were even higher at 1 day after injection at 19 dg. The placental concentration were higher than those in the fetus, but the concentrations in the membranes were only slightly higher than in the placentas.

Sikov and Kelman (1989) quantified the placental transfer of ^{241}Am using the in situ placental perfusion system described for lead and plutonium. There was no circulatory effect with injection of the same 30 μCi/kg dose that had decreased maternal blood flow to the placenta with ^{239}Pu. The clearance of ^{241}Am was not significantly different from that measured for the same activity of ^{239}Pu, but its clearance was significantly less, by a factor of 5, when corrections were made for the disrupted maternal blood flow.

Human studies are represented by the determinations of nuclide content after environmental exposure by Weiner et al. (1985). These investigators did not detect significant amounts of ^{241}Am in first-trimester abortuses, but second- trimester samples contained measurable activity, with concentrations ranging from 0.08 to 0.29 dpm/kg in the fetuses. Substantially higher values, 1.0 and 2.1 dpm/kg, were measured in umbilical cords.

c. Biokinetic Models

Americium is removed from blood more rapidly than is plutonium so that the relative amount transferred is decreased. As indicated, essentially all activity that enters the embryo/fetus remains after transfer and so is assigned the same 50-year half-time as that used for adult deposits.

The biokinetic model for americium parallels the model for plutonium, and includes the essential elements of the complex adult deposition/retention and prenatal disposition patterns. The model incorporates analogous stage-dependent changes in degree and patterns of fetoplacental deposition, localization in developing skeleton and liver, deposition patterns for bone, and metabolism compared to that of the pregnant woman.

Known and presumed quantitative differences between the biological behaviors of the two actinides are included. Americium introduced into the transfer compartment of the pregnant woman is assumed to be distributed according to the description given in ICRP Publication 67, which is the inverse of that given for plutonium. Thus, 30% of the americium is distributed to skeletal surfaces, 50% to liver, and a total of about 9% goes to the soft tissue compartments, which includes activity transferred to the embryo/fetus.

During the first 2 months of gestation, the embryo is embedded in the uterine mucosa. Selective deposition in the fetal membranes is less than for plutonium, as discussed above, but a placental barrier is not included in the model. Ossification and calcification of skeleton are modeled as subsequently progressing for calculations so that fetal bone increasingly participates in the skeletal distribution, as described above for calcium metabolism.

Thus, the average concentration is assumed to be identical to that of the uterus as given by maternal soft tissue. Concentration in the embryo/fetus is modeled as being the same as that in the "other" maternal tissues throughout the first 8 weeks of gestation. The model assumes gradual transitions during the third month because developing fetal metabolism and morphology influence partition between the pregnant woman and her embryo/fetus. These and other factors, including the lower placental transfer factor (0.03), predict a transitional period during which average concentration in the embryo/fetus is 40% of that in maternal tissue compartments.

The functional development interacts with increasing masses of bone and liver so that there is a greater than proportionate rate of increase in total radioactivity in the fetus. A smooth transition evolves from the model that predicts average fetal concentrations to be 54% of the woman's soft tissue at 13 weeks, 76% at 22 weeks, 93% at 26 weeks, and the same at 32 weeks and thereafter. Thus, total activity transferred to the near-term fetus amounts to about 0.7% of the total injected in the woman. All activity transfered to the embryo/fetus is assumed to remain, without excretion.

Based on the above model, the retained activities of ^{241}Am in the embryo/fetus are presented in Table A45.

d. Dosimetric Models

Doses from americium in the embryo/fetus were calculated using the same approach as described for plutonium. The resulting values are tabulated in Table B44.

D. Additional Considerations - Disposition and Dose

1. Residual Activity at Term

The elevated prenatal sensitivity to deterministic effects by irradiation extends beyond the time of birth, while stochastic effects may be produced and are of concern irrespective of age (Brent 1980, UNCEAR 1977, 1986, Sikov 1992). The fractions of prenatally acquired radionuclide burdens that are retained at birth, therefore, may be useful to evaluations of radiation doses during postnatal life. Accordingly, information that was given as fraction at 270 days in the tables of Appendix A was used to assemble the summary that is presented in Table 3. Only those radionuclides are included that have meaningful levels of retention following their administration at some stage of gestation.

2. Radiation Dose during Postnatal Life

In addition to stage-related differences in the fractions of these several radionuclides that remain at birth, there are differences in their biological disposition during infancy and subsequent periods. The radiation doses that result from a given burden depend on these biokinetics and on the physical half-life of the radionuclide. Interest in the potential for biological effects thus leads to questions about the absolute and relative magnitudes of these radiation doses (ICRP 1991, NCRP 1993).

Appropriate databases and methodologies are not available for calculating accurate and meaningful values of lifetime radiation dose from neonatal radionuclide content. For the interim, several extrapolations were combined to obtain approximations of the postnatal lifetime doses that are associated with the radioactivity in the newborn. The approach required the assumption that the metabolic models and dose calculations in ICRP Publications 56 and 67 (1989, 1993) for radioactivity in the 3-month infant would provide rough, but acceptable, approximations for the newborn. The dose coefficients, which are essentially the sums of weighted equivalent doses, are given in these publications as effective dose equivalent or for effective dose through age 70 in mSv per MBq intake of activity. The values tabulated in the two publications differ slightly because of changes in the models or weighting factors.

These values of mSv per MBq applicable to intakes by the 3-month infant were divided by the corresponding values given for fractional absorption from the gastrointestinal tract. This led to dose coefficients that were based on the initial radionuclide content of the newborn infant. These coefficients were converted to rem per μCi and multiplied by the values of fractional retention at birth from Table 3. This yielded sets of values that represented the radiation dose equivalents that would be received through 70 years of age from a nominal 1 μCi of radioactivity introduced into the woman's transfer compartment. Because calculation were based on weighted and effective dose coefficients, the results roughly correspond to effective dose equivalent or effective dose, as used in ICRP Publication 56 or 67. This calculation was performed for those radionuclides that were included in Table 3 and dose coeffecients tabulated in the ICRP Publications. The resulting values (in rem) are presented in Table 4.

3. Implications of Localized Deposition

Localized deposition of radioactivity in the embryo/fetus was discussed in previous sections of this report, referring to its role in the dynamics of placental transfer, dosimetric interactions with structures of the embryo/fetus and the placenta, and overall dose rates and radiation doses. These factors are illustrated by descriptions of fetoplacental behavior and biokinetic models that were given in this section for several radionuclides. Some of these examples, which were summarized in Section IV as a basis for explaining factors in metabolic dynamics, serve to better place these interactions in context. Infor-

Table 3. Fractions of radioactivity retained in the fetus at term after injection into the maternal transfer compartment at representative stages of gestation

Gestational Days at Introduction	^{3}H-I[a]	^{3}H-OB[b]	^{14}C-I-OB[c]	^{57}Co	^{58}Co	^{60}Co	^{65}Zn	^{89}Sr	^{90}Sr/Y
0	3.8E-10	4.9E-05	2.4E-07	1.8E-16	2.9E-04	3.7E-03	9.9E-03	1.1E-12	4.3E-11
30	3.1E-09	9.0E-05	4.7E-07	6.5E-15	4.1E-04	4.0E-03	1.1E-02	1.3E-11	3.5E-10
60	2.5E-08	1.7E-04	2.2E-06	2.3E-13	5.8E-04	4.2E-03	1.3E-02	1.0E-09	1.9E-08
90	2.0E-07	3.2E-04	1.8E-05	8.0E-12	8.3E-04	4.5E-03	1.5E-02	8.9E-06	1.0E-04
120	1.6E-06	6.6E-04	1.2E-04	2.8E-10	1.2E-03	4.9E-03	1.7E-02	1.2E-04	9.4E-04
150	1.3E-05	1.5E-03	4.8E-04	1.0E-08	1.8E-03	5.5E-03	2.0E-02	5.2E-04	2.7E-03
180	1.0E-04	3.4E-03	1.6E-03	3.5E-07	2.6E-03	6.1E-03	2.3E-02	1.6E-03	5.5E-03
210	8.4E-04	8.4E-03	4.9E-03	1.2E-05	4.0E-03	7.0E-03	2.7E-02	4.0E-03	9.1E-03
240	6.7E-03	2.1E-02	1.3E-02	4.4E-04	6.6E-03	8.7E-03	3.4E-02	8.2E-03	1.2E-02
270	5.1E-02	5.0E-02	2.6E-02	1.3E-02	1.8E-02	1.8E-02	4.8E-02	3.3E-02	3.3E-02

Gestational Days at Introduction	^{106}Ru/Rh	^{125}I	^{125}I(FT)[d]	^{131}I	^{131}I(FT)[d]	^{134}Cs	^{137}Cs	^{141}Ce	^{144}Ce
0	7.5E-11	2.3E-06	2.6E-05	4.0E-15	4.5E-14	3.0E-03	3.8E-03	1.1E-14	1.7E-12
30	3.4E-06	3.8E-06	4.3E-05	6.2E-14	7.1E-13	4.0E-03	4.9E-03	8.7E-10	8.1E-08
60	1.1E-04	6.4E-06	7.3E-05	9.9E-13	1.1E-11	5.3E-03	6.3E-03	4.9E-08	2.6E-06
90	7.4E-05	1.1E-05	1.2E-04	1.6E-11	1.8E-10	7.0E-03	8.1E-03	6.1E-07	1.8E-05
120	3.0E-04	1.8E-05	2.1E-04	2.5E-10	2.8E-09	9.2E-03	1.0E-02	4.4E-06	7.5E-05
150	7.1E-04	3.1E-05	3.6E-04	4.0E-09	4.6E-08	1.2E-02	1.3E-02	1.8E-05	1.8E-04
180	1.4E-03	6.0E-05	7.1E-04	7.3E-08	8.5E-07	1.6E-02	1.8E-02	6.4E-05	3.5E-04
210	2.4E-03	1.6E-04	2.0E-03	1.8E-06	2.2E-05	2.4E-02	2.5E-02	2.0E-04	6.3E-04
240	3.7E-03	6.3E-04	8.3E-03	6.7E-05	8.9E-04	3.7E-02	3.8E-02	5.5E-04	9.7E-04
270	4.4E-03	3.6E-03	3.8E-02	3.3E-03	3.6E-02	5.7E-02	5.7E-02	1.1E-03	1.2E-03

Gestational Days at Introduction	^{210}Pb	^{210}Po	^{224}Ra	^{226}Ra	^{237}Np	$^{238/239}$Pu	^{241}Am
0	1.0E-06	4.5E-12	1.4E-28	2.2E-06	5.3E-14	7.5E-14	4.6E-14
30	2.8E-06	1.8E-06	1.2E-25	6.4E-06	5.7E-07	1.0E-06	4.3E-07
60	7.6E-06	6.4E-05	9.6E-23	1.8E-05	1.2E-05	2.9E-05	7.3E-06
90	1.2E-04	4.9E-05	2.4E-19	1.6E-04	1.0E-04	3.0E-04	6.7E-05
120	9.9E-04	2.2E-04	5.0E-16	1.1E-03	5.5E-04	1.4E-03	3.2E-04
150	2.8E-03	5.7E-04	4.2E-13	3.1E-03	1.7E-03	3.5E-03	8.0E-04
180	5.9E-03	1.2E-03	2.7E-10	6.7E-03	4.7E-03	7.8E-03	1.8E-03
210	1.0E-02	2.3E-03	1.4E-07	1.2E-02	1.0E-02	1.5E-02	3.5E-03
240	1.5E-02	3.9E-03	7.1E-05	2.1E-02	1.5E-02	2.4E-02	5.1E-03
270	2.1E-02	5.3E-03	2.1E-02	2.5E-02	1.8E-02	2.8E-02	6.1E-03

(a) Inorganic; i.e. Tritiated water
(b) Organically bound forms
(c) - Either inorganic, e.g., carbonate, or organically bound forms
(d) - Fetal thyroid

Table 4. Radiation doses (rem) from radionuclides, corresponding to Effective Dose or Effective Dose Equivalent[a]. These present radiation received during postnatal life from residual radioactivity at birth after injection of 1 μCi of radionuclides into the maternal transfer compartment at representative stages of pregnancy

Gestational Days at Introduction	^{3}H-I[a]	^{3}H-OB[b]	^{14}C-I-OB[c]	^{57}Co	^{58}Co	^{60}Co	^{65}Zn	^{89}Sr	^{90}Sr/Y
0	8.9E-14	2.2E-08	1.2E-09	3.2E-18	1.3E-05	1.2E-03	1.3E-03	2.4E-13	3.4E-11
30	7.2E-13	4.0E-08	2.4E-09	1.2E-16	1.9E-05	1.3E-03	1.5E-03	2.9E-12	2.8E-10
60	5.8E-12	7.5E-08	1.1E-08	4.1E-15	2.6E-05	1.4E-03	1.7E-03	2.2E-10	1.5E-08
90	4.7E-11	1.4E-07	9.3E-08	1.4E-13	3.8E-05	1.5E-03	2.0E-03	2.0E-06	8.0E-05
120	3.7E-10	2.9E-07	6.2E-07	5.0E-12	5.5E-05	1.6E-03	2.3E-03	2.7E-05	7.5E-04
150	3.0E-09	6.7E-07	2.5E-06	1.8E-10	8.2E-05	1.8E-03	2.7E-03	1.2E-04	2.2E-03
180	2.3E-08	1.5E-06	8.3E-06	6.3E-09	1.2E-04	2.0E-03	3.1E-03	3.6E-04	4.4E-03
210	2.0E-07	3.7E-06	2.5E-05	2.1E-07	1.8E-04	2.3E-03	3.6E-03	8.9E-04	7.3E-03
240	1.6E-06	9.3E-06	6.7E-05	7.9E-06	3.0E-04	2.9E-03	4.5E-03	1.8E-03	9.6E-03
270	1.2E-05	2.2E-05	1.3E-04	2.3E-04	8.2E-04	6.0E-03	6.4E-03	7.3E-03	2.6E-02

Gestational Days at Introduction	^{106}Ru/Rh	^{125}I	^{125}I(FT)[d]	^{131}I	^{131}I(FT)[d]	^{134}Cs	^{137}Cs	^{141}Ce	^{144}Ce
0	2.3E-10	5.5E-06	3.3E-14	2.9E-04	3.0E-04	6.6E-14	8.3E-11	5.0E-05	3.5E-10
30	1.1E-05	9.2E-06	5.1E-13	3.8E-04	3.8E-04	5.2E-09	4.0E-06	1.4E-04	1.4E-04
60	3.4E-04	1.6E-05	8.0E-12	5.1E-04	4.9E-04	2.9E-07	1.3E-04	3.8E-04	5.0E-03
90	2.3E-04	2.6E-05	1.3E-10	6.7E-04	6.3E-04	3.7E-06	8.8E-04	6.0E-03	3.8E-03
120	9.3E-04	4.5E-05	2.0E-09	8.9E-04	7.8E-04	2.6E-05	3.7E-03	4.9E-02	1.7E-02
150	2.2E-03	7.7E-05	3.3E-08	1.2E-03	1.0E-03	1.1E-04	8.8E-03	1.4E-01	4.4E-02
180	4.4E-03	1.5E-04	6.1E-07	1.5E-03	1.4E-03	3.8E-04	1.7E-02	2.9E-01	9.3E-02
210	7.5E-03	4.2E-04	1.6E-05	2.3E-03	1.9E-03	1.2E-03	3.1E-02	5.0E-01	1.8E-01
240	1.1E-02	1.8E-03	6.4E-04	3.6E-03	3.0E-03	3.3E-03	4.7E-02	7.5E-01	3.0E-01
270	1.4E-02	8.2E-03	2.6E-02	5.5E-03	4.4E-03	6.6E-03	5.9E-02	1.0E+00	4.1E-01

Gestational Days at Introduction	^{224}Ra	^{226}Ra	^{237}Np	^{238}Pu	^{239}Pu	^{241}Am
0	2.4E-27	6.4E-05	7.8E-11	2.2E-10	2.3E-10	1.3E-10
30	2.1E-24	1.9E-04	8.4E-04	3.0E-03	3.1E-03	1.2E-03
60	1.7E-21	5.2E-04	1.8E-02	8.6E-02	9.0E-02	2.0E-02
90	4.1E-18	4.6E-03	1.5E-01	8.9E-01	9.3E-01	1.8E-01
120	8.6E-15	3.2E-02	8.1E-01	4.1E+00	4.4E+00	8.8E-01
150	7.3E-12	9.0E-02	2.5E+00	1.0E+01	1.1E+01	2.2E+00
180	4.7E-09	1.9E-01	7.0E+00	2.3E+01	2.4E+01	4.9E+00
210	2.4E-06	3.5E-01	1.5E+01	4.4E+01	4.7E+01	9.6E+00
240	1.2E-03	6.1E-01	2.2E+01	7.1E+01	7.5E+01	1.4E+01
270	3.6E-01	7.2E-01	2.7E+01	8.3E+01	8.7E+01	1.7E+01

(a) Values developed from entries in Table 4 and tabulations of effective doses and effective dose equivalents (see text)
(b) Tritiated water
(c) Organically bound forms
(d) Either inorganic such as carbonate or organically bound forms

mation was provided for phosphorus, strontium, radium, and actinides to exemplify radionuclides for which localized deposition influenced the fetoplacental dynamics.

To avoid additional repetition, attention is drawn to the more detailed descriptions and biokinetic models given for these radionuclides in this section of the report.

One primary objective of the project and this report was to provide information and methods that would help radiological protection professionals comply with recommendations and regulations. The approach taken for all radionuclides was to provide radiation dose to the entire embryo/fetus, values that are compatible with usual statements of dose limitation. Inhomogeneities also become of dosimetric importance when there is interest in radiation dose to specific prenatal tissues. This nonuniform radiation dose could be meaningful to the dosimetry of an individual medical or accidental radionuclide intake by a pregnant woman or to epidemiologic evaluations of deterministic or stochastic effects related to specific tissues.

Radioiodine is probably the most striking example; exposure and effects on the fetus have been recognized and demonstrated in several situatons. The concerns associated with such exposures were sufficiently great that separate sets of calculations were performed for the fetal thyroid gland and tabulations are presented in this report. In the case of some iodine isotopes and gestational ages, the radiation dose to the thyroid gland was orders of magnitude greater than the average embryo/fetus dose or dose to the remainder of the fetus. Moreover, the desirability of calculations of thyroid dose for ^{99m}Tc was suggested by metabolic similarities. In that case, however, differences were not so marked.

The analogous nonuniformity of radiation dose could be especially meaningful to evaluations of radionuclides that localize in the developing skeleton. As was described for the modeling, the increasing deposition with progressive ossification and calcification is a controlling process in overall concentration and total activity in the fetus. The concentration ratio in developing bone and its progenitor tissues compared to concentration in nonspecific soft tissues changes with stage of gestation. These relationships also differ quantitatively among radioelements that have such inhomogeneous distribution.

This localization was not taken into account for calculating alpha or beta doses to skeleton or bone as individual tissues. Moreover, the relative radiationdoses may be greater because of the progressively increasing density and mineralization of bone.

As was discussed above, there is potential interest in postnatal doses from radionuclides that were retained at birth following prenatal exposure. With many radioelements, postnatal retention would be related to deposition in specific tissues. The effect on these tissues might be of greatest interest although methods are not yet available for quantifying dosimetric evaluation. However, this situation emphasizes the desirability of considering these tissues in prenatal dosimetric evaluations.

There will be high localized concentrations in the developing placental structures and membranes that may result in radiation doses that are as great as or greater than those to any maternal tissues. Because of their short path lengths, alpha particles from these extraembryonic areas would not reach the embryo. As was discussed, however, it is during the embryonic stages that deposition in the yolk sac has the greatest potential for producing deleterious effects on stem cells. Exposure of these cells might be included in dose received by the embryo or in lifetime hematopoietic dose (Harrison et al. 1991).

VI. NOBLE GAS MODELS, KINETICS, AND DOSE FACTORS

A. Underlying Concepts and Methods

The concepts and methods for radiation dosimetry of the embryo/fetus from maternal exposures to inert gases are different from those that apply to other radionuclides. The models developed for other radionuclides were based on intravenous injection into the transfer compartment of the pregnant woman. These approaches did not require specific consideration of radionuclides in the woman's environment, which were involved in her deep dose equivalent, and only radioactivity that entered the woman was considered for internal dose evaluation. Although external radiation doses from noble gases can likewise be ignored, internal doses cannot be considered apart from the circumstances associated with inhalation of the gas.

This is because the volumetric concentration of external gas and duration of inhalation exposure directly influence gas concentrations in the pregnant woman and in the embryo/fetus. Thus, this section presents recommendations regarding approaches and methodologies for modeling, calculating, and expressing radiation doses to the embryo/fetus from inert gases. The approaches that will be described differ from those used to generate dose factors and tabulations of radiation dose for general radionuclides. Information about the biological and physical behaviors of elemental noble gases was used to predict placental transfer factors and to develop biokinetic models.

Many concepts are applicable to all inert gases and there are general similarities among the specific methodologies appropriate to individual gases. There are differences among the parameters and gestational-stage-related models applicable to the individual gases and their radioisotopes. These differences thus affect calculated dose rates and cumulative doses to the embryo/fetus. Because the behaviors also vary among exposure scenarios, these differences markedly affect dose rates and cumulative doses to the embryo/fetus.

For inert gas, therefore, maternal exposure conditions must be included, a need that could be circumvented in evaluation of other materials. As with other physical forms, the dose factors are presented by stage of gestation. They are expressed as the concentration in the atmosphere being inhaled. Exposure duration replaces time after administration, the factor used for other radionuclides. This section of the report compares approaches appropriate to three representative gases - krypton, xenon, and radon - based on their chemical and radiological characteristics and likely exposure scenarios.

B. Components of the General Models

As was done with other materials, information from the radiation protection literature was combined with physiological principles to provide a qualitative and a quantitative basis for modeling. This information was used to establish kinetic models of bidirectional placental transfer, partition rates, and dynamic ratios of the gas concentrations in the conceptus to those in the woman. From among the general methodologies, those that contained components applicable to inhalation of noble gases were emphasized. The process thus involved generalizing the placental transfer, partition, and retention coefficients to provide the related dose rate parameters from time-adjusted activity and distribution. Many of the likely scenarios for exposure of pregnant women to krypton or xenon are similar to one another, while exposures to ubiquitous natural gases such as radon involve markedly different circumstances, locales, and time courses.

1. Exposure Scenarios

One scenario for exposures to krypton or xenon includes the fact that they are generated and accumulated during normal reactor operation, and there are possibilities for releases to the occupational or general environment. Intakes from such releases likely would be acute or subacute and would involve exposures from the external cloud of radioactive gas. The radiation dose from an internalized nuclide would be superimposed. Under such conditions, the reasonable conclusions by the ICRP in Publication 30 (1980) and the NCRP in Report No. 44 (1975) are that the cloud would contribute most of the radiation dose. Nevertheless, the internal dose to the embryo/fetus requires calculation.

An alternative exposure scenario for xenon (and krypton, to a lesser extent) involves uses in nuclear medicine. Potentially, exposures of patients and nuclear medicine personnel could occur under conditions such that exposures and radiation dose would result almost entirely from internal activity. These procedures are used for evaluating pulmonary morphology and function and for cardiac imaging. They are primarily relevant to xenon, although the same dosimetric concepts are also applicable to krypton. In most of these examinations, radioactive gas is breathed by the patient from a spirometer although, for other clinical evaluations, dissolved gas may be intravenously injected. Inhaled gas may be held for a brief period that is followed by a washout period, or the spirometer content may be rebreathed for a several-minute period. The examination times are insufficient to attain equilibrium; however, tissue concentrations progressively increase during rebreathing studies, and there is subsequent clearance that can be described by multicompartment models.

Another scenario relates to occupational exposures of nuclear medicine technologists who perform these examinations on a continuing basis. Because of the amounts of xenon used, such persons may develop measurable body burdens, with primary deposition in fat. This can lead to exposure of the embryo/fetus in the event that the technologists are or become pregnant. There is a more remote possibility of occupational exposure to personnel who are engaged in research with the noble gases or who prepare these gases for industrial or medical usage.

Radon is a naturally occurring radioactive gas that is generated by decay in the radium series. Relatively elevated and persistent concentrations of radon are a common situation in the home environment of many geographic locales. In these areas, radon and its decay products may constitute a major source of chronic low-level environmental radiation. Radiation doses may be received by members of the general population, which includes pregnant women, so that the embryo/fetus can also receive radiation doses. Moreover, radon decays to a series of radioactive daughter products that may be deposited in tissues and result in continuing radiation doses. This is in contrast to krypton and xenon, which decay to stable nuclides.

2. Age-Dependent Considerations for Biological Behavior

a. Behavior in Adults

As noted, ICRP and NCRP assume for inert gases, such as krypton and xenon, that the internal irradiation from radioactivity absorbed in tissue or contained in the lungs would be negligible in comparison with the external irradiation from the gas cloud. This assumption is not completely applicable to irradiation of the embryo/fetus under many scenarios involving plumes. Moreover, it does not pertain to exposures that result from nuclear medicine evaluations and is largely inapplicable to radon, another noble gas of interest.

One facet of a general model for adults is based on biological parameters developed by MIRD for xenon in patients. This is integrated with information for krypton from animal experiments. MIRD considers that follow-

ing five minutes of breathing xenon and air from a spirometer in nuclear medicine examinations, the concentration of radioxenon in the lungs will be approximately the same as that in the spirometer. Fractional activities of ^{133}Xe in tissue relative to total body content, which is primarily in lung, are 0.02, 0.14, and 0.23, for a single inhalation and for 5-minute and 10-minute inhalation periods, respectively. MIRD indicates that equilibrium concentrations require up to 30 hours of rebreathing.

The general model derives from the report of Susskind (1977) that the half-time for washout from the compartment with the slowest turnover averaged 10.5 hours (range 7.59 to 17.04 hours). The person with a half-time of 7.59 hours had 24.2% body fat while the person with a half-time of 17.04 hours had 63.5% body fat. MIRD assumes that the rate constant for the slowest compartment for xenon clearance represents fatty tissues. These patterns are compatible with the physical biochemistry as well as with the broad patterns from animal studies of krypton. It is important to note, however, that partition coefficients are the limiting factor for the rate and amount of transfer among compartments. Accordingly, the coefficients for the specific gases are incorporated into the models.

b. Behavior in the Pregnant Woman and in the Embryo/Fetus

Following is a synopsis of the salient background descriptions that are given later in this section. Autoradiographic studies with ^{85}Kr found nonuniform distribution of activity in the uterus and placenta and no radioactivity in the rat fetus during a 1-minute period of study. The distribution in most tissues, as determined by radioanalysis, was similar to that in the same tissues of the dam following exposure of pregnant rats to krypton. Krypton concentrations were measured in fetal and maternal blood during and following exposure of pregnant ewes by face mask. Concentrations rose rapidly and attained steady-state-levels at about 1 hour of exposure. There were no overt differences among collection sites but kinetic analyses showed differences in time to equilibrium and in blood clearance rates. Tissue concentrations in the ewes following re-exposure decreased in this order: lung → adipose tissue → lymphoid tissue → adrenal gland. Other than lung, most tissues of the lambs followed a similar rank order.

Bergeron et al. (1973) postulated that noble gases such as krypton and xenon must dissolve into plasma lipids and reach an equilibrium in plasma before reaching the placenta for transfer. This would be more clearly evident with xenon than with krypton because of the partition coefficient. They suggested that the transfer rate corresponded to that of lipids and that transfer occurred by pinocytosis rather than by diffusion.

3. Physical Factors and Biological Disposition

The model used by MIRD assumes that equilibrium concentrations require up to 30 hours of rebreathing of xenon. Measurements and experimental data indicate that reasonable steady-state conditions should be attained with krypton within 2 hours. On the basis of the cited study of Susskind (1977), MIRD assumes that the rate constant for the slowest compartment for xenon clearance represents fatty tissues. These patterns are compatible with the physical biochemistry as well as the broad patterns from animal studies of krypton and may be accepted as a basis for a general model that incorporates partition coefficients. Noble gases are more soluble in lipids than in water so that tissues with high fat content have the highest concentrations. Partition coefficients differ among the noble gases; these coefficients have quantitative roles in determining the relative concentrations achieved and affect clearance.

4. Comparative Characteristics

The ICRP (1980) position on dosimetry of adults for external radioactive gases is valid for krypton and xenon but is overly broad for assessment of dose to the embryo

or fetus; however, it does not pertain to alpha-emitters such as radon. As a rough approximation for many purposes, the dose to the fetus from immersion of a pregnant woman in a cloud of ^{85}Kr or ^{133}Xe might be assumed to equal the adult deep dose equivalent. This approach would not be appropriate for medical exposures in which the gas is inhaled from a spirometer. Moreover, infinite cloud conditions do not pertain to many occupational exposure scenarios, which might involve plumes, so that methods for internal dosimetry are needed.

Dosimetry for radiopharmaceuticals can be based on the calculations of ICRP Publication 53 (1988), which follows the MIRD model for ^{133}Xe (Atkins et al. 1980), and considers both the penetrating photons and the non-penetrating beta contributions. The radioisotopes used in nuclear medicine have relatively short half-lives so that uterine doses, which are calculated as the sum of doses from photons and nonpenetrating emissions, are appropriate measures of the dose to the embryo during early pregnancy.

Fetal tissue concentrations become progressively more similar to maternal tissue concentrations with increasing exposure time. Thus, predictions from the kinetic model are not directly applicable to times as short as used in clinical examinations. Calculations of gamma dose at later stages of gestation from maternal radioactivity require adjustment for increased fetal size. Although not considered for analyses of this project, estimates of dose from external clouds, also are influenced by the size of the woman and the fetus and would establish an internal basis for comparison.

For reasons unrelated to the relative magnitude of the dose from an external cloud, expression of dose factors requires a different basis than used for internal dose from intravenous injection. Assumed introduction of activity into the transfer compartment is not relevant to inert gases because the blood levels are incompletely related to activity in the breathing atmosphere. They are more dependent on length of exposure and related factors. The equilibrium or steady state that is reached through interplay of these factors controls activity in maternal tissue and the fetoplacental unit. Even if evaluated as dissolved and injected, analogous to the model for tritiated water, these agents are so rapidly exhaled that injected activity would be less than meaningful. Accordingly, tissue activity and dose factors should be calculated and expressed relative to scenario-dependent breathing atmosphere concentrations and times.

Radon exposures to members of the general population usually are continuous and are associated with environmental sources. The considerations that apply to radiation doses from occupational exposures, such as those to miners, also differ from those described for krypton and xenon. There is essentially no direct information about radiation doses or consequences to the embryo/fetus associated with exposure of pregnant women to radon and only few data from studies of pregnant experimental animals. Conclusions from animal data yield acceptable correlations with information concerning the behavior of other noble gases. It would not be unreasonable that determining the radiation self-dose to the embryo or fetus from radon could be approached use the same methodology as that for xenon and krypton. It may be expected that radon would readily cross the placenta in both directions, but that predominant fractions of the radiation exposure from the radon per se would cease following the inhalation period.

Based on the foregoing, the radiation dose to the embryo/fetus associated with radon usually would be similar to or less than that to the pregnant woman. From the behavior of lead and radium in human tissues, it appears that some radon decay products can cross the placenta and so enter or leave the fetus. In contrast, polonium and other nuclides have minimal accessibility to the fetus from maternal blood but are deposited in placental structures. It may be surmised that these radionuclides might not cross the placenta after formation in the fetal compartment. Their contributions are not considered as part of the radiation doses from radon as such and should be evaluated independently for their specific exposure conditions.

C. Descriptive Approaches to Exposure Scenarios

As discussed in the previous section, approaches to modeling inert gas concentrations in the body differ among the major exposure scenarios. Additionally, these conditions have different impacts during the build-up, steady-state, and clearance phases and so generally pertain differently to krypton and xenon exposures than to radon, which is primarily a chronic environmental exposure situation.

It is first necessary to describe the build-up phases at the beginning of an inhalation period; two alternative functions should be sufficient. One function would be generic so that it could be used for exposure times of 0.25 day and greater. The other would relate to exposures for periods that were nominally less than 1 hour in duration. This function would pertain in situations such as a localized containment release or breathing from a reservoir during medical evaluations. Clinical exposures, which are commonly for 10 minutes or less in practice, also can be addressed by these approaches.

Two, or possibly three, sets of element-specific functions would be required for describing activity levels at times that follow the initial exposure. The basic functions would pertain to situations that involve steady-state periods during inhalation exposures of moderate duration and could include the subsequent clearance after cessation of exposure. A parallel set of functions would be used to describe activity in a person who had a long-standing, equilibrium, or steady state burden as well as the subsequent clearance of radioactive gas from body tissues upon cessation of exposure. Another function would address clearance of short-term, partial burdens such as those of a nuclear medicine patient and her fetus. These functions would consider embryo/fetus activity from a pregnancy occurring during the pre-burdened and/or continued intake steady-state period. The clearance relationship would be similar for a burden that resulted from a reactor release; the build-up and clearance functions would accommodate events during a 0.25-day exposure interval to exposures of 1 day or greater.

The model reasonably predicts that fetal tissue concentrations of krypton and xenon will become progressively more similar to maternal tissue concentrations during continued exposure. Concentrations could be considered to have become essentially identical within several hours. Details will depend on the parameters selected, including the value assigned to fractional lipid content.

The approach to dosimetry of krypton would incorporate the concept under which blood concentrations continue to increase and approaches steady state during the initial hour of exposure although a true equilibrium would require a longer time. As noted, the krypton fetal blood activity follows that in maternal blood with minimal delay. However, kinetics are not directly applicable to times as short as those used in clinical examinations.

Longer times would be required to accommodate the equilibration times associated with xenon. The general model is consistent with increasing values of tissue concentration with rebreathing time, as indicated for the ICRP Publication 53 nuclear medicine model.

Radon behavior in the body should be similar to prolonged environmental exposures to krypton or xenon, although adjustment of steady-state levels would be required to account for partition and the short physical half-life. This approach to methodology considers only the radon exposure per se. In practice, decisions that are unrelated to the project would be required, such as whether and how to factor radon daughters into the dosimetric scheme.

D. Formal Modeling

1. Published Efforts and Approaches

The model used for medical exposures by the ICRP (1988) and MIRD (Atkins et al. 1980) posits a complex four-component clearance in adults with a half-time of several hours for the slowest component. This approach is com-

patible with a more general model that uses a smoothed clearance. The additional precision affects only dose from nuclear medicine procedures. This degree of precision in clearance is relatively unimportant quantitatively for dosimetry of the embryo/fetus, which involves numerous additional approximations.

Calculations by RIDIC for medical use serve as a prototypic situation. This follows the MIRD model for ^{133}Xe and takes into consideration both the penetrating photons and the nonpenetrating beta contributions. The use of the dose to the nonpregnant uterus as an estimate of dose to the earlier embryo is applicable under these conditions, and should serve adequately for the two lighter noble gases. The surrogate radiation dose from the gas per se would be a less accurate approximation for radon and would not consider the decay products.

The energy deposition from the content of radioactive gas in the 3-month and later fetus must be considered. The above models and available information would allow establishing reasonable values of radioactivity in the embryo/fetus under most scenarios, but only a range of estimates would be available for short periods of re-breathing. There is a greater relative percentage of fat in the newborn human, and presumably the fetus, than in rats and most other animal species (Widdowson 1968). These factors are major influences on biological behavior and should be incorporated into models.

For exposures to xenon or krypton, other than medical, the radiation dose from the surrounding "infinite" cloud or from a plume can be a major factor in many cases. This can make differing relative contributions to the total dose and it does not pertain with radon. The increasing size of the fetus and of the woman at sequential stages of gestation will have a marked influence on the contribution of the external gas cloud to the embryo/fetus dose.

Ideally, the approach to internal dosimetry would allow for stage of gestation and for the fat and/or lipid content of the woman and, especially, of the embryo/fetus. Such an ideal model would allow for such known prenatal changes, as well as for tissue perfusion, although interpersonal variability could overwhelm these factors in practice. Thus, broad inclusion would be adequate for validity of concept while attempts at precision would not be meaningful.

2. Mathematical Models and Approximations

These seemingly complex analyses can be simplified by introducing minor approximations into the formal mathematical analysis of kinetic behavior. Consider that continuing exposure will start with a build-up period toward maximum or saturation levels of gas concentrations in tissues. This would be followed by a steady state or equilibrium at these concentrations, and a desaturation period that would follow discontinuation of exposure. For a given tissue or the average in the body, the steady-state plateau is given by a factor that depends on the average partition coefficient. The overall fractional build up to this level and subsequent clearance from a composite of the body compartments may be given by generalized equations and parameters that describe the curve. The typical relationship is here illustrated by the actual families of curves for krypton (Figure 4). Although inspection suggests that the individual rise and fall curves are mirror images of each other, this is not quite true in the quantitative sense.

Suppose the exposure time is T. Assuming a single compartment model, during the exposure, the activity in an organ or tissue (in this case the embryo/fetus) is given by equation (15):

$$A = k(1-e^{-bt}) \tag{15}$$

where b is the rate constant for tissue deposition (or absorption). The constant k is the product of the conver

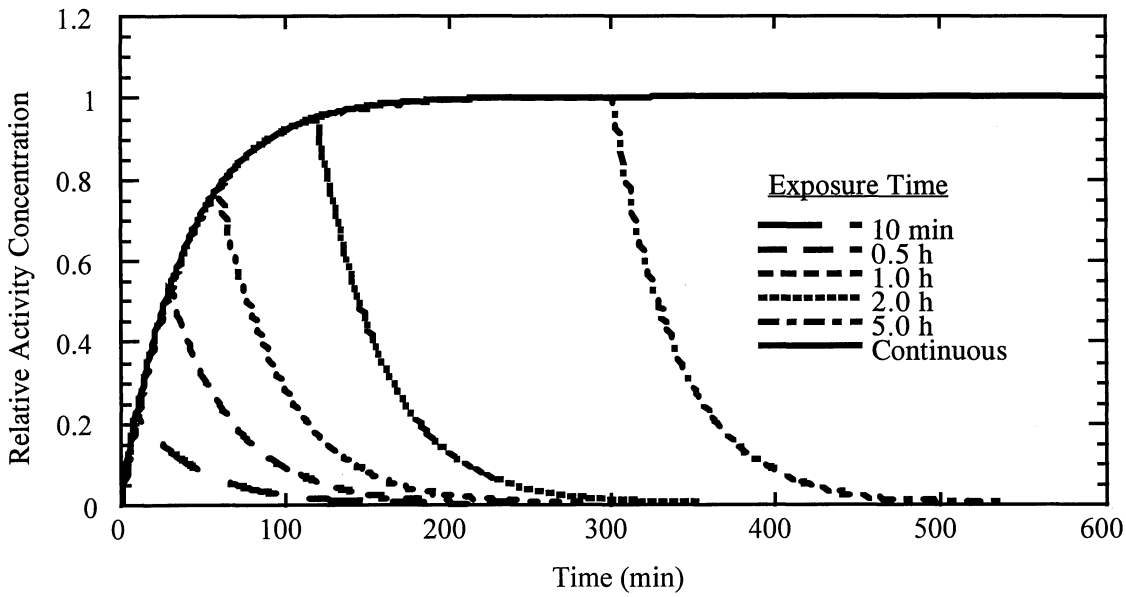


Figure 4. Typical curves illustrating relationships between relative activity concentration, exposure duration, and time after initiation of exposure. Values plotted for this example are as determined from Equations 15 and 16 using parameters for ^{85}Kr.

sion from air to average tissue concentration and the tissue partition coefficient. Assuming that the rates of absorption and clearance are similar, the activity after the exposure is, therefore:

$$A = (1-e^{-bT})\, e^{-b(t-T)} \qquad (16)$$

It is reasonable to assume that the exposure time to inert gas is short enough to assume that the mass of the embryo/fetus, and thus the energy absorbed fractions for different radiations remains constant. Therefore, the dose received by the embryo/fetus is proportional to the integral of the activity with respect to time. In the case when exposure time is long enough that the concentration of the inert gas in the embryo/fetus is almost the maximum, the cumulative activity and the dose to the embryo/fetus would be proportional to the exposure time (= kT).

To avoid the need to precisely define the equilibrium level, consider that at time = t, concentration is at 95% of the plateau. Then, $1 - e^{-bt} = 0.95$, $e^{-bt} = 0.05$, $-bt = \ln 0.06$ or -2.9957, and $t = 3/b$ or $b = 3/t$. For the three radioactive gases of primary interest:

^{85}Kr	t = 2 hours	b = 1.5 h^{-1}
^{133}Xe	t = 20 hours	b = 0.15 h^{-1}
^{222}Rn	t = 6 hours	b = 0.5 h^{-1}

Values of k (μCi/g in composite tissue per μCi/ml in air) for these calculations were obtained on the basis of values in Kirk (1975), Thrall and James (1996), Atkins et al. (1980), and Peterman and Perkins (1979). The derived values are:

^{85}Kr	0.148
^{133}Xe	0.404
^{222}Rn	1.34

As a consequence, descriptions of dosimetry in the following descriptions will be addressed using the comprehensive models described in the preceding subsections. Tables were developed on the basis of the rate of increase of gas concentration in the woman, her uterus, and the fetoplacental unit. These provide the basis for development of broad gestational-stage-related dose factors.

A simplified approach that can be used as an alternative in some circumstances has been suggested by Watson.[a] If gas is uniformly distributed in body fat, concentration could be obtained by dividing the activity by the mass of the fat content of the body (typically 12,500 g) and multiplying by the fractional fat content of the organ or tissue of interest. Because of unequal blood perfusion rates, gas distribution among fatty tissues would not be uniform and higher ratios would be attained in organs that have relatively high blood perfusion rates such as brain, adrenals, and gonads. A modification of this approach would provide a basis to estimate activity in the embryo/fetus although allowance would be required for increasing total mass throughout pregnancy as well as increasing percentage fat and altered perfusion.

E. Descriptions of Representative Noble Gases

1. Krypton

a. General Model

Krypton is an inert gas with six stable isotopes that have abundances ranging from 0.4% to 56.9%, but it is not a natural constituent of the human body. Several radioisotopes are produced in nuclear reactors, among which two, ^{79}Kr and ^{85}Kr, are of relevance to embryo/fetus dose.

The general model is developed on the basis of the assumption that inert gases (including krypton, xenon, and radon) have similar biological behavior in the body. It stems from the xenon model described by the MIRD Committee for studies in humans (Atkins et al. 1980). In this model, the concentration of radioxenon in the lungs rapidly approximates that in the spirometer although body equilibrium would require up to 30 hours of rebreathing xenon and air. As discussed above, the noble gases differ in their biological dispositions in the woman and the embryo/fetus because of individual partition coefficients and temporal factors associated with the conditions of exposure.

Consideration of these factors and relevant experimental findings leads to the specific biokinetic models. The behavior of krypton thus relates to the specific biological parameters, especially to partition coefficients. Thus, body equilibrium with krypton occurs more rapidly that with xenon and gas is lost from the body more rapidly after cessation of exposure.

b. Fetal and Placental Information

In one of the earliest studies with krypton gas in pregnant animals, Bergeron et al. (1973) administered ^{85}Kr to pregnant rats at 17 days of gestation via an arterial catheter and took samples at 5, 15, 30, 45, and 60 seconds later. Autoradiographs showed that the distribution of krypton was not uniform through the uterus and the placenta; regions corresponding to the fetus showed no radioactivity during the brief period of study. The authors suggested that because the gas is dissolved into plasma lipids, it must reach an equilibrium in maternal plasma before it can reach the placenta to be transferred. The rate of transfer corresponding to that of lipids would be slower and would occur by pinocytosis and not by diffusion.

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[a] E. E. Watson, Oak Ridge Institute of Science and Education, Personal Communication, 1993.

The kinetics of inhaled ^{85}Kr in the blood of pregnant ewes and their fetuses were studied during exposure of pregnant ewes via a face mask for 1.5 to 2 hours and a subsequent 1-hour clearance period (Andrew et al. 1978). Blood samples were collected from indwelling arterial and venous catheters in the ewe and in an artery or vein of the fetus. The concentrations rose rapidly and attained steady state levels by approximately 1 hour of exposure. Overt differences among the four sites were not detected by inspection of the curves but analyses of kinetics showed differences in time to attain equilibrium levels. There were more marked differences in blood clearance rates: concentrations dropped to 10% of the maximum in the maternal artery about 9 minutes after exposure ceased, in the maternal vein about 32 minutes after exposure ceased, and in the fetal artery at about 60 minutes.

Following re-exposure and euthanasia, tissue concentrations in the ewes were found to decrease in this order: lung → adipose tissue → lymphoid tissue → adrenal gland. There were few differences between fetal and maternal tissue concentrations of krypton except for in the maternal lung, which had been occluded, and adipose tissue depots, which have the highest concentrations and slowest clearances because of the high lipid solubility of krypton. The applicability of the lower concentration in adipose tissues may not relate directly to the human because there is proportionately more fat in human newborns than in experimental animals. This extrapolation from the fraction of fetal fat is important in the biokinetics and dosimetry.

Andrew et al. (1979) continuously exposed pregnant rats for five consecutive days to ^{85}Kr atmospheres to evaluate developmental toxicity. No evidence of increased intrauterine mortality nor of external or skeletal malformations were seen in the exposed fetuses. The only significant embryotoxic effect observed was decreased fetal weight, which was probably secondary to effects of the exposure on the dam's nutrition. The distribution of krypton was essentially the same as that in studies performed with approximately 1000 times less activity and also was compatible with distribution in the sheep.

2. Xenon

a. General Model

Xenon is a noble or inert gas with nine stable isotopes and more than 20 radioactive isotopes. The radiosotopes include ^{133}Xe and ^{135}Xe, which are produced in large quantities by neutron irradiation in air-cooled nuclear reactors. Nuclear medicine diagnostic studies that evaluate pulmonary morphology and function commonly use inhalation of ^{133}Xe; injection of ^{133}Xe is used for cerebral blood-flow studies.

The assumption in ICRP Publication 30 is that dose equivalent rates from gas absorbed in tissue or contained in the lungs would be negligible compared to the dose equivalent rates to tissues from external irradiation. This assumption does not apply to nuclear medicine studies or exposures from localized plumes associated with escape of gas from containment. Under conditions involving immersion of the pregnant woman in a cloud or a plume of xenon, however, the dose to the embryo/fetus could be assumed to equal the adult deep dose equivalent. Given the concentration values of the air immersion, the dose could be calculated for the specific isotope of interest.

The MIRD Committee developed biological parameters for the distribution of xenon as used for ventilation studies in humans (Atkins et al. 1980). This forms the basis for the ICRP 53 and the RIDIC models and calculations. As with krypton, exposure conditions and experimental results form the basis for the models, parameters, and dose factors.

Dissolved gas may be intravenously injected for certain studies. More commonly, however, xenon is breathed by the patient through a spirometer mouthpiece or a mask. The inhaled xenon is held for a 30-second period, followed by a washout period, or the spirometer content may be rebreathed for a 5- or 10-minute period. As presented in ICRP 53, the tissue concentrations of xenon progressively

increase during rebreathing studies. At the end of five minutes, the concentration of radioxenon in the lungs is approximately the same as that in the spirometer.

These times are insufficient to attain equilibrium, which would require up to 30 hours of rebreathing (Susskind 1977). Relative to total body burden, which is primarily in lung, fractional tissue activities of 0.02, 0.14, and 0.23, respectively, are reached with single inhalation and 5- and 10-minute inhalation periods. In ICRP Publication 53, as based on MIRD (Atkins et al. 1980), total body retention of xenon is considered to be the sum of four exponentials that represent lung (tissue and air), lean body mass, and two fat compartments. For general purposes, and especially for development of dosimetry for the embryo/fetus, it is assumed that the xenon that is not in lung is uniformly distributed through the rest of body.

In MIRD Dose Estimate Report No. 9 (Atkins et al. 1980), the compartment with the slowest turnover rate constant was assumed to represent fatty tissues. The half-time for washout from this compartment, as measured by Susskind (1977), averaged 10.5 hours and ranged from 7.59 to 17.04 hours. The person with a half-time of 7.59 hours had 24.2% body fat, while the person with a half-time of 17.04 hours had 63.5% body fat with 13% of the 10 minute burden associated with the slowest component.

b. Fetal and Placental Information

Little or no direct information about the behavior of xenon during pregnancy is available although there are anecdotal suggestions that nuclear medicine technologists develop persistent body burdens. In the event of immersion of a pregnant woman in a cloud of xenon, the dose to the fetus could be assumed to be equal to her deep dose equivalent. Given the concentration in the air, this dose could be calculated from the ALI values for the specific isotope of interest.

As noted for krypton, if the gas is considered to be uniformly distributed in body fat, the concentration can be obtained by dividing the activity by the 12,500-g mass of the fat content of the body and multiplying by the fractional fat content of the organ or tissue of interest. Because of unequal blood perfusion rates, the gas distribution among the fatty tissues will not be uniform. Higher ratios will be attained in organs such as brain and gonads that have relatively high blood perfusion rates. The fraction of fetal fat is important in the biokinetics and dosimetry. As noted for krypton, there is proportionately more fat in the human newborn than in experimental animals.

The information regarding ^{85}Kr behavior in pregnant animals was generalized to derive biokinetic and dosimetric approaches to inhalation of noble gases during pregnancy given above. As indicated, blood concentrations of krypton continue to increase and approach steady state within several minutes. These experimental results are consistent with the increasing values of tissue concentration with rebreathing time, as indicated above for the ICRP 53 model. Krypton kinetics are more rapid than would be expected with xenon and, moreover, are not directly applicable to times as short as those used in clinical examinations. It would be expected, however, that fetal blood activity follows that in maternal blood with a minimal delay and that fetal tissue concentrations would become progressively more similar to maternal tissue concentrations in this situation.

There may be occupational exposures of nuclear medicine technologists who perform these examinations on a continuing basis and develop persistent body burdens (with primary deposition in fat) in the event that they are or become pregnant. There is a remote possibility of occupational exposure to personnel who are engaged in research with the noble gases or prepare these gases for industrial or medical usage.

3. Radon

a. General Model

Radon is a radioactive gas that is generated by decay of radium in the naturally occurring actinium, thorium, and uranium series. Half-lives of the natural isotopes range

from a small fraction of a second to the 3.8-day alpha-emitting ^{222}Rn, which is considered the isotope of particular dosimetric importance for exposure of the embryo/fetus.

Peterman and Perkins (1988) proposed a kinetic model that provides a basis for estimating equilibrium specific activities of inhaled radon and its daughters in the human. The resulting values predict the highest organ activity concentration values to be in lung, followed by kidney and liver, and a lower value in the femur. As a consequence of their high partition coefficient for lipids, fat and fatty tissues would have the greatest concentrations.

b. Fetal and Placental Information

Much of the direct data on deterministic effects of high radiation doses from radon as well as inferential information about its placental transfer is derived from a study reported by Gudernatch and Bagg (1920) and Bagg (1922). They placed sodium chloride into a sealed container with an amount of radon, referred to as "radium emanations," stated to be originally equivalent to 0.5-g radium (500 mCi). The salt was then dissolved in water to produce isotonic saline and the solution was used for subcutaneous or intravenous injection of rats prior to mating or at various stages of gestation.

These exposures resulted in increased prenatal mortality and produced a variety of effects including macroscopic hemorrhage in placentas, fetuses, and offspring. Similar results were obtained when rats were injected subcutaneously, as early as three weeks before mating. Bagg did not measure placental transfer but he inferred that radon crossed the placenta because fetal death and hemorrhages of the placentas or fetuses occurred within 24 hours after intravenous injection of higher doses during late gestation. Radon progeny could have been involved but Bagg's inference is consistent with free transfer of dissolved radon across the placenta. Possible explanations for effects of injection before fertilization range from placental transfer of radon decay products to maternal toxicity produced by the exposure.

Inhaled radon and its progeny in pregnant rats was measured to calculate embryo/fetus dose as part of an evaluation of the developmental toxicity of prolonged inhalation exposures (Sikov et al. 1992). Experimental design allowed for different decay schemes and partition coefficients but considered that radon would have biological behavior similar to that of krypton. Thus, radon in blood was expected to freely cross the placenta in both directions, and alpha particles from placentally transferred radon and progeny would make the primary contribution to intrauterine radiation dose. To account for the behavior of radon progeny, it was assumed that most decay products formed in the fetus would tend to remain there.

Specific activities of ^{214}Pb in tissues were determined on the last day of 13 daily exposures, and corresponding dose equivalent rates were calculated from the measurements. The lungs had the greatest activity concentrations and dose rates; this was not predicted by the ^{222}Rn model. The measured specific activity was almost 1000 times greater than predicted because of inhalation of radon progeny. The next highest specific activities were in kidney, but were more than an order of magnitude lower than in lung. Many nuclides in the decay chains are excreted through the kidney, accounting for it having the highest specific activity of the tissues and organs evaluated. The measured activity was markedly higher than predicted on the basis of only inhaled radon, but the differential was substantially less than with the lung, presumably because of a lesser role of inhaled radon progeny. Concentrations in other tissues such as the femur and liver were several-fold lower than in kidney.

Radionuclide concentration in the placenta was similar to that in the femurs and livers of the pregnant rats. Its activity concentration was about three times that of the fetus. These results are in agreement with others that indicate that radon decay products are not freely transferred to the conceptus during and after inhalation exposures. Measurable quantities of these nuclides enter the fetus, however, even though there is sequestration in the placental tissues. The fraction of fat in the fetus and placenta is important to the biokinetics and, as described

above, the relative lipid content of the human fetus is greater than that of most experimental animal species.

Tentative conclusions derived from these measurements are reasonably consistent. They suggest that dose equivalent rates from the radon daughters at the end of a prolonged inhalation exposure essentially mirror measured activity concentrations and reflect the reduced levels of translocated radon decay products in the fetus. The calculated dose rates to fetoplacental structures of the rat may not apply at early gestational stages, when the placenta and embryo/fetus are less well developed and actual values may be lower. However, the fetoplacental unit should receive radiation doses that, at maximum, are no higher than the dam. Their concentrations were no higher than those in most maternal soft tissues and much less than lung and fat.

F. Dosimetric Considerations

The build-up, steady-state, and clearance values of activity concentration of a noble gas in a pregnant woman and her embryo/fetus during inhalation exposure are described by Equations (15) and (16). When these equations are solved using the appropriate parameteric values for exposure time and gas characteristics, curvilinear and plateau relationships result, as illustrated by the family of curves in Figure 4.

The numerical values of the time integral of activity concentration were calculated for a series of exposure times and stages of gestation. The associated radiation doses were calculated based on the beta particle and photon emissions from ^{85}Kr or ^{133}Xe in the woman's body plus self-dose from emissions in the embryo or fetus. The parallel series of radiation doses were calculated for self-dose from alpha emissions within the embryo/fetus in the case of ^{222}Rn (without daughers) and considering only the decay of the radon itself.

The resulting values of dose to the embryo or fetus, in rad, are given in Table 5 for the three representative radioactive noble gases. Factors are given as dose (rad), based on a scenario in which the woman breathed a nominal atmosphere of 1.0 μCi/ml for various lengths of time up to 1 day. Multiplication of the 1-day doses by total times will give approximate values for exposures of longer duration.

The relationships between dose, exposure time, and gestational age differ among the three radionuclides. The dose values pertaining to the several exposure times are not all precise multiples of the relative exposure times. This is explained by the fact, discussed in Subsection D, that the rise and fall functions are not mirror images, even though they appear as such in Figure 4.

The numerical values for exposure-time-dependent doses from ^{85}Kr are seen to be the same through all of the fetal period, but they are roughly one-half of the corresponding doses received by the early embryo. This results from the physical dosimetry related to the energy distribution and physical size of the embryo/fetus.

Gestational-stage and exposure-time-dependent dose factors for the same concentration of ^{133}Xe are similar to those from ^{85}Kr, although slightly higher. A similar relationship between dose to the early embryo and the fetal stages pertains, but there are slight decreases with increasing gestational ages. This results from interac tions between the physical size of the woman and the embryo/fetus, the related partition parameters, and the physical aspects of the calculation based on the penetrating and non-penetrating energy per decay.

Calculations for ^{222}Rn considered only the decay of the radon itself, yielding results as given in Table 5. These radiation doses are markedly higher than the doses resulting from the same atmospheric concenration of krypton or xenon, reflecting the greater energy deposition associated with the alpha particles. In general, the model reasonably predicts that the radiation dose to the embryo or fetus from the initial decay of the radon per se is similar to that in the pregnant animal or woman.

Table 5. Factors for radiation dose to the embryo/fetus resulting from a pregnant woman breathing representative radioactive noble gases at relevant times or period of gestation. Factors are given as dose (rad) resulting from breathing nominal atmospheres of 1.0 μCi/ml of ^{85}Kr, ^{133}Xe, or ^{222}Rn for various lengths of time up to 1 day. Approximate values for exposures of longer duration are calculated as multiples of the 1-day doses.

Gestational Days at Exposure	Exposure Times 5 min	10 min	15 min	30 min	1 hr	2 hr	6 hr	1 day
Krypton								
0	1.3E-02	2.7E-02	4.0E-02	8.0E-02	1.6E-01	3.2E-01	9.6E-01	3.8E+00
90	6.6E-03	1.3E-02	2.0E-02	4.0E-02	7.9E-02	1.6E-01	4.7E-01	1.9E+00
180	6.6E-03	1.3E-02	2.0E-02	4.0E-02	7.9E-02	1.6E-01	4.7E-01	1.9E+00
240	6.6E-03	1.3E-02	2.0E-02	4.0E-02	7.9E-02	1.6E-01	4.7E-01	1.9E+00
Xenon								
0	2.1E-02	4.4E-02	6.5E-02	1.3E-01	2.6E-01	5.2E-01	1.6E+00	6.2E+00
90	1.1E-02	2.2E-02	3.3E-02	6.7E-02	1.3E-01	2.7E-01	8.0E-01	3.2E+00
180	1.1E-02	2.1E-02	3.2E-02	6.4E-02	1.3E-01	2.6E-01	7.7E-01	3.1E+00
240	1.0E-02	2.1E-02	3.1E-02	6.3E-02	1.3E-01	2.5E-01	7.5E-01	3.0E+00
Radon								
0	1.3E+00	2.7E+00	4.0E+00	8.0E+00	1.6E+01	3.2E+01	9.6E+01	3.8E+02
90	1.3E+00	2.7E+00	4.0E+00	8.0E+00	1.6E+01	3.2E+01	9.6E+01	3.8E+02
180	1.3E+00	2.7E+00	4.0E+00	8.0E+00	1.6E+01	3.2E+01	9.6E+01	3.8E+02
240	1.3E+00	2.7E+00	4.0E+00	8.0E+00	1.6E+01	3.2E+01	9.6E+01	3.8E+02

As noted, the calculations from animal experimental data indicated that the radiation dose to the conceptus from radon progeny was the same as orless than dose to the pregnant animal, and presumably this would pertain also to the human. These residual decay products would be the primary (or only) contributors to postnatal radiation dose from the prenatal exposure.

VII. RADIOPHARMACEUTICALS

A. Overview

1. Concepts

The practice of nuclear medicine is based on administration to patients of pharmaceuticals that are radioactive or have radioactive labels. The distributions and/or rates of movement of the radioactivity are determined for diagnostic purposes, but localized radiation doses from large quantities of activity are also used for therapeutic procedures. Except for those used for placental localization, radiopharmaceuticals are not routinely administered to women who are known to be pregnant. There are circumstances under which such intakes may occur; consequently it may be appropriate to make prospective estimates of the potential prenatal dose. There may be a need for post facto determinations of radiation dose in other situations, including assessments in support of epidemiological studies. In addition, their widespread use creates a potential for intakes by personnel engaged in the production or administration of radiopharmaceuticals or during research and development.

As with exposure to radionuclides in other situations, the amounts of radioactivity in the embryo/fetus that contribute to radiation dose are affected by the biokinetics. This section assembles and integrates information concerning the biological disposition and dosimetric considerations for selected radiopharmaceuticals. Accepted pharmacological models and calculations for radiation doses to adults have been extended to the pregnant patient and her conceptus. These derived from the biokinetic models that were developed in Section V. The results of the dose calculations are presented. In addition, quotation or modifications of tables from calculations by other workers are included to provide a more comprehensive basis for assessment of radiation absorbed dose to the embryo/fetus.

2. Selection of Radiopharmaceuticals

Radiopharmaceuticals that were selected for inclusion are primarily those that are in common use in the practice of nuclear medicine. Insofar as possible, consideration was given to the agents used in the types of examination that would be most likely in pregnant women or in women of child-bearing age. Thus, radioiodines are included, with emphasis on sodium iodide and the most common isotopes, ^{123}I and ^{131}I. Technetium, particularly ^{99m}Tc in the form of pertechnetate, was evaluated directly and results are included. Tables developed by others are presented for a selected set from among the many labeled compounds.

Some radioisotopic tracers that are commonly used were evaluated and modeled in Section V. Biokinetic patterns that were described in that section were used to derive the associated dose factor tables that will be presented in this section for radionuclides such as gallium and indium, which are mostly encountered as radiopharmaceuticals. The biokinetic behavior of cobalt as the chloride and as vitamin B-12 in normal persons was described in Section V. The radiolabeled vitamin is mainly used as a radiopharmaceutical and the dose factors are considered in this section.

There is another group of radioelements that were widely used in the past and pregnant women were exposed in clinical studies. They are discussed here primarily to provide a basis for ex post facto dosimetric evaluations, which recently have received renewed interest. These elements, including phosphorus and iron, were evaluated in Section V and some clinical implications are considered in this section.

Another category of radiopharmaceuticals consists of inert gases used for imaging or physiologic determinations. The primary member of this group is xenon although krypton is occasionally encountered. These were specifically evaluated in Section VI of this report, both as general gases and as radiopharmaceuticals, and will not be considered again.

3. Sources of Models, Methods, and Parameters

The models and parameters for the biological disposition of the more common forms of ingested radionuclides in

their general elemental forms were described in Section V. These descriptions also serve as the basis for modeling and dosimetric assessment of many of these materials in the forms that are used as radiopharmaceuticals or released from compounds. Published information concerning biological disposition during pregnancy was superimposed onto the underlying data for the models, which were derived from models adopted by the ICRP in Publication 30 (ICRP 1979, 1980, 1981). Revisions to these models, as well as parameters applicable to persons of other ages, are given in ICRP Publications 56 (1989) and 67 (1993).

The dosimetric approaches described in Sections III and IV of this report are based on the methodology developed by the MIRD Committee of the Society of Nuclear Medicine and compiled in Loevinger et al. (1988). The ICRP internal dosimetry system, as described in Part 1 of ICRP Publication 30 (1979), is conceptually similar to the MIRD methodology. The several MIRD dose estimate reports and pamphlets (some of which are reprinted in Loevinger et al. 1988) and models from ICRP Publication 30 provided a primary input to ICRP Publication 53 (1988). That document describes pharmacokinetic models and dose factors for radiopharmaceuticals after administration to adults and to children at several representative ages.

The information concerning models and parameters from these documents, with appropriate modifications from the literature, has been incorporated into calculations and reports generated by the Radiation Internal Dose Information Center (RIDIC) of the Oak Ridge Institute for Science and Education (ORISE). There are relatively minor differences in calculated dose among the biokinetic models that are employed for calculation. In addition, calculations using the MIRD schema, such as those by RIDIC staff, are based on determination and use of explicit values of residence times (see Sections III and IV). These are only generally implicit in the model ing used in Section V of this report. Differences in the calculations and results for the two approaches will be illustrated in this section for a few representative elements.

The RIDIC staff have used some of their estimates of dose to the uterus, together with mathematical models of the pregnant woman, for estimating prenatal doses from radiopharmaceuticals, especially for early gestation and the 3-month fetus. These tabulations, as compiled and reported by Watson et al. (1992) and Stabin (1992), are considered here. This section and Section V also refer to models and calculations for specific agents that have been published in the open literature and in symposium publications and reports. Many of the models and parameters used by RIDIC for the adult are based on MIRD documents and ICRP Publication 53. These documents also were used as sources to prepare this section and to generate additional calculations.

The approaches and models were adjusted using applicable information concerning placental transfer, prenatal biokinetics, and dosimetry presented in other sections of this report. The parameters were modified, as appropriate, with values from the clinical and experimental literature as well as from the indicated reports. The several documents indicated in the previous paragraphs serve as compilations of biological behavior and provide metabolic data and models. They also may be regarded as compendia that provide most of the previously available estimates of radiation dose to the embryo/fetus.

As mentioned previously, a compilation and expansion of mathematical descriptions for the pregnant woman at each trimester of gestation were published recently (Stabin et al. 1995a), and a revised computer code and database for dose calculation that incorporated these phantoms (MIRDOSE 3, Stabin 1996) also became available during final preparation of this NUREG. When feasible, these factors were included in the calculations of tables here and in Section V.

Additional radiopharmaceutical dose estimates for the embryo/fetus that used this code were performed and reported in a thesis by Russell (1995). A summary of these results was presented at the 1995 Annual Meeting of the Health Physics Society (Russell et al. 1995). When appropriate, these dose estimates are provided as supplemental tables in this section by their quotation and citation, especially for ^{99m}Tc.

B. Models and Methods for Assessment

1. Gestational Stage Considerations

The dependence of the patterns of embryo/fetus dose from radionuclides on gestation stage was discussed in previous sections of this report. As indicated, this dependence derives from the progressive increases in dimensions and mass of the embryo/fetus that accompany its anatomical and physiological development as well as its relationships to placental and maternal structures. Moreover, the physical aspects of the calculation are dependent on factors contained in the specific phantoms for the trimesters of gestation (Stabin et al. 1995a). Thus, dose estimates from radiopharmaceuticals are best presented as general relationships to developmental stage of the embryo/fetus.

A continuum of ages for assessment, identical to those used to display the gestational-stage-dependent biological behaviors of general radionuclides, was used for most of the original evaluations of radiation dose from radiopharmaceuticals given in this section. Because of the recent availability, RIDIC has begun to present results relative for each trimester of gestation; they plan to continue expansion of this approach. Their analyses provide broad applicability to radiopharmaceutical agents, such as the wide range of ^{99m}Tc-labeled compounds that are not addressed in detail by this project. To increase completeness, these results will be quoted, with adjustment and acknowledgment.

Isotopes with short physical half-lives ordinarily are selected to produce diagnostic radiopharmaceuticals. Essentially all of the absorbed dose to the embryo/fetus after administration during pregnancy will be delivered within hours or days after administration and so will relate to the specific stage of gestation. Even with longer-lived materials, concentrations almost certainly will be reduced to insignificant levels during the remainder of gestation.

2. Metabolism and Placental Transfer

Special considerations are required for the wide array of agents that are radiolabeled with iodine or technetium. These pharmaceuticals are widely used for assessing clinical deficits, such as the status of functional capabilities or pathophysiology and anatomical integrity or pathology. Often, the administered radioactivity is bound to pharmacologic agents that do not cross the placenta so that direct placental transfer will be negligible.

In the case of agents that have potential for being diluted in the body's normal metabolic pool, it needs to be determined whether the embryo/fetus also participates in the pool. Further, the diagnostic goal determined by several of the radioisotopes is to measure metabolic behavior. The degree to which the label is released from the pharmaceutical and is present as a free ion must be considered, as well as the extent to which it is released during in vivo catabolic degradation of the pharmaceutical and destruction or death of the cell. Failure to account for availability to the embryo/fetus of radionuclides that have emissions with a significant non-penetrating component can lead to underestimates of dose, but this is of less consequence with penetrating emissions.

Additional allowances could be considered for changes in biological disposition and related biokinetic models that result from disease or from interventional clinical procedures such as thyroid blocking (administration of stable iodine) when using radioiodinated pharmaceuticals. In

most instances, however, the degree of applicability of these considerations to the embryo/fetus is uncertain. In some cases, it may be appropriate to consider boundary or worst-case conditions to provide conservative estimates of dose.

3. Localized Deposition in the Embryo/ Fetus

Many of the prenatal dosimetry models are based on metabolic patterns that involve inhomogeneous distribution within the fetus. As discussed in Section IV and illustrated in Section V, this can result in developmental-stage-dependent patterns of radioactivity kinetics in the embryo/fetus. This consideration is particularly relevant with radiopharmaceuticals or simple elemental compounds that are used as radiopharmaceuticals because their use is predicated on such localization. With beta-emitters in particular, this localization may result in a several-fold difference between total dose to the embryo/fetus and dose to individual tissues of the fetus.

Inhomogeneous distribution of radiopharmaceuticals does not necessarily complicate dose calculations in instances for which radiation dose to the total embryo/fetus will suffice. Such situations arise because there are gestational stages at which concentrations of agents, such as radiophosphorus in fetal bone or radiocobalt-labeled vitamin B-12 in liver, are greater than in general soft tissue of the embryo/fetus. These local elevations of concentration can result in increased total burdens of radioactivity in the embryo or fetus. Prenatal doses ordinarily are calculated as average dose to the embryo/ fetus and, other than as relates to absorbed fraction, it makes little difference where in the embryo/fetus the energy is dissipated. Therefore, even when prenatal metabolic patterns result in differential disposition in fetal bone or liver, total activity is used in calculations so that it is not necessary to take the localization into account for expressing the absorbed dose to the embryo/ fetus. Realization of the localization leads to the question of whether the local dose may be a sufficiently great multiple of the total body dose that it should be evaluated separately.

For example, the pronounced stage-related localization of radioiodine in the fetal thyroid leads to increased levels of total radioactivity in the conceptus. The localized activity in the thyroid gland serves as a source of self-dose and of dose to the total fetus, and so requires calculation of the thyroidal contribution to the dose from nonpenetrating radiations. Because this dose is of such great relative magnitude and is of interest to the clinician, separate calculations and tabulations of activity in the thyroid and radiation dose are given in addition to factors for the total embryo/fetus. Analogous considerations of lesser magnitude might be anticipated to pertain for ^{99m}Tc-pertechnetate, for which similar calculations and tables were developed.

4. Other Considerations in Estimation of Dose to the Embryo/Fetus

In earlier evaluations, RIDIC used distribution and retention information, uterine doses, and a phantom representing the pregnant woman, for calculations of dose to the 3-month fetus for a wide array of radiophar maceuticals. As mentioned above, recent calculations using the new mathematical models now consider size (Russell 1995, Russell et al. 1995). These include doses from photons emitted by maternal radioactivity and nonpenetrating emissions from radionuclides deposited in the embryo/fetus. These reports have included preliminary estimates of placental transfer in the calculations for many compounds.

The results of calculations for other materials, which are based on these extended physical descriptions and more complete biokinetic models, are given in the present report. As described above, these calculations include the self-dose from nonpenetrating radiations in situations where the model indicates that there are significant amounts of radioactivity in the embryo/fetus. Additional calculations established boundary conditions or estimates

of maximal dose, based on placental transfer of the radioisotopic label per se and its localization in the embryo/fetus.

Tabulated values of uterine dose may be adjusted and used for estimating dose from pharmaceuticals for which models are not available. Such extrapolations would be based on presumptions of similar chemical structure, metabolic characteristics, or biological behavior.

C. Evaluations: Radioiodinated Pharmaceuticals

1. Sodium Iodide

The in vivo evaluation of thyroid function involves oral administration of ^{123}I or ^{131}I, as sodium iodide. The ^{123}I has a 13-hour half-life; ^{124}I is a common contaminant of preparations. This contaminant has a half-life of about 4 days and could make a disproportionately large contribution to dose. The fraction of the activity present as the ^{124}I contaminant is not constant because it increases with irradiation time in the accelerator as well as time after irradiation due to decay. The longer-lived isotope, ^{125}I, is employed for diagnostic procedures such as plasma volume determinations and may be used in therapeutic applications.

Assessment of prenatal dosimetry of iodine isotopes is based on the time-weighted generalized scenario employed for adult biokinetic models. Following the ICRP convention, the time for gastrointestinal uptake is assumed to be 30 minutes so that oral and intravenous models are similar when half-lives are on the order of several hours or longer. Thus, the prenatal biokinetic models and dose evaluations given in Section V of this report for sodium iodide in the transfer compartment provide a basis for further calculations with other isotopes. The following is a synopsis of the basic models described in that section.

Inorganic iodides freely cross the placenta but iodinated thyroid hormones are transferred less freely. Although the iodide is readily available, it does not localize in the embryo or early fetus. There is a generalized distribution of iodide during this period and tissue concentrations are assumed to approximate those in the uterus and other maternal soft tissue. The fetal thyroid begins to trap iodide at about 10 to 11 weeks of gestation but does not metabolize significant quantities into hormone until about 13 weeks of gestation. These functions increase with progressive development so that specific details of the biokinetic models change throughout gestation. Depending on exposure conditions, the fetal thyroid concentration of some isotopes of iodine may exceed that of the woman towards mid- or late-gestation.

As was discussed in Sections IV and V, the radiation absorbed dose to the embryo/fetus is a combination of energy from radioactivity distributed throughout the woman, emissions from iodine in the fetal and maternal thyroids, and the contribution of iodine distributed throughout the embryo/fetus. The radiation doses to the fetus and fetal thyroid are affected by the half-lives and emissions of the individual isotopes in addition to stage-dependent influences of anatomical relationships and tissue concentrations. Because of its localization in the fetal thyroid and relationship to the prenatal development pattern, dose factors for sodium iodide are tabulated separately for the embryo/fetus and for its thyroid.

The maximum dose rates and the monthly doses to the embryo/fetus and fetal thyroid from administration of 1 μCi of ^{123}I to a pregnant woman at selected times of gestation are presented in Tables C9a and C9b. Comparable tables, using initial dose rates instead of maximum rates, are given for administration of ^{131}I in Tables C10a and C10b.

2. Radioiodinated Organic Molecules - Hippuran and Serum Albumin

Several organic molecules have been labeled with radioiodine and used in nuclear medicine for measurements of physiological functions and anatomical compartments. It is a common clinical practice with such radiopharmaceuticals to administer stable iodide to reduce thyroid uptake of unbound radioiodide (blocking) and to accelerate its excretion. This situation is assumed in the dosimetric modeling of radiopharmaceuticals that have a potential for release of free iodide so that radiation doses to the thyroid gland are minimized.

RIDIC dose estimates for radioiodinated compounds have included dose to the non-pregnant uterus. These estimates used the phantom of Cristy and Eckerman (1987) and are consistent with those in ICRP Publication 53 (1988). Radioiodinated hippuran and serum albumin illustrate the range of kinetic and dosimetric considerations for these types of radiopharmaceutical.

In particular, the models for orthoiodohippurate and radioiodine-labeled hippuran in adults were given in a report by RIDIC (Watson et al. 1992). The biological half-lives, T_b, for total body are given as 0.285 hour for 49% and 0.0392 hour for 51%. Residence time in the kidneys is 6.2 minutes and all activity is cleared through the urinary bladder with a voiding interval of 4.8 hours. The ICRP indicates that clearance is slower in diseased kidneys so activity would remain in blood for a longer period. With bilateral renal impairment, the clearance rate is assumed to be 1/10 of normal and renal transit time increases to 20 minutes from the normal 4 minutes. The total body half-life is 4.2 hours and a fraction of 0.04 is retained in liver with the same 4.2-hour half-life. With unilateral renal blockage, an assumed fraction of 0.5 is taken up by one kidney, slowly released to the blood with T_b = 5 days, and excreted by the other kidney.

The RIDIC model used for radioiodinated human albumin in the adult, which is based on the model in ICRP Publication 53, was modified by the assumed fractional distribution pattern of blood. All unbound radioiodine is assumed to be rapidly excreted because of thyroid blocking, as indicated, and the large excess of iodide should also block the fetal thyroid. The radioactivity of the iodinated serum albumin in blood is also reduced by dilution in the total exchange pool, which may be 2 to 3 times as large as the intravenous pool. The disappearance curve for blood is described by the sum of three exponential components: 6.8 hours (40%); 1.29 days (22%); and 19.4 days (38%). Corresponding values for the whole body are 6.8 hours (1.5%), 1.29 days (3.5%), and 19.4 days (95%).

Stabin (1992) extended calculations that were based on photons and nonpenetrating emissions from retained fractions of administered radioactivity to include estimates of dose to the embryo/fetus. As noted above, these have been subsequently recalculated using the recent mathematical models of the pregnant woman at each trimester (Russell 1995, Russell et al. 1995). A summary of these doses to embryo/fetus at each trimester of human gestation is shown in Table 6.

3. Considerations for Clinical Conditions

Because the thyroid is commonly blocked with stable iodide, gestational biokinetic models for essentially all radioiodinated compounds assume that most free iodide is excreted rapidly and that the remaining portion of the administered iodine is bound to the pharmacologic agent. Because of its renal clearance specificity and short available time in the circulation, the prenatal model assumes that none of the hippuran activity crosses the placenta or enters the embryo/fetus. The embryo/fetus and placenta may participate in the total albumin exchange pool although quantification is not readily available. As an

Table 6. Gestational-stage-related cumulated radiation doses (rad/μCi) to the embryo/fetus following intravenous injection of radioiodine-labeled human serum albumin or hippuran (after Russell et al. 1995).

	Albumin		Hippuran	
Gestational Stage at Injection	^{125}I	^{131}I	^{123}I	^{131}I
Early	9.2E-04	1.9E-03	1.2E-04	2.4E-04
3 months	2.9E-04	6.8E-04	8.7E-05	1.8E-04
6 months	1.4E-04	5.8E-04	3.1E-05	7.1E-05
9 months	9.7E-05	4.9E-04	2.9E-05	6.6E-05

approximation, the model for albumin considers that little of the activity that crosses the placenta as albumin or as free iodide will persist in the embryo/fetus. The foregoing consideration should not be indiscriminately extended to radioiodinated agents for which biokinetic and distribution information are not available. As noted, maternal tissue distribution, including localization, would have been considered in calculations involving photons. Failure to account for entry into the embryo/fetus of any radiolabel that has a significant nonpenetrating component may lead to an underestimate of dose.

In the case of radioiodines, the boundary conditions, or upper limits to potential exposure, may be represented by doses to the embryo/fetus or fetal thyroid from the corresponding isotopes of sodium iodide. The fetal doses from ^{131}I at 3 or 6 months of gestation are not appreciably greater than those from the organic agents, but the corresponding doses to the fetal thyroid are markedly higher.

Thus, the RIDIC dose estimates for the non-pregnant uterus are based on self-dose from nonpenetrating radiations plus gamma exposure from maternal radioactivity. They are relevant to the first months of pregnancy and also accommodate calculations based on photon exposures from activity in maternal tissue and phantom of a 3-month pregnant woman. The further refinement of these calculations are resulting from the full gestational phantoms, but these values provide conservative estimates of dose at later stages of gestation.

D. Evaluations: Technetium (^{99m}Tc)-Labeled Radiopharmaceuticals

Radiopharmaceuticals that are labeled with technetium (^{99m}Tc) are the most frequently encountered group of agents in nuclear medicine. The compounds that are in clinical use range from the pertechnetate that is used directly after elution from a molybdenum generator to a variety of complex molecules. As a consequence of their extensive use, the potential doses to the embryo/fetus must be included in any comprehensive summary of prenatal dosimetry.

The general characteristics and biological behavior of ^{99m}Tc-pertechnetate as a general radionuclidic compound were described in Section V and provided a basis for the general biokinetic model. This information included the descriptions given in ICRP Publications 30 and 6, and from reported measurements of placental transfer and biological disposition that were described in Section V for deriving the biokinetic models. Gestational-stage-related values for initial deposition fractions and subse-

quent retention fractions of pertechnetate in the embryo/fetus were calculated from these models and presented in Appendix A. The corresponding pertechnetate dose factors for the embryo/fetus were given in Appendix B for that section. These values are repeated in Appendix C.

The number and range of characteristics of ^{99m}Tc-labeled pharmaceuticals is so extensive that detailed consideration is beyond the scope of this report. Summaries of reports concerning the fetoplacental disposition of relevant other compounds during pregnancy are provided in the following paragraphs. The prenatal dosimetry of many of these agents have been addressed in documents that will be cited and relevant data included. Patterns and summaries of results on the behavior and dosimetry for radiopharmaceuticals that are most relevant to exposure during pregnancy are reviewed in this section and the reader is referred to the sources described for additional information.

Based on similarities in several of their biological behaviors, modeling of pertechnetate during pregnancy was patterned after models for iodide. Also, drawing from the parallel to radioiodinated compounds, there are additional uncertainties about technetium-labeled agents for which little kinetic and distribution information is available, including placental transfer and embryo/fetus disposition. Calculations of embryo/fetus dose from photons can be misleading when there is significant localization of the agents in maternal tissue. Few of the compounds with a ^{99m}Tc label, other than those that remain localized to specific sites of administration, result in marked inhomogeneities of dose throughout the embryo/fetus. These patterns, which include time in kidney and bladder, have been considered in many of the current RIDIC calculations of dose to the embryo/fetus so that these estimates should reasonably apply.

As emphasized above, it is necessary to recognize that calculations must consider the beta dose from radiopharmaceuticals that cross the placenta intact or that significantly release a ^{99m}Tc-label, which then enters the embryo/fetus. This situation is covered by the biokinetic model presented in Section V; the dosimetry will discussed here.

As was mentioned in Section V, multicompartmental models that describe pertechnetate distribution in adults at early times after intravenous administration are not of major consequence to radiation dosimetry of the embryo/fetus. The information assembled in ICRP Publication 67 (1993) is an expansion of Publication 30 and provided an adequate presentation to construct a simple model of the distribution and retention of pertechnetate in the adult that is adequate for extrapolating to placental transfer and deposition in the embryo/fetus.

The model for pertechnetate considers the biological half-time in the transfer compartment to be 0.02 day. Of technetium leaving the transfer compartment, 4% is assumed to translocate to the thyroid where it is retained with a biological half-time of 0.5 days. The model assumes another 10% of technetium leaving the transfer compartment to be translocated to the stomach wall, 3% to the liver, and the remaining 83% to be uniformly distributed throughout all other organs. Of technetium translocated to organs and tissues other than the thyroid, 75% is assumed to be retained with a 1.6-day biological half-time, 20% with a 3.7-day biological half-time, and 5% with a 22-day biological half-time. This will lead to a higher thyroid dose. However, the 17% should not affect an assumption of general uniform distribution for purposes of the model.

The information that follows gives in more detail the description in Section V for pertechnetate as well as information for other ^{99m}Tc-labeled compounds. There are significant differences among results of workers who measured the placental transfer and distribution of pertechnetate in animals, as evident in the compilation of fetal to maternal concentration ratios by Roedler (1987). A comparative overview among agents is available in the study of Mahon et al. (1973). In that study, organ distribution of various materials used for placental localization was measured, including several radiopharmaceuticals

with a ^{99m}Tc-label, after intravenous injection in pregnant rabbits. At one hour after administration, the ratio of ^{99m}Tc-pertechnetate in a single placenta to that in a single fetus was 0.22 and of placenta to blood was 0.037.

Lathrop (1976), determined the quantitative distribution patterns of intravenously administered ^{99m}Tc sodium pertechnetate in the adult and its fetus and compared the effects of perchlorate. At 1.5 hours after administration, the ratio of technetium concentration in the placenta to that in blood was 2.1 without perchlorate, but was 0.49 with perchlorate pretreatment. The ratio of ^{99m}Tc with perchlorate to that without perchlorate was 0.34 in the placenta and 0.32 in the fetus.

Wegst et al. (1983) estimated cumulated activity for ^{99m}Tc-pertechnetate distribution data in nonpregnant and pregnant rats at times between 13 and 21 days of gestation. Activity concentrations in fetal tissue and cumulated activities were not the same at all ages. The maximum value of cumulated activity in the fetus was found with injection on 13 days, then fell by a factor of 2.5, and rose again at term. The placental tissue concentration remained essentially constant over time. Wegst (1992) extrapolated these data to estimate radiation absorbed dose for the human. She determined that the mean fetal dose for months 1 to 2 of gestation would be 0.086 mGy/MBq (3.2×10^{-4} rad/μCi) administered to the woman.

Wegst (1992) also presented results from studies of ^{99m}Tc distribution in pregnant rats and estimated cumulated activities for nonpregnant animals and pregnant rats at different stages of pregnancy. She extrapolated the animal data to estimate that the mean absorbed dose received by a human fetus during early pregnancy would be 8.2×10^{-3} mGy/MBq (3.0×10^{-4} rad/μCi) of ^{99m}Tc diethylenetriaminepentaacetic (DTPA) administered to the mother.

Estimates were made of fetal absorbed dose from ^{99m}Tc macroaggregated albumin (MAA) and ^{99m}Tc DTPA aerosol for pulmonary studies in the mother at different stages of pregnancy. The dose estimate for all gestational ages was 0.0022 mGy/MBq (8.1×10^{-5} rad/μCi) administered to the mother.

The metabolic behavior and radiation dosimetry of ^{99m}Tc human serum albumin in pregnancy were studied in volunteers with pregnancies of 32-weeks gestation or more (Herbert 1969). Sastry et al. (1976) published absorbed dose estimates for several radionuclides used in placentography. They presented values for the time-integrals of activity (μCi h/g per μCi administered) as ^{99m}Tc human serum albumin of 0.00014 in the maternal whole body, 0.00094 in the maternal blood, 0.0016 in the fetal whole body, 0.000033 in the fetal blood, and 0.00075 in the fetal thyroid. They also estimated the radiation dose to some maternal and fetal tissues for an investigation done during the thirtieth week of pregnancy.

Roedler (1987) also used reported data to derive concentration ratios for some other technetium-labeled compounds . The fetal-to-maternal concentration ratio was 0 to 0.05 for technetium-labeled DTPA in the total body. For technetium-labeled human serum albumin, the range of ratios for plasma was 0.025 to 0.051 while ranges for some other materials included 0.002 to 0.11 for colloids, 0.006 to 0.018 for polyphosphate, and 0.0038 to 0.05 for pyrophosphate.

A study of pregnant rabbits by Mahon et al. (1973) included several ^{99m}Tc-labeled radiopharmaceuticals. They reported values for the ratio of activity in a single placenta to a single fetus at 1 hour after administration. The ratio for ^{99m}Tc-pertechnetate was 0.22, but it was 10 for ^{99m}Tc -polyphosphate and for ^{99m}Tc-sulfur colloid. A 32-week pregnant patient was studied with ^{99m}Tc exametazime (HMPAO) (Maguire 1990). A focal fetal accumulation was seen in an image of the patient's abdomen. A region of interest yielded an estimate of 4.5% of the activity found in the maternal liver. After delivery, the infant was imaged to determine the localization of the ^{99m}Tc. Most of the activity was present in the liver, and no significant cerebral concentration was

found. The diminished uptake in the fetal brain may be related to the immaturity of glutathione metabolism in the fetus or may result from the fact that about 50% of the umbilical venous blood returning to the fetus from the placenta passes through the fetal liver.

Hedrick et al. (1988) found little uptake of ^{99m}Tc methylene diphosphonate (MDP) in fetuses of two patients undergoing bone scintigraphic procedures. They estimated radiation doses under the assumption that no activity entered the fetus and that most of the dose was from the activity in the urinary bladder of the mother. The resulting dose was calculated to be 4.6 x 10^{-3} mGy/MBq (1.7 x 10^{-5} rad/μCi) administered to the mother for a 8-week fetus and 2.6 x 10^{-3} mGy/MBq (9.6 x 10^{-6} rad/μCi) for an 18-week fetus.

A summary of doses to embryo/fetus at each trimester of human gestation from relevant ^{99m}Tc-labeled radiopharmaceuticals has been excerpted from tables by Russell et al. (1995). The results are shown in Table 7.

Table 7. Gestational-stage-related cumulated radiation doses (rad/μCi) to the embryo/fetus following intravenous injection of commonly used ^{99m}Tc-labeled radiopharmaceuticals (after Russell et al. 1995)

Radiopharmaceutical	Embryo	3-Months	6-months	9-months
Disofenin	6.4E-05	5.6E-05	4.3E-05	2.5E-05
DMSA	1.9E-05	1.7E-05	1.5E-05	1.3E-05
DTPA	4.7E-05	3.2E-05	1.5E-05	1.8E-05
DTPA aerosol	2.1E-05	1.6E-05	8.4E-06	1.1E-05
Glucoheptonate	4.4E-05	3.4E-05	1.7E-05	1.5E-05
HEDP	2.7E-05	1.9E-05	9.9E-06	8.9E-06
HMDP	1.9E-05	2.0E-05	1.1E-05	9.1E-06
HSA	2.0E-05	1.1E-05	9.7E-06	8.2E-06
HMPAO	3.3E-05	2.5E-05	1.8E-05	1.4E-05
MAA	1.1E-05	1.5E-05	1.9E-05	1.5E-05
MAG3	6.6E-05	5.0E-05	2.0E-05	1.9E-05
MIBI	5.6E-05	4.4E-05	3.1E-05	2.0E-05
MDP	2.3E-05	2.0E-05	1.0E-05	8.9E-06
Albumin microspheres	1.5E-05	1.1E-05	9.1E-06	7.8E-06
RBC - in vitro label	2.5E-05	1.8E-05	1.3E-05	1.0E-05
Sulfur colloid (IV)	6.8E-06	7.7E-06	1.2E-05	1.4E-05

Particularly with technetium, it is important to account for availability to the embryo/fetus of activity because the nonpenetrating component can lead to underestimates of dose. Most ^{99m}Tc-labeled radiopharmaceuticals would not be expected to undergo rapid placental transfer so that total activity that reached the embryo/fetus would be further restricted by the 6-hour half-life. Preliminary surveys have not determined any agents that should be expected to pose a significant requirement for special analysis. Therefore, consideration will be restricted to the hypothetical potential and boundary doses for agents crossing the placenta.

The dose rates and the monthly doses to the embryo/fetus and fetal thyroid from administration of 1 μCi of ^{99m}Tc-pertechnetate are presented in Tables C7a and C7b, respectively, of Appendix C. The boundary conditions for compounds with a ^{99m}Tc label could be represented by doses to the embryo/fetus from sodium pertechnetate. However, because of the short physical half-life of ^{99m}Tc, and the pattern and kinetics of distribution in the adult, pertechnetate does not deliver a radiation dose to the adult thyroid that is markedly greater than the dose to general soft tissue. This is true even without administration of a blocking agent.

The absence of elevated dose should also be applicable to the thyroid of the embryo/fetus, which is consistent with not having yet identified special dosimetric situations. As a consequence, the primary source of prenatal radiation dose would be expected to be photons originating from ^{99m}Tc in tissues of the woman, together with a stage-dependent dose component from nonpenetrating emissions from radioactivity in the uterus.

E. Radiopharmaceutical Evaluations: Miscellaneous Radiolabels

The following prenatal models include radiopharmaceuticals for which the metabolic patterns result in nonuniform distributions of radioactivity throughout the fetus. As was noted, this affects biokinetics and activity in the embryo/fetus but does not necessarily complicate dose calculations. The range of examples is shown by gestational stages at which the concentrations of radiophosphorus in fetal bone or of radiocobalt-labeled vitamin B-12 in liver are greater than in general soft tissue, which leads to greater total burdens of radioactivity in the embryo/fetus. Prenatal doses are calculated as the average or total body dose to the embryo/fetus and, except for determining absorbed fraction, it makes little difference where in the embryo/fetus the energy is dissipated. Thus, assumptions underlying the prenatal metabolic model allow for differential disposition in fetal bone or liver, but this localization has not been included in the calculation of beta doses to individual tissues of the embryo/fetus.

1. Sodium Phosphate

Radiation doses to the embryo/fetus associated with the clinical use of ^{32}P-phosphate are now largely of historical interest. Information from Section V is reviewed briefly in this section to facilitate ex post facto analyses.

The model in ICRP Publication 53 (1988), which is used for calculations with sodium phosphate in the adult, is based on the description presented in ICRP Publication 30 (1979). The assumed distribution and retention model assigns 30% of the activity to skeleton, which represents a reference 15% of body weight. Skeletal radiophosphate is assigned biological half-times that are infinitely long compared tophysical half-lives of important phosphorus isotopes (14 days for ^{32}P). The other 70% of the activity is in the 85% of body weight made up by the remaining tissues, which are assigned biological half-lives of 12 hours (14%), 48 hours (14%), and 456 hours (42%). In this situation, it is clear that physical half-life is the important aspect of the overall dose.

This description was extended by introducing additional information into these biokinetics. This led to the general operational model given in Section V for prenatal distribution that was used for calculating self-dose to the embryo/fetus. This information involved extrapolations of patterns from animal experiments and descriptions of the anatomical and biochemical development of the human embryo/fetus. During the first 2 months of gestation, which is prior to significant skeletal development, a steady-state relationship was assumed. The initial and subsequent concentrations in soft tissues of the embryo/fetus were considered to be the same as in the general soft tissue compartments of the woman so that activity is given by the ratio of masses of the embryo/fetus and the woman.

The steady-state situation for soft tissue radioactivity in the embryo/fetus and maternal soft tissue tissue compartments also pertains at later times. The model in Section V accounts for the developing skeleton, playing an increasingly important role in the biokinetics at these later stages and assuming gestational-time increases for skeletal concentrations. The average fetal skeletal concentration should be an increasing fraction of that in maternal bone so that its concentration at times after 3 months of gestation is considered to be 2.8 times that in the woman's general soft tissue compartments. Activity in the fetus would progressively increase and would be given by proportionation of fractional mass and concentration at these ages.

Tabulations of deposition and retention are given in Table A4, Appendix A, and dose factors in Table B4 of Appendix B.

Intraperitoneal or intrathoracic infusion of colloidal chromic phosphate (^{32}P), which is adsorbed onto serous membranes, was used to treat ascites or pleural effusion, respectively. Anecdotal evidence indicates that the colloid is not absorbed and that there is no or minimal uptake in blood or placental transfer.[a] This agent therefore would have little or no relevance to radiation dose to the embryo/fetus.

Recent clinical investigations are using massive interstitial injections of chromic phosphate into the liver for treatment of neoplasms. To the extent that unbound phosphorus is released, it would be assumed to behave as described above for the phosphate.

2. Chromium-Labeled Erythrocytes or Platelets

A model of the gestational-stage-dependent deposition and retention of elemental chromium (^{51}Cr) in the embryo/fetus was presented in Section V. This model provides a basis for dosimetry of chromium that is not bound or is released from labeled cells. This information does not directly relate to the dose from primary clinical uses such as injection of erythrocytes that were labeled in vitro or from labeled platelets.

The biological model for the dosimetry of labeled cells in the adult used by RIDIC (Watson et al. 1992) is based on the description given in ICRP Publication 53. The model was modified to include use of blood to determine total body residence time, followed by subtraction of liver, spleen, and red marrow residence times to obtain cumulated activities for the remainder of the body. Gamma doses to the conceptus from circulating, sequestered, and dying cells, which do not significantly cross the placenta, are given in calculations by RIDIC (Stabin 1992). These are based on their indicated effective distributions and residence times of 27.4 hours for cells in liver (25%), 4.53 hours for red marrow (4%), 51.6 hours for spleen (42%), and 543 hours for other tissues (29%).

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[a] Sikov, M. R., Unpublished calculations based on clinical measurements by J. E. Lofstrom et al., Wayne State University College of Medicine, 1962.

To estimate the other extreme of radiation dose, the 29% of the activity in other tissues from intravenously injected labeled red cells is assumed to be released in ionic form and transfered across the placenta. The activity enters over time but the initial concentration in the embryo/fetus is assumed to be equal to that in the general soft tissues of the woman. The same effective half-time of 543 hours would pertain because growth of the embryo/fetus would more than compensate for ingrowth.

Alternatively, the model for chromium chloride (ionic ^{51}Cr III) that is released from cells could be considered for the dose calculations for labeled erythrocytes. As considered in Section V, intravenously injected chromium chloride, which is firmly bound by plasma proteins and total body retention in the human, has half-life values of 8 hours (30%), 10 days (30%), and 160 days (40%). Scans and compartmental analysis yield a distribution of 25% to liver and 2.5% to spleen; an uptake half-time of 6 days and elimination half-time of 160 days are assumed.

The resulting values of gestational-stage-related deposition and retention in the woman and the embryo fetus were tabulated in Tables A5a and A5b of Appendix A. The corresponding dose factors for the embryo/fetus were given in Table B5 of Appendix B.

Embryo/fetus radiation dose estimates for ^{51}Cr-labeled cells were made by Stabin (1992). Values from this report are summarized in Table 8. The model used for calculation does not include self-dose from ionic chromate transferred across the placenta but this would make a contribution of less than 10%.

3. Radioisotopes of Iron

Three radioisotopes of iron (^{52}Fe, ^{55}Fe and ^{59}Fe) are of interest for their use in clinical investigation and medical practice. Models for ^{55}Fe and ^{59}Fe were described in Section V. The results of deposition and retention calculations are presented in Tables A6 and A7 and corresponding dose factors in Tables B6 and B7. These models are based on early deposition in marrow, incorporation into erythrocytes, and their release to the circulation. The dosimetry does not apply to ^{52}Fe, a positron-emitting radionuclide with a half-life of 8.28 hours. There would not be sufficient time for significant incorporation into circulating before it decayed.

Table 8. Gestational-stage-related cumulated radiation doses, rad/μCi to the embryo/fetus following intravenous injection of ^{51}Cr-labeled erythrocytes or leukocytes (after Stabin 1992)

Gestational Stage at Injection	Radiation Dose
Non-pregnant uterus (or early gestation)	4.0E-04
3-month fetus	3.0E-04

As was described in Section V, investigators have calculated radiation doses to patients from iron used as a radiopharmaceutical and have extended the results to obtain dose estimates for the embryo/fetus. Current interest in historical aspects has also led to evaluations of past exposures of human subjects. Information from these descriptions will be summarized here to provide for comparisons among models, approaches, and results.

Many of the published dosimetric evaluations incorporated considerations of fetoplacental disposition that were based on ^{59}Fe transport experiments across of the placenta of monkeys (van Dijk 1977). The experimental data were used to develop a compartmental model of iron transport and calculated rate constants for a five-compartmental system. The results of the compartmental analyses agreed with the MIRD compartmental model for radiopharmaceutical iron (Robertson et al. 1983).

This model assumes that the activity is cleared from plasma and accumulates in the red marrow where it is incorporated into and remains in erythrocytes. The radio-

iron is not released until after the death of the cell (120 days), when the cycle is repeated. Based on assumed red cell distribution, that the distribution of longer-lived radioisotopes is such that 5% of administered activity in circulating RBC is in liver, 5% in spleen, 4% in the marrow, 8% in the heart, and 78% in other organs and tissues of the body. Short half-lived radioisotopes, such as ^{52}Fe and its daughters, may decay before the iron is incorporated into the red cells.

As indicated in Section V, human dose estimates are available through evaluation of the nutritional studies in which iron (^{59}Fe) was orally administered to 819 pregnant women during early pregnancy. In addition to the metabolic information, these studies found that 1% to 3% of the administered activity was present in fetal blood at birth (Hahn et al. 1951). Dyer and Brill (1969) obtained further metabolic information that allowed estimates of the intrauterine radiation doses received by three children from this series, who subsequently developed malignancies (Dyer et al. 1973). One fetus exposed at 13 weeks was estimated to have received 0.10 rad from 2.56 μCi of ^{59}Fe absorbed by the mother; one exposed at 23 weeks was estimated to receive 1.8 rad from 44.4 μCi of ^{59}Fe absorbed by the mother; and one exposed at 20 weeks was estimated to receive 0.036 rad from 0.90 μCi of ^{59}Fe absorbed by the mother. Re-evaluations of this dosimetry using the MIRDOSE 3 factors for calculation yielded only relatively slight changes in absolute values (Stabin et al. 1995b).

Based on his review of the literature, Roedler (1987) used the MIRD kinetic model of iron to calculate ratios of activity concentrations of iron in the adult and the fetus at times from 9 to 22 weeks of gestation. The ratio of activity concentration in the fetal liver to that in the adult was given as 80. The physical and effective half-times of ^{59}Fe, corrected for growth, were estimated as 45 days in the adult and 3.2 days in the fetus. In the fetus, 12% was assumed to be in storage and 88% in erythropoiesis with effective half-times of 10.7 days and 2.2 days, respectively. Roedler estimated the liver doses in the adult as 12 mGy/MBq (0.04 rad/μCi) administered; however, doses to the fetal liver were greater, with 28 mGy/MBq (0.1 rad/μCi) administered to the mother.

To provide additional bases for comparison of approaches for use with radiopharmaceuticals, results of calculations by Watson with ex post facto addition of dose factors in traditional units, are shown in Table 9. This illustrates the explicit use of calculated values of residence time, which is the common analysis for dose from clinically related exposures.

She first derived residence times of iron radioisotopes in the placenta and fetal tissues from the transfer rate constants for two of the experiments (Experiments 3 and 4) by van Dijk (1977). She then calculated radiation absorbed dose estimates for the fetus through the first two months of pregnancy, using a mathematical model that described the nongravid uterus for early pregnancy (Cristy and Eckerman 1987), and for the fetus during the period from three through five months from Davis et al. (1987). The resulting dose factor estimates for the embryo/fetus again demonstrate relationships among isotopes based on their physical characteristics.

The dose estimates for the period of 3 to 5 months of gestation encompass the above-indicated estimate by Roedler (1987) of 28 mGy/MBq (0.1 rad/μCi) to the fetal liver. The dose factor is somewhat higher than the estimate given for this gestational stage in Table B7 or that given by Dyer et al. (1973), which is similar to that in Table B7.

Table 9. Residence times of iron in placenta and fetal tissues (hours) and corresponding radiation absorbed dose estimates for the fetus from intake of radioiron by mother in mGy/MBq (After Watson[b]; corresponding doses in rad/μCi are given in parentheses below each entry.)

	Residence Times					
	^{52}Fe		^{55}Fe		^{59}Fe	
Source Organ	Expt. 3	Expt. 4	Expt. 3	Expt. 4	Expt. 3	Expt. 4
Placenta	0.009	0.005	0.012	0.058	0.012	0.006
Fetal plasma	0.20	0.081	0.37	0.15	0.37	0.15
Fetal tissues	0.47	0.19	2400	960	110	43

Absorbed dose estimates for embryo/fetus in mGy/MBq and (rad/μCi)

	0 through 2 months pregnancy		3 through 5 months pregnancy	
Radioisotope	Expt. 3	Expt. 4	Expt. 3	Expt. 4
^{52}Fe	1.2 (0.0044)	0.50 (0.0019)	0.26 (0.001)	0.088 (0.0003)
^{55}Fe	100 (0.37)	41 (0.15)	18 (0.067)	7.1 (0.026)
^{59}Fe	150 (0.56)	63 (0.23)	34 (0.13)	15 (0.056)

4. Radiocobalt-Labeled Vitamin B-12

The general chemical and biological behavior of important cobalt radioisotopes, including relevant fetoplacental considerations and the biokinetic model, were described in Section V. These concentrated on the inorganic form although the description included vitamin B-12 in the normal individual. This latter is the form that specifically relates to its use as a radiopharmaceutical.

Basic metabolic and kinetic models for these forms are based on descriptions given in ICRP Publications 30 (1979) and 67 (1993) and those presented in ICRP Publication 53 and MIRD, specifically for vitamin B-12. The assumptions for the intravenous administration of vitamin B-12 without carrier provides a basic model for its consideration as a radiopharmaceutical. After injection in a normal person, 10% of the activity is assumed to be retained in the body with a biological half-time of 0.1 day and 90% with a biological half-time of 500 days. The liver takes up 60% and retains this with a half-time of 500

[b]Unpublished calculation by E. E. Watson, ORISE, 1992 and included here with her permission.

days. The remaining 40% is distributed throughout the rest of the body and eliminated with half-times of 1.0 day for 25% and 500 days for 75%.

The gestational-stage-dependent radiation dose rates and doses to the embryo/fetus from 1 μCi of cobalt-labeled vitamin B-12 injected into maternal transfer are given in Appendix C. The values are given for a normal woman under unperturbed conditions and are shown for ^{57}Co in Table C1, for ^{58}Co in Table C2, and for ^{60}Co in Table C3.

There are three additional scenarios that are relevant to the dosimetry as applies to radiopharmaceutical use. For glomular filtration rate (GFR) studies that use intravenous injection with carrier vitamin B-12, the total body retention is described by a two-exponential function with half-times of 100 minutes (90%) and 500 days (10%). Typically, 5% is taken up by the liver and retained with a half-time of 500 days; another 5% is assumed to be uniformly distributed throughout all other organs and tissues and retained with a half-time of 500 days. It is assumed that 90% is retained in the body with a half-time of 100 minutes and is excreted via the kidneys according to a kidney-bladder model described in ICRP Publication 53 (ICRP 1988).

When the labeled vitamin is administered orally and not flushed with the stable vitamin, the assumption is that 70% of the material is absorbed; 10% is retained with a half-time of 1 day and 90% for 500 days. A small amount of the absorbed vitamin is taken up by the liver and retained with a half-time of 500 days. The remaining fraction of the absorbed vitamin is distributed throughout the body and eliminated with half-times of 1 day (25%) and 500 days (75%).

After oral administration and flushed with unlabeled vitamin B-12, 70% of the administered material is absorbed by the normal individual; 34% is retained with half-times of 100 minutes, 6% for 1 day, and 60% for 500 days. The liver takes up 40% of the absorbed vitamin, which is retained with a half-time of 500 days. The remainder is partly excreted by glomerular filtration with a half-time of 100 minutes according to the kidney-bladder model (ICRP 1987), the remainder being eliminated with half-times of 1 day and 500 days.

A summary of doses to embryo/fetus at each trimester of human gestation from vitamin B-12 under various conditions of administration and clinical state has been prepared from Russell et al. (1995). The results are shown in Table 10.

5. Gallium

The general characteristics and biological behavior of gallium and its biokinetic model were described in Section V. Four of its several radioisotopes are of particular interest because of their use in nuclear medicine. These isotopes and their half-lives are: ^{66}Ga, 9.5 hours; ^{67}Ga, 3.26 days; ^{68}Ga, 68.1 minutes; and ^{72}Ga, 14.1 hours.

The biokinetic model was used as the basis to calculate gestational-stage-dependent initial deposition and subsequent retention fractions of ^{67}Ga in the woman and the embryo/fetus. These values are presented in Tables A15a and A15b.

This evaluation incorporated information from the biokinetic model that was developed by Watson (1992) for an intravenous injection of gallium citrate to a pregnant woman after about four months of pregnancy. These models both use the data of Mahon et al. (1973); the time-activity data of Wegst (Wegst 1981, Wegst 1992) and Lathrop (Lathrop 1992); and the biokinetic model of gallium from MIRD Dose Estimate No. 2 (Cloutier 1973). Roedler (1987) also reported fetal-to-maternal ratios of activity concentrations for gallium ranging from 0.2 to 4.

Table 10. Cumulated radiation doses to the embryo/fetus, rad/μCi, following oral administration of vitamin B-12 labeled with radiocobalt isotopes at representative stages of gestation relative to clinical status and procedure (after Russel et al. 1995)

Gestational Stage at Injection	No Flushing			Flushing		
Normal Patients						
	57Co	58Co	60Co	57Co	58Co	60Co
Early	3.2E-03	1.1E-02	7.2E-02	3.0E-03	1.0E-02	6.4E-02
3 months	2.8E-03	1.0E-02	5.6E-02	2.7E-03	9.7E-03	5.1E-02
6 months	2.5E-03	1.0E-02	4.0E-02	2.2E-03	9.0E-03	3.5E-02
9 months	1.2E-03	5.6E-03	1.7E-02	1.2E-03	5.6E-03	1.7E-02
Pernicious Anemia Patients						
Early	4.1E-04	1.4E-03	9.2E-03	3.8E-04	1.3E-03	8.2E-03
3 months	3.6E-04	1.3E-03	7.2E-03	3.4E-04	1.2E-03	6.5E-03
6 months	3.2E-04	1.3E-03	5.1E-03	2.8E-04	1.1E-03	4.5E-03
9 months	1.5E-04	7.2E-04	2.2E-03	1.5E-04	7.1E-04	2.1E-03

The results derived from the model of Section V show that effective placental activity deposition are about 10 times the fetal activity and that little decrease occurs after uptake. This agrees well with the results of studies in animals. The ratio of the concentration of gallium in the fetus at term to the concentration in the maternal total body immediately after injection, as derived from this model, would be about 0.85, which fits well with the model of other tissue values.

The values calculated from this model for fractional deposition and retention in parts A and B of tables of Appendix C; resulting dose rates and cumulated doses to the embryo/fetus are given in parts C and D. These values are shown in Table C4 for ^{66}Ga (9.5 hours), in Table C5 for ^{67}Ga (3.26 days), and in Table C6 for ^{72}Ga (14.1 hours). Doses to the embryo/fetus from ^{68}Ga are not presented because the short half-life of 68.1 minutes would not allow significant placental transfer.

Watson established residence times from her model and used mathematical models of the pregnant woman (Watson 1992a) to calculate the radiation dose at the end of the first, second, and third trimesters. Her results are given in Table 11 as a basis for comparisons.

6. Rubidium

The characteristics and biological behavior of rubidium as a general radionuclide were described in Section V. Rubidium radioisotopes are used for clinical evaluations such as cardiac function and muscle metabolism. From

Table 11. Estimated absorbed doses for the embryo/fetus from intravenous administration of radioactive gallium citrate, mGy/MBq, administered to the mother (from Watson 1992; corresponding doses in traditional units, rad/μCi, are shown in parentheses below each entry)

Target Organ	^{66}Ga	^{67}Ga	^{68}Ga	^{72}Ga
Embryo (0 through 2 mo)	2.5E-1 (9.3E-4)	9.6E-2 (3.6E-4)	1.9E-2 (7.0E-5)	3.1E-1 (1.1E-5)
Fetus (End of 1st trimester)	2.1E-1 (7.8E-4)	1.6E-1 (5.9E-4)	1.2E-2 (4.4E-5)	2.1E-1 (7.8E-4)
Fetus (End of 2nd trimester)	1.8E-1 (6.3E-4)	1.5E-1 (4.8E-4)	1.2E-2 (4.4E-5)	2.1E-1 (7.0E-4)
Fetus at term	1.7E-1 (6.3E-4)	1.3E-1 (4.8E-4)	1.2E-2 (4.4E-5)	1.9E-1 (7.0E-4)

a general radiation protection standpoint, the isotopes of greatest interest are ^{84}Rb and ^{86}Rb. These radionuclides, which have half lives of 32.8 days and 18.7 days, respectively, formed the basis for the biokinetic model that was presented in Section V. The calculated values for stage-related initial deposition and subsequent retention fractions of ^{86}Rb in the embryo/fetus were presented in Table A16, and the corresponding dose factors were given in Table B12.

Rubidium is a natural constituent in the human body and it is almost completely absorbed from the gastrointestinal tract. Based on metabolic considerations and similarities to potassium, the metabolic and biokinetic models for rubidium during pregnancy anticipate that there is continued exchange among compartments, there is a steady-state condition, and clearance or growth of the embryo/fetus would be compensated by transfer from the woman.

Pertinent findings are that intravenously injected ^{86}Rb is nearly 100% extracted after 20 seconds into almost every organ and that, with the exception of the parenchymal organs, significant changes occur in the blood distribution of the individual organs in the fetus and in the normal living and hypoxic newborn (Saperstein 1958, Boda et al. 1971).

The ICRP (1980) assumed that 25% of rubidium leaving the transfer compartment is deposited in the skeleton and the remainder is distributed uniformly throughout all other organs and tissues. All rubidium translocated to tissues of the body is assumed to be retained with an overall biological half-time of 44 days or with components of 5% (5 days) and 95% (60 days). The biological retention values are of relatively little consequence because the isotopes of clinical relevance are the short half-lived ^{81}Rb and ultrashort ^{82}Rb. The ICRP (1980) assumed that the 2.1 x 10^5 year half-lived ^{81}Kr that is formed by decay of the 4.6-hour ^{81}Rb will escape from the body before decay. The other isotope, ^{82}Rb, with a half-life of 1.3 minutes, would not be of consequence for radiation dose to the embryo/fetus.

7. Indium

Two short-lived radioisotopes of indium are routinely used in nuclear medicine. One of these, ^{111}In (2.8-day

half-life) is the isotope that was used to derive a general biokinetic model in Section V. Values of initially deposited fraction and retained fraction were given in Tables A21a and A21b. This other radiopharmaceutical, ^{113m}In, has a half-life of 1.7 hours and is used for some types of studies.

As was described in Section V, indium is poorly absorbed from the gastrointestinal tract and fractional absorption, f_1, was assigned a value of 0.02 (ICRP 1980). After intravenous injection, carrier free ionic indium is rapidly bound to plasma transferrin or to a transferrin-like protein which influences its transport and disposition in normal adults as well as in pregnant women. Carrier-free ^{113m}In that reaches the placenta is released from transferrin and accumulates in the placenta but does not cross into the fetal circulation (Wochner et al. 1970). This was also found by Graber et al. (1970) who determined that virtually no indium crossed to the fetus of rats but that large amounts accumulated in the placenta. Mahon et al. (1973) likewise found that the activity concentration of carrier-free ^{113m}In in the placenta at 1 hour after administration to rabbits was more than 800 times that in the fetus. The ratio of activity in an individual placenta to an individual fetus was about 70.

Much of our information on fetoplacental disposition is obtained from-comparisons of the localization and retention of radiogallium and radioindium in pregnant and nonpregnant mice and guinea pigs (Lathrop et al. 1992). They constructed linear compartmental models with associated rate constants and fitted to the data points for nonpregnant and pregnant animals. The patterns from that report were incorporated as a major basis for the biokinetic models described in Section V.

The resulting biokinetic model considers that the initial binding to transferrin is essentially instantaneous and that the partition half-time is 0.25 day. Radioactive indium reaching the placenta is considered to be released from transferrin. Large amounts accumulate in the placenta with the same partition time. Indium does not rapidly cross into the fetal circulation, and conclusions from experiments with short-lived ^{113m}In, to be described below, are not universally applicable.

The fetoplacental component of behavior for biological disposition of the longer-lived radioisotope, ^{111}In (2.8-day half-life), is similar to that of gallium. Both are routinely used in nuclear medicine and have similar models, differing mostly in quantitative values for parameters. The models for placental deposition and transfer to the embryo/fetus were discussed in Section V for indium as a general radionuclide. The corresponding dose factors, which are given in Table C8, present dose factors under clinical conditions and correspond to the deposition values of ^{111}In given in Tables A21a and A21b.

Studies with a near-term dog found 2.5% of the activity remaining at 45 minutes after intravenous injection with ^{113m}In was in the placenta, but less than 0.01% was in the pup (Niehoff et al. 1970). They used these data to extrapolate doses for the human based on an estimated maternal blood volume of 5250 ml with 250 ml in intervillus species, a total uterine blood volume of 1000 ml, and an assumed average uterine radius of 13 cm and a placental radius of 8 cm. Correcting for soft tissue attenuation, they calculated that the total dose from 1 μCi was 36 mrad at 1 cm from the placenta and 3 mrad at 14 cm.

Using these data, Sastry et al. (1976) calculated that at 30 weeks of pregnancy in the human, 0.8% of administered activity crosses the placenta and has an effective half-time equal to the physical half-life of ^{113m}In. Based on blood volumes, they estimated that the placental content of ^{113m}In would be 4.8% of the administered activity and the uterine wall content would be 1.8%. Their estimated dose to the fetus at 30 weeks of gestation was 0.017 rad from administration of 1μCi (0.0046 mGy/MBq), a value that is within the same range.

Indium radioisotopes also have been used to label blood elements such as lymphocytes and platelets for nuclear

medicine procedures. However, no studies have been reported with these agents in pregnant women other than as noted. Any inferences that might be made would be based on data with other radiolabels.

8. Osmium and Iridium

The most commonly encountered isotope of osmium, ^{191}Os, is used in generators to produce ^{191m}Ir for medical imaging. Based on physical properties and potential for exposure, this isotope is relevant to general dosimetry and to this section specifically and has been evaluated for this report. It was described in Section V. Gestational-stage-related fractions initially deposited and remaining at subsequent times in the pregnant woman and in the embryo/fetus are presented in Tables A31a and A31b, respectively. The dose to the embryo/fetus was assumed to consist of the sum of the dose due to photons emitted by the ^{191}Os in the woman's body plus the self-dose from betas and photons emitted by activity in the embryo/fetus. The radiation dose rates and doses to the embryo/fetus are given in Table B26.

Based on physical properties, the beta-gamma-emitting isotope, ^{192}Ir, with a 74-day half-life was used as the generalized form for assessment of embryo/fetus exposure and was selected to perform calculations for illustrative purposes. The gestational-stage-related fractions of ^{192}Ir in the woman and embryo/fetus are shown in Tables A32a and A32b (Appendix A) and the radiation dose rates and doses to the embryo/fetus in Table B27 (Appendix B).

The isotope of iridium that is used in nuclear medicine for radionuclide angiography, ^{191m}Ir, has a 4.96-second half-life. There would not be adequate time for placental transfer or internal dose to the embryo/fetus.

9. Thallium

Thallium is used in industry, as rat poison, and is a trace environmental toxic pollutant. Radiothallium is used in nuclear medicine imaging for determination of cardiac perfusion.

Thallium is a normal trace constituent of the human body and is readily absorbed from the gastrointestinal tract as the sulfate or nitrate. Thallium is uniformly distributed throughout the body except for kidneys, which contain about 3 % of the activity. The biokinetic model assumes that the element is instantaneously translocated from blood. Except for kidneys, which contain about 3% of the activity, the remaining 97% is uniformly distributed throughout all organs and tissues. Thallium is considered to be lost from all tissues with a biological half-life of 10 days (ICRP 1981) or with two half-lives: 7 days (63%) and 28 days (37%).

Based on the uniform distribution, the embryo is considered to be at the same concentration as the uterus during the first 2 months of gestation. The average concentration of the fetus is at one-half of the woman's concentration initially; activity is then lost with the same biological half-life of 10 days.

The most relevant thallium radioisotope for evaluating exposure of the embryo/fetus is accelerator-produced ^{201}Th, which decays by electron capture with a half-life of 73 hours. The stage-related values of the chloride, which is in clinical use, was used in Section V to model behavior and calculate deposition and retention. The gestational-stage-dependent values of deposition and retention of ^{201}Th are shown in Table A33a for the pregnant woman and in Table A33b for the embryo/fetus. The gestational-stage-dependent dose factors for the embryo/fetus are shown in Table B28 (Appendix B).

F. Operational Approaches to Dosimetry of the Embryo/Fetus

1. Estimating Activity Burden

Determining a basis for calculating estimated dose to the embryo/fetus from maternal burdens or intakes from

radiopharmaceuticals should be readily accomplished because of the administration procedures (see Section VIII for assumptions). The agent and its radioisotopic label usually will be known, as will the date and time of intake and stage of gestation. Maternal characteristics, including weight, physical condition, and disease, and interventional measures will have been established, and measurements or imaging associated with the specific test may have been performed.

Maternal blood samples and external counts may be used to modify available metabolic models for the administered agent although their usefulness will depend on the interval between administration and recognition of the pregnancy. Repeated quantitative measurements and imaging of radioactivity over the maternal abdomen may provide further information concerning the radioactivity burden in the embryo/fetus and its change with time. This information, together with knowledge of maternal radioactivity, could be used to calculate self-dose to the embryo/fetus and dose from maternal radioactivity.

2. Use of Radiation Dose to the Nonpregnant Uterus

The use of radiation doses to the uterus of the nonpregnant woman as a surrogate for dose to the embryo/fetus is presented in Regulatory Guide No. 8.36 (NRC 1992) and discussed in Section VIII of this report. The surrogates are primarily applicable to situations in which simple compounds of radionuclides are ingested or inhaled but prenatal disposition had not been modeled. Concerns that were expressed about the use of the dose to the uterus as a surrogate for dose to the embryo/fetus are less relevant when applied to radiopharmaceuticals. The minor reservation about dose equivalent is not applicable to radiopharmaceuticals because they are not labeled with isotopes that emit densely ionizing particles. Uterine doses for specific radiopharmaceuticals after intakes by common routes and for relevant medical conditions are provided in ICRP Publication 53 (ICRP 1988).

The greatest reservation related to the fact that committed doses were tabulated while it was the dose during pregnancy that was of interest. Because radioisotopes with relatively short half-lives are used in nuclear medicine, the numerical values for these two doses will be essentially the same. The uterine doses, which are calculated as the sum of doses from photons and nonpenetrating emissions, are appropriate measures of the dose to the embryo during early pregnancy.

3. Uncertainties in Dose Estimates

The most prominent source of uncertainty involves the inadequate information about the placental transfer of pharmaceutical agents and their radioisotopic label and their disposition by the embryo/fetus. Because of their large numbers and diverse behaviors, radioiodine-and technetium-labeled pharmaceuticals provide primary examples of the need for special evaluation. Beyond placental transfer and metabolic factors, radiation dose is influenced by the degree to which the label is present as a free ion or released during in vivo degradation of the pharmaceutical.

Dosimetric allowances have been made for many of the known differences in the biokinetics of radiopharmaceuticals in disease states and for interventions associated with the diagnostic procedures. For example, separate calculations account for the clinical situations associated with the use of radiocobalt-labeled vitamin B-12. However, there are other conditions, such as the increased total body residence time of radioiodine-labeled hippuran in persons with bilateral renal impairment, that have not been formally considered in intrauterine dosimetry. In situations of that sort, the photon dose to the embryo/fetus could be increased by a factor of 10, which, according to the ICRP, is the factor

by which the clearance rate is reduced and the total body retention is increased.

4. Boundary Estimates

When data suggest that there is radioactivity in the embryo/fetus, expanded models allow inclusion of self-dose from nonpenetrating radiations. A major uncertainty arises when it is not known whether and to what extent such an adjustment should be made. To establish boundary conditions or estimates of maximal possible doses for selected instances, therefore, worst-case assumptions were made about placental transfer of the radioisotopic label and its location in the embryo/fetus.

Excess stable iodide routinely is administered to reduce thyroid uptake and accelerate excretion of extraneous radioiodide present in or released from radiopharmaceuticals. This situation is assumed in biokinetic modeling, so most calculations are based on negligible radioiodide in the fetal thyroid. Moreover, for injected radioiodinated serum albumin and hippuran, considered here, the models do not include placental transfer of the radiopharmaceutical. Thus, the dose factors for ^{131}I are 1.0×10^{-3} rad/μCi and 1.9×10^{-4} rad/μCi, respectively, for the 3-month fetus; similar doses would pertain at later stages. One set of boundary conditions is represented by the doses to the embryo/fetus from the mother's intake of sodium ^{131}I-iodide at 3 and 6 months of pregnancy. These values, 6.7×10^{-4} rad/μCi and 3.0×10^{-3} rad/μCi, are not markedly different from the modeled doses.

Another set of boundary conditions may be given by the fetal thyroid doses corresponding to the total fetus doses. These two doses are essentially identical for the 3-month fetus for either of the iodinated compounds. The corresponding thyroid radiation doses from iodide are 0.46 rad/μCi and 2.4 rad/μCi, for administration at 3 and 6 months of gestation. These are almost 1000-fold larger than the total body doses for administration of iodide at these times.

As a parallel consideration, the boundary condition for ^{99m}Tc-labeled compounds may be regarded as doses to the embryo/fetus or its thyroid gland from sodium pertechnetate. Because of the short physical half-life of ^{99m}Tc and the pattern and kinetics of distribution in the adult, pertechnetate delivers a radiation dose to the adult thyroid that is about three times the dose to the uterus. The uterine dose was used to calculate embryo/fetus dose so that this lack of a markedly elevated thyroid radiation dose should also be applicable to the thyroid of the embryo/fetus. Moreover, most of the pharmaceuticals would not be expected to undergo rapid placental transfer so that the total activity reaching the embryo/fetus would be further restricted by the 6-hour half-life. Preliminary surveys have not determined any agents that should be expected to pose a significant requirement for special analysis.

VIII. ESTIMATION OF EMBRYO/FETUS DOSE IN RADIATION PROTECTION PRACTICE

A. Identification of Operational Needs

Operational health physicists suggested that this report provide information formats that would facilitate compliance with regulations and recommendations, guiding them through operational situations. Another suggestion was to provide control levels that related to values derived from objective criteria, consolidating the degree of placental transfer and the fetoplacental concentrations. These could be related to the potential for exposures to these radionuclides in their usual chemical forms, route, and pattern of intake. Thus, tables could be compiled to facilitate interpolation, extrapolation, and calculation, especially for materials with inadequate information.

Beyond those given in preceding sections, there are a number of formats for presenting dose factors for the radionuclides in the physical or chemical forms in which they may be encountered. Certain of these formats are more amenable to use in operational radiation protection situations. Additional approaches can be used to obtain approximate values of comparable dose factors for the wide range of radionuclides and forms for which biokinetics in the embryo/fetus have not been established. The more straightforward approaches include relating maternal intakes prior to or during pregnancy with the radiation doses that would be received by the embryo/fetus throughout the remainder of gestation.

One of the practical situations that may be encountered involves determining radiation dose to an embryo/fetus from chronic maternal intakes of radionuclides by inhalation or ingestion during pregnancy. Another situation relates to radionuclide burden in the woman prior to the time at which her pregnancy begins. It could be assumed in either situation that internal doses to the embryo/fetus ordinarily would be related to maternal intake, which is restricted in terms of the ALI. Accordingly, dose factors that are given relative to fractions or multiples of ALI might be useful. Such relationships also could provide a basis to estimate radiation doses to the embryo/fetus from maternal intakes of radioactivity from the atmosphere or drinking water, which would be useful to epidemiological evaluations.

A further operational need may evolve from the requirement of 10 CFR 20.1208(d) that if the dose to the embryo/fetus is found to have exceeded 0.5 rem (5 mSv) or is within 0.05 rem (0.5 mSv) of this dose by the time the woman declares pregnancy, the licensee must limit additional doses to the embryo/fetus to 0.05 rem (0.5 mSv) during the remainder of the pregnancy. Thus, a licensee may wish to make an a priori determination of intakes that lead to cumulative doses to the embryo/fetus that are not likely to exceed the specified 0.05 rem.

Additional calculations have been performed for the most common physical and chemical forms of the radionuclide groupings that are addressed in Section V of this report. Tabulations of results are presented in terms of radiation doses that result from an ALI. Intake levels that would result in a dose of 0.05 rem (0.5 mSv) to the embryo/fetus are also given; these are expressed as fraction of ALI and as activity in μCi. Other tables give results of similar calculations to obtain surrogate dose approximations that are based on values of committed dose equivalent to the uterus.

B. Estimates of Prenatal Dose from Known Maternal Intakes or Burdens

The concepts and methods described in foregoing sections of this report are readily applied to many operational settings. This would be especially convenient for radionuclides and groupings that had been evaluated in sufficient detail for dose factors to be tabulated. The approaches were designed so as to facilitate addressing other radionuclides. General suggestions regarding application of these approaches are summarized below.

Assumptions

- The radionuclide(s) will be known or can be identified.

- The dosimetrist will be able to estimate one of the following:

  -- Integral air concentration of radionuclide exposure in DAC-hours (Derived Air Concentration).

  -- Intake of radionuclide by the woman in μCi (Bq)

  -- Maternal body burden in μCi (Bq)

- The dosimetrist will be able to relate the date(s) of exposure or intake or period of burden to the stage of gestation.

- The dosimetrist will wish to determine either the dose rate at the time of maternal body burden determination or the integral dose to the embryo/fetus following the exposure/intake.

Method

- Determine the date of intake and approximate stage (days) of gestation at intake.

- Compute the maternal radionuclide burden in the conventional way. That is, use biokinetic analysis for radionuclides not amenable to direct (in vivo) bioassay procedures, and employ whole body and/or specific organ counting for those situations where direct bioassay is appropriate.

- Use the procedures and tabulated data from this report to estimate activity in the embryo/fetus and the consequent radiation dose rate at monthly intervals. The dose due to activity in the maternal organs was included in the calculation of tabulated doses to the embryo/fetus and should be included also in calculations for other materials.

  The suggestion for calculations of dose due to activity in maternal tissues is to use the uterus or uterine contents as the target tissue. For doses to the embryo/fetus during the first month of pregnancy, consider the dose to the nongravid uterus. Appropriate mathematical models for the stage(s) of gestation should be used in calculations for radionuclides when available, such as MIRDOSE 3 (Stabin 1996). Dose to the uterus, as a surrogate, can be obtained from publications of the ICRP and other organizations cited in other sections of this report.

- Compute the integral dose for the entire pregnancy.

  When the dose rates are known at different time points throughout the pregnancy, then the total dose estimate would be given by the equation:

$$D\ total = 1/2\ \Sigma\ [R(t_{i+1}) + R(t_i)]\ (t_{i+1}) - t_i) \qquad (17)$$

  where the dose rates (R) and the time (t) differences are given in consistent units. In effect, this equation applies the trapezoidal rule to the integration shown in Equation 7 of Section III.

  The appropriate time spacing for dose calculations are chosen to minimize the error introduced by use of the trapezoidal rule. In most cases evaluated in this report, the dose rates at the beginning of each 30-day postexposure interval were given. As was noted, however, dose rates decrease rapidly for many of the radionuclides. This decrease is sometimes more than an order of magnitude during a monthly period so that use of a 30-day time spacing for integration would significantly overestimate dose. Therefore, unless otherwise stated, one day was the time interval used for calculating the tabulated dose factors. Dose rates for each day (or

shorter time period) were determined by cubic spline-fitting for purposes of integration.

C. Concepts for Use of Annual Limits on Intake (ALI) - Dosimetry and Calculations

1. Basic Concepts

Previous sections described the gestational-stage-dependent methodology and dose factors applicable when radioactivity was introduced as a bolus directly into the maternal transfer compartment. Additional approaches are required to utilize these procedures for evaluating multiple radionuclide intakes during gestation or activity that entered prior to pregnancy. Extending these approaches involves estimating activity that enters the transfer compartment from repeated or chronic exposures through all or significant fractions of gestation or from burdens incurred by the woman before pregnancy.

The ALI provides a convenient and well-defined nominal value of total maternal intake to use for developing tables that relate intakes to burdens and to radiation dose to the embryo/fetus. Chronic exposures can be approximated by a series of intakes corresponding to 1/9 ALI at the beginning of successive 30-day periods of pregnancy. Similar approaches can be used as a basis to develop approaches to evaluate doses from pre-existing body burdens derived from intake of an ALI. The underlying procedure involved multiplying intake or burden by appropriate conversion factors to obtain activity in the transfer compartment.

The above-indicated evaluations were extended to encompass the intake phases or pre-existing burdens to prepare tabulations and to compare results. Many of the calculations are based on the stage-related deposition and retention fractions or absorbed dose factors for radionuclides that were considered in Section V of this report. For other radionuclides, later paragraphs of this section discuss the use of doses to the nonpregnant uterine as surrogates for embryo/fetus dose factors and consider the limitations to these approximations. These surrogates were used as the basis for calculations relative to radionuclides that are not otherwise evaluated in this report.

2. Radionuclide Intakes During Pregnancy

Foregoing descriptions provided the general concepts and approaches to practical situations that require determination of radiation doses to the embryo/fetus from ingestion or inhalation of radioactivity by a woman during pregnancy. Information regarding radionuclides that were evaluated may be extended by building upon the values of deposited fractions and dose factors. Because biological disposition has been described by the behavior of radionuclides in the transfer compartment, i.e., blood, the multiplication of maternal intake by an appropriate conversion constant, gastrointestinal absorption fraction, f_1, or pulmonary transfer fraction, TF_1, will translate intake to activity in the transfer compartment. These values may be used to convert the tabulated values of gestational-stage-dependent fractional deposition and retention in the embryo/fetus and the associated dose factors to perform further calculations.

Values of gastrointestinal absorption factors were presented as part of the descriptions in Section V of this report. It is anticipated that values more recently adopted by the ICRP in Publications 56 and 67 (1989, 1993) will become generally accepted and so were noted in the descriptions for some nuclides. To maintain internal consistency in this report, however, currently accepted blood uptake factors, f_1, for intakes of several forms of these radionuclides are provided in Tables D1 through D4 of Appendix D relating to this section. These factors, as adapted from Federal Guidance Report No. 11 (Eckerman et al. 1988), are the numerical equivalent of the transfer fractions, f_1, that were given in ICRP Publication 30 (1979, 1980, 1981) and ICRP

Publication 48 (1986). In most instances, the maximum tabulated value is shown when more than one was available.

a. Routes of Intake

The gastrointestinal absorption factors that were used to calculate stage-dependent dose factors for ingestion of the selected radionuclides are listed in Tables D1 and D3 of Appendix D. Dose equivalent factors for the uterus, as a surrogate for the embryo/fetus, were used to derive estimates for other radionuclides and are tabulated in Appendix E of this report. The results of calculations based on these values provide reasonable estimates in most situations although they are less meaningful than the directly calculated factors for many radionuclides or chemical forms (e.g., see Table D7).

Transfer of inhaled activity from lung to blood is ordinarily approached by the use of ICRP lung models that consider incremental movement and clearance class. A less sophisticated method serves as an adequate approximation for most situations involving gestational exposure. This approach makes general allowance for the behavior of lung clearance classes, but assumes that uptake into blood is instantaneous. The clearance class of radionuclides in their selected chemical forms was determined from Federal Guidance Report No. 11 (Eckerman et al. 1988). Corresponding values of the pulmonary transfer fraction (TF_1) were calculated by using the specific equation for that class and the corresponding value of f_1. Accordingly, different values of TF_1 are used for each of the three inhalation classes to determine activity in blood from activity inhaled:

$$TF_1 = 0.48 + 0.15\ f_1 \text{ for class D}$$
$$TF_1 = 0.12 + 0.51\ f_1 \text{ for class W}$$
$$TF_1 = 0.05 + 0.58\ f_1 \text{ for class Y}$$

These factors were used to calculate stage-dependent dose factors for inhalation of the radionuclides. These followed the general scheme that was described for ingestion and yielded the results shown in Tables D2 and D4. Surrogates were likewise calculated for inhalation and the values are given in Table E2 of Appendix E to this report. Comparisons of parallel values are provided in Table D8.

b. Simulation of Chronic Intakes

Single intakes, irrespective of whether by injection, ingestion, or inhalation, pertain primarily to exposures that result from accidents or medical administration. Many situations in radiological protection involve repeated or chronic exposures, however, which require extension of concepts and generalization of exposure scenarios. In particular, the ALI may be assumed to be the nominal intake level for each radionuclide and form.

To simulate chronic exposure, the nominal activity was considered as being subdivided into incremental intakes. It was necessary to obtain a balance between sufficiently small increments of intake and the substantial individual uncertainties that are associated with such situations. As a compromise, chronic exposure was approximated by intakes of 1/9 ALI that occurred at the beginning of each successive month of gestation.

These values of ALI and the corresponding dose factors (cumulative dose in the period from exposure to term) provided the basis for calculations related to the representative radionuclides. These dose factors were adjusted by the absorbed fractions from maternal intakes of 1/9 ALI at successive 30-day intervals that correspond to the beginning of months 1, 2, 3, ... 9 of gestation. The sums of all increments from the time of exposure through term were obtained by simple addition and were used for developing Tables D1 and D2.

Similar calculations were performed to derive these complementary intake-dose relationships using uterine dose as a surrogate for other radionuclides for which biokinetic models and dose factors are not yet available. The values of ALI were taken from Federal Guidance Report No. 11 (Eckerman et al. 1988) and usually were

those with the lowest ALI for the selected forms. The resulting values are given in Tables E1 and E2 of Appendix E .

Ingestion. In applying these parameter values to chronic ingestion, the dose equivalent (rem) resulting from the fractionated ingestion of ALI by the woman was calculated. The list of radionuclides and forms considered in Section V was expanded to include insoluble chemical forms, when applicable. Values of ALI and fractional gastrointestinal absorption for these forms of the radionuclides were multiplied by the previous gestational-stage-dependent dose factors to calculate the cumulated radiation absorbed doses from repeated intakes. Accepted values for quality factor (1 for beta or gamma and 20 for alpha) were used to convert radiation absorbed doses to dose equivalents (see Table D1).

The inverse relationships, fraction of an ALI and the ingested activity (in μCi) that would deliver a cumulated dose equivalent of 50 mrem to the embryo/fetus, will often be of interest. These complementary values were also calculated and are presented in Table D1. Using uterine dose as a surrogate for calculations with other radionuclides, parallel sets of derivations were performed to obtain these three intake-dose relationships: dose equivalent per ALI, fraction of ALI, and ingested activity. These calculations were based on the corresponding values of dose equivalent factor so that it was not necessary to make adjustments for quality factor.

Inhalation. Comparable calculations were performed for chronic inhalations of these radionuclides and forms. The approaches were parallel to those used for ingestion, as above, and the list of selections again was refined on the basis of ALI. As was done for ingestion, three complementary expressions of dose (dose equivalent per ALI, fraction of ALI, and ingested activity [in μCi] to deliver a cumulated dose equivalent of 50 mrem to the embryo/fetus) were calculated for these radionuclides and forms (see Table D2).

The corresponding intake-dose relationships were also calculated, as above, for other radionuclides for which biokinetic models and dose factors have not yet been developed. Doses were calculated for all inhalation classes using the ALI values listed in Federal Guidance Report No. 11 (Eckerman et al. 1988). The input values were committed dose equivalents to the uterus per unit intake and the corresponding fractional absorption values from the gastrointestinal tract or lung. As with ingested activity, these calculations were based on the corresponding values of dose equivalent factor, DF_i, so that it was not necessary to adjust for quality factor. The entries for the common inhalation classes of D, W, and Y are identified and segregated in both Tables D2 and D4.

3. Pregestational Maternal Radionuclide Intakes

Another practical need is to establish dose to the embryo/fetus that would result from radionuclide burdens that exist in a woman prior to her pregnancy. Conventional bioassay and biokinetic modeling approaches ordinarily would be used to estimate a woman's burden, which could then be adjusted to the beginning of pregnancy. Metabolic models and information given in documents and reports cited in previous sections of this report could provide quantitative and time-dependent release kinetics from which to estimate the entry of this activity into the transfer compartment.

Although it would be complex, such information could allow calculating placental transfer of radioactivity and its disposition in the embryo/fetus at subsequent intervals throughout the pregnancy. Adequate information and methodologies are not readily available, however, to evaluate the mobilization of most radionuclides throughout gestation or their availability to the embryo/fetus. This situation requires nominal substitutes, and worst-case scenarios were selected to develop conservative evaluations of absorbed dose from pre-existing burdens.

It was assumed that the greatest potential dose to the embryo/fetus would result when the total body burden at the beginning of pregnancy was available for entry into the woman's transfer compartment. Therefore, calculations were based on ingestion or inhalation intake of an ALI immediately before pregnancy, and initial activity in the transfer compartment was taken to be ALI multiplied by the transfer fraction. The dose factors presented in Appendix B of this report can be applied to these radionuclides under these conditions. In most instances, the appropriate dose factor would be the cumulated dose that corresponded to radionuclide introduction on the 0-day of gestation. The cumulated doses to the embryo/fetus occasionally were negligible for injection at 0 days because of interactions between the biokinetics and time of development of embryonic structures. It would be appropriate and most convenient to use the entry for cumulative dose from exposure at the start of the second 30-day period in those cases, although a value could be calculated for an intermediate time.

Based on the foregoing, calculations were made of the dose equivalents to the embryo/fetus that result from intakes of an ALI of the selected radionuclides by ingestion (see Table D3) or by inhalation (Table D4). In addition, the inverse values, fractions or multiples of ALI to deliver 50 mrad (0.5 mSv) during pregnancy, were also calculated and are tabulated. Comparable exposure scenarios and dosimetry may be used for other radionuclides through use of the surrogate dose factors that will be identified below and discussed in Subsection E.

4. Surrogates For Estimation

The foregoing approaches are most relevant to situations involving radionuclides for which embryo/fetus dose factors are available, such as those described in Section V and tabulated in Appendix B to this report. Surrogates provide the required alternative for estimating dose equivalent in situations when other dose factors are not available. Tabulated values of doses to the uterus from internal radionuclides are considered to provide the most general surrogates for dose to the embryo/fetus and are particularly relevant to early embryonic stages.

Details associated with the conversion of uterine committed dose equivalents from activity in the transfer compartment to dose equivalent factors (DF_i) for the embryo/fetus will be addressed in Subsection E, below. Values of committed dose equivalent to the uterus per unit intake were adjusted by the corresponding fractional absorption value to generate an additional set of calculated factors.

These factors, which are tabulated in Appendix E, were calculated for all radionuclides, including those that were evaluated in Section V of this report. Additional calculations were performed to facilitate using these factors to estimate dose for ingested or inhaled radioactivity, as well as to provide a basis for examining relationships among parameters and estimators. This included formatting so that the tables of Appendix E showed the three complementary intake-dose relationship expressions comparable to those used in Tables D1 through D4.

Because the surrogate doses were based on values of dose equivalent factor, DF_i, which includes quality factor, the values represented dose equivalents for intakes of ALI. To facilitate comparisons, the tabulated values of cumulated radiation absorbed dose for radionuclides that were modeled in Section V (Tables D1 and D2) were re-expressed as dose equivalents. These re-expressed values and the corresponding values from Appendix E are tabulated in Tables D7 and D8 of Appendix D. Comparisons between the values calculated from the biokinetic models and the surrogate values will be made in Subsection E.

D. Calculated Dose Factors and Interpretations

The dose factors for the series of radionuclides described in Section V were derived for single direct introductions

into maternal blood, and were calculated for each 30-day interval of pregnancy. The contributions of factors such as route of administration, reproductive status, and gestational stage during the exposure period were incorporated into the calculations from which values were determined. Through use of the approaches described in Subsection C, the results and values from Section V and from Appendix A and Appendix B were incorporated into further calculations to obtain factors relating to exposures by chronic inhalation or ingestion intakes during or before pregnancy.

1. Intakes Of Radionuclides During Pregnancy

a. Ingested Radionuclides

Cumulated radiation doses to the embryo/fetus from maternal ingestion of an ALI were calculated for the expanded series of radionuclide groupings that have been evaluated and are shown in Table D1. The steps used for calculating such doses, based on the approaches described in foregoing sections, are as follows:

1. Chronic intakes were simulated by assuming ingestion of 1/9 ALI at start of each 30-day interval of gestation that encompasses the exposure period.

2. A cumulative dose factor was selected corresponding to a single intravenous injection at each applicable gestational time using values from Appendix B of this report.

3. The cumulative dose factor for each interval was multiplied by absorbed fraction, f_1, to convert ingestion intake of 1/9 ALI to radiation absorbed dose.

4. Values of cumulative dose for each interval were added to obtain total dose.

5. Radiation absorbed doses were multiplied by quality factor (1 for beta or gamma and 20 for alpha) to convert to dose equivalent.

As an operational simplification, the original electronic files used to derive dose factors were manipulated for many of the further calculations involving ingestion or inhalation of these radionuclides. In effect, average stage-related cumulative dose factors were determined by adding the nine individual cumulative dose values and dividing by nine. Multiplication of ALI by these averages provides values that are mathematically and numerically identical to those obtained by the full calculations for exposure during all of gestation. These average dose values and transfer fractions were programmed for direct calculation of the entries to Tables D1 and D2. The resulting dose factors, applicable to chronic intakes throughout pregnancy, are summarized in Tables D5 and D6.

b. Inhaled Radionuclides

Table D2 presents cumulated radiation doses to the embryo/fetus from maternal inhalation of the series of representative radionuclides and forms. The entries for the common inhalation classes of D, W, and Y are identified and segregated in this table. The calculations, which parallel those of Table D1, build upon tabulations of dose factors that are based on single direct introductions into maternal blood. An operational simplification, based on average dose factors, also was used with inhalation for calculations leading to Table D2. The following steps for performing direct, or independent, calculation for inhalation of any of the selected radionuclides or forms differ from those for ingestion only in the use of the transfer fraction:

1. Chronic intakes were simulated by assuming inhalation of 1/9 ALI at start of each 30-day interval of gestation that encompasses the period of exposure.

2. A cumulative dose factor was selected from Appendix B corresponding to a single intravenous injection at each applicable gestational time.

3. The appropriate value of the transfer fraction (TF_1) was calculated from the corresponding value of the absorbed fraction, f_1, and the conversion equation for inhalation class.
4. The cumulative dose factor for each interval was multiplied by transfer fraction (TF_1) to convert inhalation intake of 1/9 ALI to radiation absorbed dose.

5. The values of cumulative dose for each interval were added to obtain total dose.

6. Radiation absorbed doses were multiplied by quality factor (1 for beta or gamma and 20 for alpha) to convert to dose equivalent.

c. Use of Tables D1 and D2 to Find Cumulated Doses from Chronic Intakes

The radionuclides and forms that are characterized in Table D1 are listed in the first and second columns, respectively. Their f_1 values are given in the third column and the corresponding values of ALI are shown in the fourth column. A similar arrangement is used in Table D2, but the inhalation classes are interposed as a third column.

To provide information for chemical forms of general interest and potential importance in operational situations, calculations were performed for additional radionuclidic compounds beyond those evaluated here in detail. Values comparable to ALI were calculated from information provided in Federal Guidance Report No. 11 (Eckerman et al. 1988). It was considered desirable to use common formats for Tables D1 and D2 to facilitate internal and between-table comparisons.

The three right-most columns of Tables D1 and D2 present the results of the calculations designed to facilitate assessment of radionuclide exposures of pregnant women in operational situations. In particular, they provide factors that can be used to determine dose equivalent to the embryo/fetus from chronic radionuclide intakes by a pregnant woman. The third column from the right presents the calculated dose equivalents (rem) that result from ingestion of an ALI under the above conditions.

As noted above, 10 CFR 20.1208 specifies 0.05 rem as the additional increment that should not be exceeded if the dose to the embryo/fetus had exceeded 0.5 rem at the time the woman declares pregnancy. To facilitate determination of this limiting value, the last two columns of these tables give the values inverse to dose per ALI, i.e., chronic intakes that would deliver a cumulative dose equivalent of 0.05 rem (50 mrem). These are expressed in the second column from the right as fraction of an ALI and in the right-most column as the activity (μCi).

d. Explanations and Interactions

Tables D1 and D2 list more radionuclidic compounds than other tables. The increased numbers of materials reflect the fact that many radionuclides may enter the body in a variety of soluble compounds or as insoluble forms with differing behavior. Ingested tritium is included as sugars or amino acids and cobalt isotopes are included as vitamin B-12 because the form in blood is the same as that ingested; they are omitted from Table D2 for practical considerations.

As suggested by entries in both tables, route-related differences pertain to the alkaline earths, strontium/yttrium, ruthenium/rhodium, and heavy elements such as uranium and plutonium. The transfer fractions (f_1) of these forms may differ, as is also involved in differences among the corresponding values of ALI. The solubility differences that pertain for inhaled forms of the heavier radionuclides are more prominent than for ingestion, but the insoluble forms were not included under oral ingestion in 10 CFR 20.

Other intuitively obvious comparisons and patterns among the results may be noted. Similar quantitative behaviors among isotopes of an element lead to similar values of fractional uptake from the gastrointestinal tract or lung, but half-life differences may affect differences in biological disposition. Other factors include the effects of solubility on entry into the transfer compartment and, accordingly, on the ALI. Placental transfer is not directly related to transfer fraction, so that the time course of activity in the conceptus may differ from that in the woman.

Differences among half-lives of isotopes of an element also lead to differences in biokinetics, fractional deposition, and retention in the embryo/fetus. Likewise, interplay between the energy of emissions and physical dimensions is responsible for different relationships between the deposited fraction of the energy in the woman and in the conceptus. In turn, the relationships between absorbed activity and radiation dose may vary among isotopes of an element in a given physical or chemical form.

Calculations in Tables D1 and D2 employed the maximum values of f_1 derived from Federal Guidance Report 11 (Eckerman et al. 1988) and ICRP Publication 48 (ICRP 1986). Values of ALI and f_1 were rounded to one significant figure in the original documents. Multiplication of these numbers by derived factors, such as constants used to obtain TF_1 for inhalation or the dose factors given here, occasionally led to slight distortions of relative dosimetric values. An analogous uncertainty of ± 1 in the single-digit significant figure also is attributable rounding values when used for calculating entries to Tables D3 through D6. The slight inaccuracies in factors that can also lead to minor inconsistencies among entries in tables should be ignored. There were no adjustments to account for rounding when the resulting differences were a single figure or there was not a reversal between entries in the two tables. When particularly egregious discrepancies were noted, comparable calculations were performed using the underlying data to obtain the values that were tabulated.

It might be expected that because the ALI is determined from the committed effective dose equivalent limit, the dose to embryo/fetus per ALI should be the same for similar isotopes in a given chemical form. However, doses to the embryo/fetus for ^{134}Cs and ^{137}Cs differed. The tables show differences among dose factors for forms and isotopes that evolve from biokinetics and physical constants. Comparable differences in retention and dose factor are found in the tables of Appendixes A and B but they are rarely apparent because there are not occasions for direct comparison. This apparent discrepancy identifies other considerations that deserve explanation.

Because of the impact of their different half-lives on biokinetics, the retained fraction of activity in the embryo/fetus decreases more rapidly with ^{134}Cs than with ^{137}Cs and results in a greater difference from the maternal pattern (see Tables A27 and A28). The disparity between the relative retention of the two isotopes is partially obscured by effects attributable to decay pattern, energy per emission, and absorbed fraction of emissions. The interplay among these several factors leads to the differences between corresponding dose factors in Tables B22 and B23. The differences noted in Tables D1 and D2 result from an almost two-fold difference between the underlying average dose factors, 8.6E-02 and 4.5E-02, which were used for calculations with the two isotopes (see Tables D5 and D6).

Most other results in Tables D1 and D2 generally are internally consistent and in accord with other descriptions. Nevertheless, there will be differences in entries for isotopes or forms of elements that may, upon first inspection, seem to be discrepancies or errors of calculation or tabulation. However, as with the difference between ^{134}Cs and ^{137}Cs, reasonable and instructive explanations may be found.

There is agreement between the complementary dose factors for ingestion and inhalation of tritium or carbon during pregnancy but differences between the dose factors for tritiated water and for organic tritium as a sugar

or amino acid. The biokinetic models predict significant retention of organic tritium as persistent compounds in the embryo/fetus compartment (see Section V). This persistence results in a higher absorbed dose than that for tritiated water, which is cleared with a 10-day half-life.

There are marked differences between the doses per ALI to the embryo/fetus from maternal ingestion of the two forms of ^{89}Sr even though the tabulated ALIs are similar. The ALI value for insoluble forms ($f_1 = 0.01$) is nonstochastic and is based on dose to the woman's intestinal wall. Little of this activity enters the transfer compartment and becomes available for placental transfer. The soluble form ($f_1 = 0.3$) is associated with a stochastic ALI and a substantially greater fraction of the activity is transferred to the embryo/fetus. There are several-fold differences between the inhalation ALI values for the two forms of both ^{89}Sr and ^{90}Sr /^{90}Y, some of which are stochastic and others nonstochastic. The magnitudes of the differences among the corresponding embryo/fetus doses per ALI are even greater by as much as tenfold. There are comparable differences between the oral ALI values for soluble $^{90}Sr/^{90}Y$ tabulated in 10 CFR 20 and the derived value for the insoluble form. Nevertheless, differences in absorption lead to there being little difference between the doses per ALI.

Finally, the time course of metabolism, such as uptake of the radioiodines by the fetal thyroid, must be taken into account in interpretation of results. This temporal factor can have a significant influence by permitting relatively greater placental transfer and localization in the thyroid of longer-lived radioiodines. This affects the fraction of radioactivity intake in the fetus, but it does not lead to relative doses that are completely monotonic with half-life. The departure from a simple pattern reflects variations among the energies of the beta particles emitted by the several isotopes, as well as the associated gamma energies per decay.

2. Pre-Existing Radionuclide Burdens

Doses to the embryo/fetus also may derive from radionuclide body burdens that remain after ingestion or inhalation intakes of radioactivity by a woman before she became pregnant. Conventional bioassay and biokinetic modeling approaches will serve to estimate the woman's burden at the beginning of pregnancy. Further modeling to account for mobilization of this activity and its entry into blood, placental transfer, and deposition and retention in the embryo/fetus usually will be complex.
The use of substitutes to obviate the need for more sophisticated determinations was also described. The resulting approach, which was used to calculate the values given in Tables D3 and D4, can be employed to provide conservative or worst-case estimates of absorbed doses to the embryo/fetus. The scenario considers that the total body content at the beginning of pregnancy is available for uptake to the woman's transfer compartment and that this radioactivity is transferred instantaneously. Consequently, the initial activity in the transfer compartment is calculated as the ALI multiplied by the transfer fraction relating to the ingestion or inhalation intake.

The dose factors in Appendix B are also applicable to dosimetry of these radionuclides under these conditions. In most instances, therefore, the corresponding dose factor was taken to be the cumulated dose for radionuclide introduction on 0-days of gestation. Because of interactions between the biokinetic model and time of development of structures in the embryo/fetus, in some instances the cumulated doses to the embryo/fetus were negligible following introduction at the start of the first month of gestation. In these cases, the entry for cumulative dose for exposure at the start of the second month can be used instead.

a. Ingested Activity

Dose to the embryo/fetus was calculated under the assumption that total body burden at the beginning of pregnancy was available for uptake to the woman's transfer compartment. This situation was simulated using ingestion of an ALI immediately prior to pregnancy. Thus, the resulting burden corresponded to ALI multiplied by the transfer fraction from the gastrointestinal tract; this was taken as being present in the transfer compartment. Radiation absorbed dose was obtained by multiplying this content of radioactivity by the corresponding dose factor.

The dose factor usually was taken to be the cumulated dose associated with introduction of the radionuclide in its indicated form on 0-days of gestation. In some instances, the biokinetics were such that the cumulated dose for the first month was negligible; in these instances, the entry for the second month was used instead. Multiplication by values for quality factor (1 for beta or gamma and 20 for alpha) was used to convert radiation absorbed doses to dose equivalents. The inverse relationships, i.e., the fraction of an ALI and the ingested activity (in μCi) that would deliver a cumulated dose equivalent of 50 mrem to the embryo/fetus, were also calculated and are presented in Table D3.

The foregoing approach is directly applicable only when dose factors are available, such as the radionuclides considered in Section V. In other situations, dose equivalent to the embryo/fetus would be estimated as the product of maternal burden and a dose equivalent factor.

b. Inhaled Activity

The scenario used to evaluate dose corresponding to a burden from inhalation of an ALI prior to pregnancy paralleled the approach for ingested activity. Inhalation of an ALI immediately prior to pregnancy was assumed; thus, the resulting burden corresponded to the ALI multiplied by the inhalation transfer fraction, and total body content at the beginning of pregnancy was available for uptake to the woman's transfer compartment. Thus, the resulting burden corresponded to ALI multiplied by the transfer fraction from the lung. This activity was taken as being present in the transfer compartment and absorbed dose was obtained by multiplication by the corresponding dose factor.

It also was assumed that intake occurred during the first month of gestation so that the corresponding dose factor was the cumulated dose for radionuclide introduction on 0-days of gestation. In instances in which cumulated dose was negligible for the first month, the entry for the second month was used instead. Values of 1 for beta or gamma and 20 for alpha were used to convert radiation absorbed doses to the tabulated values of dose equivalent (Table D4). The corresponding inverse relationships, i.e., the fraction of an ALI and the inhaled activity (in μCi) that would deliver a cumulated dose equivalent of 50 mrem to the embryo/fetus, were also calculated and are presented in Table D4.

c. Use of Tables D3 and D4 to Find Cumulated Dose from Pre-Existing Burden

Tables D3 and D4 show the results of dosimetric analyses associated with pre-existing burdens of the expanded lists of radionuclides and forms. The resulting dosimetric results for the embryo/fetus are given in the three right-most columns. The value of ALI is shown for each form (compound and class) of each radionuclide to facilitate comparisons with the parallel descriptions given for Tables D1 and D2.

The last two columns of Tables D3 and D4 provide complementary information in terms of the inverse values to dose per ALI. These are the full burdens from simulated intakes at the inception of pregnancy that would deliver a cumulative dose equivalent of 0.05 rem (50 mrem). These are shown in the second column from the right as fraction of ALI, and the right-most column presents the same values expressed as activity (μCi). The information in these columns should facilitate determination of this limiting value and may be useful in operational situations.

d. Explanations and Interactions

In the discussion of Tables D1 and D2, it was noted that the use of the rounded values of ALI could lead to apparent discrepancies in relationships among the dosimetric values for some radionuclides. Unrounded values of ALI were employed for calculation in these cases to obviate confusion. Analogous perturbations were found to occur through rounding of values that were used for calculating entries in Tables D3 and D4. For consistency, when unrounded values had been employed for Tables D1 and D2, the same values were used for Tables D3 and D4.

The relationships considered for chronic exposure in the preceding section are further illustrated and emphasized by comparisons based on these tabulations. As is to be expected from the basis for estimation, there is reasonable agreement between relative doses from burdens resulting from ingestion and inhalation of tritium, carbon, and cesium isotopes prior to pregnancy. The pattern of calculated doses are in general accord for these materials, all of which are uniformly distributed, have relatively simple biokinetic models, and readily cross the placenta. Moreover, about 1% of ALI or more is required to yield the limiting dose of 0.05 rem.

Agreement is not as good among entries relating to cobalt, strontium, and iodide, where there are more complex differences relating to absorption, biokinetics, placental transfer, half-life, and dosimetry. However, fractional

activities of greater than 0.01 ALI of these radionuclides are required to obtain the 50-mrem dose. There is good correspondence among values for isotopes of uranium and of plutonium after ingestion, but values for inhaled uranium are further affected by the isotope, form, and route. Nevertheless, prototypic pregestational maternal intakes in excess of a full ALI of these isotopes of uranium, plutonium, or americium should give cumulated doses to the embryo/fetus of less than 0.05 rem.

E. Radionuclides Not Otherwise Considered

1. Concepts in Use of Uterine Doses as Surrogates

The use of the nonpregnant uterus or uterine contents at selected gestational stages as surrogates for the embryo/fetus has been considered in detail. For radionuclides that had not been otherwise evaluated, calculations that relate intake of radioactivity to radiation dose are tabulated in Appendix E of this report. Beyond the tables developed here, compilations of specific absorption fraction are available that can be used to develop other estimates. The validity and accuracy of using values of uterine dose from maternally distributed activity as surrogates for dose to the embryo/fetus warrants consideration, especially for photons. There are stage-related deviations from correlation because target sizes affect geometric relationships and specific absorbed fraction. Similar uncertainties have been noted for the use of the calculated DS86 uterine doses as surrogates for dose to the embryo/fetus in Japanese people exposed in utero to atomic bomb radiation.

Clearly, the location and dimensions of the nongravid uterus does not provide an accurate representation of the near-term fetus but accuracy is increased by the models of the pregnant woman, by trimester, that have been developed at Oak Ridge (Stabin et al. 1995). Current dosimetric models generally assume the composition to be homogeneous soft tissue. Masses with elevated absorption that assume increasing importance as the fetal skeleton undergoes ossification are a relatively minor source of uncertainty when compared to other assumptions and approximations.

The dosimetric calculations of contributions from maternal tissues that are provided in this report do not all consider localization in structures such as bone, liver, or bladder. It may be shown, however, that this would not

affect the result when the energy of the photons is above 0.01 MeV, irrespective of the complexity of the decay scheme. This would be true also with use of a uterine-content surrogate for the embryo/fetus although the dose contribution from soft photons emitted by radionuclides in maternal tissues would be less accurate in both cases.

The analogous approach for estimating self-dose from localized beta-emitter deposition in the uterine mucosa must be considered. As was discussed in various contexts in the preceding text, approximations that assume equivalence to the concentration of uterine mucosa might be the closest to a reasonably accurate estimate during early embryonic stages. We have calculated estimates of the impact of disparities between uterine and embryonic concentrations. This would range from a two-fold or three-fold overestimate or underestimate, corresponding to concentration differences of the same magnitude.

Another major inaccuracy during early stages would be the precision to which the activity in the uterus or uterine mucosa can be estimated, but there is no basis to generalize these to those in the later fetus. This is most pertinent for radioelements and/or compounds for which such estimations will be mostly required - those for which minimal information is available. As was suggested above, assumption of average uniform fetal activity that is the same as average maternal soft tissue concentration for beta self-dose seems to be the most conservative. But all of the indicated caveats apply! If there is reason to expect skeletal or hepatic localization, however, this might be factored into the scheme, although there seems to be little likelihood of accomplishing this for poorly studied materials.

2. Validity of Uterine Surrogates

Questions will arise as to how well the approximations afforded by committed dose equivalent to the uterus represent the absorbed doses to the embryo/fetus directly calculated from the biokinetic models. As discussed, numerical differences can result from differing time-scale concepts for the underlying committed dose determinations, which form the basis from which the uterine doses are calculated relative to those for absorbed dose from exposure during gestation. The dose equivalent limit is specifically stated as cumulated dose to the embryo/fetus during the 9 months of pregnancy while the committed dose involves total decay in situ and so could extend beyond term. The time periods over which radiation doses are cumulated will be similar when the radionuclides have relatively short physical or biological half-lives, so that differences in expression will not have a detectable impact. For long-lived materials, however, these same factors can lead to overestimates of radiation dose to the embryo/fetus.

a. Single Intakes

It will be obvious that there will be uncertainties and inaccuracies, especially as relates to stage of gestation and the associated metabolic factors. Comparisons show good agreement for materials such as tritiated water that involve uniform distribution and relatively short biological (and thus effective) half-lives. With alkaline earths, such as strontium, an overestimate resulting from the long retention component is counterbalanced by the increasing amounts that enter the conceptus throughout gestation so that there is reasonable agreement of net values.

With many actinides, there is a comparable set of retention and increasing activity factors so that a pronounced diversity in the range of relative values may result. Inasmuch as values for the transuranic elements of greatest interest are tabulated in Appendix D, this will not be a cause for concern. It is suggested, however, that the uterine dose should not be used as a surrogate for other alpha-emitting actinide elements. Instead, greater (but incomplete) accuracy would be obtained by use of the ^{241}Am tabulations, with correction for alpha emission if desired.

b. Chronic Intakes

The surrogate does not account for uptake into fetal organs; as was illustrated by the radioiodines, this distribution difference can lead to higher doses than estimated from the uterus. Another consideration that was also illustrated by the radioiodines is the differing effect that rates of incorporation into and release from the transfer compartment will have for isotopes with either long or short half-lives. This relationship will directly influence relative uterine doses for elements and further allowance must be made for the impact of short half-lives on placental transfer and target-organ distribution.

The differences among the isotopes of chlorine provide a striking illustration of the impact of this situation on the surrogate represented by uterine dose. Although not directly modeled or calculated, it is a logical expectation that these would have an even greater effect on dose to the embryo/fetus. Chlorine-36, with a half-life of 3 x 10^5 years and a 0.27 MeV average beta-particle energy, has a stochastic ALI of 2 x 10^3 μCi while the non-stochastic (stomach wall) ALI for the short-lived isotopes of mass 38 and 39, which have more energetic beta-particles, are 10 times higher or (2 x 10^4 μCi).

Because of the interactions among factors, intake of an ALI of ^{36}Cl would yield a committed dose of 6 rem to the uterus. The times required for uptake from the gastrointestinal tract and for tissue deposition lead to a marked contrast with other isotopes. Thus, the committed dose from ^{38}Cl (1.5 MeV, half-life of 37 minutes) is 0.6 rem, and from ^{39}Cl, which has a less energetic particle and slightly longer half-life (0.8 MeV, half-life of 55.6 minutes) gives a dose of 0.8 rem; both total doses would be delivered within hours after intake. Similar comparisons pertain to inhaled uptakes of these isotopes. Moreover, the comparable differences among isotopes of several other elements that are evident throughout Tables E1 and E2 are amenable to similar explanations.

3. Comparison of Results: Direct, Surrogate, and Maximized Dose Calculation

Tables D7 and D8 were prepared to facilitate comparison of the direct and surrogate approaches to determining embryo/fetus dose. The doses listed in column 3 (Table D7) or column 4 (Table D8) of these tables (expressed as rem from ingestion or inhalation of 1/9 ALI at the beginning of each 30-day period of gestation) are those also given as dose per ALI in Tables D1 and D2, respectively, of this report. The following columns in Tables D7 and D8 repeat the corresponding values of dose to the uterus given in Tables E1 or E2. The following column in Tables D7 and D8 presents the ratio of the directly calculated doses to the embryo/fetus to the uterine dose.

The listings of radionuclides are truncated from those of Tables D1 and D2, being restricted to those for which all three dose values were available. This still allows inclusion of separate entries for tritium as water and in organic form and inhalation of elements with markedly different solubilities and inhalation classes. Where feasible, doses for the maximum value of DF_i were used and their chemical forms are listed.

Radionuclides and forms with reasonable agreement include ^{3}H (both as water and organic compounds). As was noted for Tables D1 and D2, organic compounds give a higher dose because their metabolites are retained in the embryo/fetus, while tritiated water is cleared with a 10-day half-life. The differing retentions are a consequence of high rates of structural protein synthesis in the embryo/fetus, which does not apply to organs such as the uterus. Discussion was provided above to explain the interplay between retention and embryo/fetus dosimetry that followed intakes of ^{134}Cs relative to ^{137}Cs. These considerations relate equally to the embryo/fetus and to the uterus, so that the ratios are similar.

There are marked differences between dose to the embryo/fetus and the uterus from soluble and insoluble forms of ^{89}Sr. Dose factors presented in Table D9 differ by a factor of three, depending on the time of intake resulting from stage-dependent differences in deposited fraction. The dose factors are much higher than for the uterus subsequent to the first two months of gestation. Because each gestational-stage-dependent dose factor contributes equally to the final dose factor, the pattern results in a higher dose to the embryo/fetus than to the uterus.

The ratios are nearly zero for $^{106}Ru/^{106}Rh$. As noted in the discussions of Tables D2 and D3, the literature showed that placental transfer was negligible but the initial fetal concentration was assumed to be 10% of that in the pregnant woman to provide a nominal value for activity. Thus, essentially none of the activity was present in the embryo/fetus. This distribution pattern, together with the high energy of the rhodium beta particles, leads to much higher doses to the uterus than to the embryo/fetus.

The radioiodines also yield disparate doses because their high uptake by the fetal thyroid in later gestation leads to substantially higher fetal doses than doses to the uterine surrogate. This interacts with additional time for placental transfer and thyroid localization of isotopes with longer half-lives, but the relative doses are not monotonic with half-life. The departure from a simple pattern reflects variations among the energies of the beta particles and gammas of the several isotopes, and the associated impact on absorbed fractions for direct calculation of doses to the embryo/fetus and the uterine surrogate.

For uranium, plutonium, and americium, the underlying model does not assume any clearance after the radionuclide has been deposited in the embryo/fetus. Also, initial fetal concentrations are assumed to be 1.5 to 3 times higher when the intakes occur subsequent to two months of pregnancy although this factor is compensated by growth of the embryo/fetus. The results show a reasonable agreement between uranium doses to both the embryo/fetus and the uterus. For plutonium and americium, the new f_1 values of ICRP Publication 48 (ICRP 1986) were used for the prenatal dose calculations, which leads to disagreement of a factor of 10, as shown for both ^{238}Pu and ^{239}Pu. In the model for ^{241}Am, however, the fetal concentration is assumed to be one-fifth that for plutonium, which led to less disagreement. Similar explanations pertain for the differences with inhalation of these elements (Table D8).

The two columns on the far right of Tables D7 and D8 present a third set of dose estimates, maximized dose to the embryo/fetus, which allow examining the impact associated with a simplification in Regulatory Guide 8.36 (NRC 1992). Comparable doses were calculated for each radionuclide on the basis of the maximum dose factor tabulated in Appendix B to this report. The ratio of the directly calculated dose to this maximum dose is given in the right-most column. In some instances, a ratio of 1 or slightly less is shown although it is often in the range of 0.5. Such relationships are expected and confirm that the simplification will yield conservative estimates of dose.

IX. CONCLUSIONS AND RECOMMENDATIONS

A. Radionuclide Content and Radiation Dose Factors

Inadequate quantitative information about fetoplacental disposition of radionuclides following intakes during pregnancy resulted in uncertainties about calculating radiation doses to the embryo/fetus from internally deposited radionuclides. These uncertainties led to this project, which was undertaken to locate and interpret available information and to develop recommendations to the NRC for calculating of radiation doses to the embryo/fetus from internal radionuclides.

Comprehensive quantitative data was limited, as expected; the amount of information was more extensive than anticipated and had not been fully utilized. Qualitative reports also were located and these yielded coherent patterns that were expanded by incorporating knowledge of general placental and fetal physiology. Moreover, published biokinetic models and dose factors for radionuclides in human adults and children provided an accepted foundation on which to build. These baselines were extended through analyses of data and patterns contained in the literature on placental transfer and biological disposition of radionuclides in the embryo/fetus and the pregnant animal or woman. Expanded approaches to using fetal-to-maternal concentration ratios were integrated with dynamic modeling techniques. The combination provided reasonable estimates of prenatal radioactivity levels as a function of time after injection into a pregnant woman.

Groupings of occupationally significant radionuclides, which provided a spectrum of metabolic and dosimetric characteristics, were selected. Biokinetic analyses and modeling provided results that were integrated with data from placental transfer models. These were used to calculate and tabulate radionuclide deposition and retention in the embryo/fetus as a function of gestational age at exposure and elapsed time after exposure.

Comparisons of biological behavior is the embryo/fetus of some radionuclides for which information was available in human and animal pregnancies usually demonstrated agreement, or the data provided rational explanations of differences. Positive responses have been received to interim reports that described methods and results. Taken together, it is concluded that generally accepted values have been obtained from the biokinetic evaluations.

Methodologies described by the Medical Internal Radiation Dose (MIRD) Committee were extended to formalize details for calculating radiation absorbed doses to the embryo/fetus. These formalisms were used for calculations based on a model scenario that assumed a single intravenous injection of 1 μCi of the radionuclide. Calculations provided values of self-dose based on stage of gestation and contribution to radiation dose from activity in the woman, and made allowance for configuration and size of the embryo/fetus and woman throughout pregnancy. Separate calculations were performed for administration at successive months of pregnancy to accommodate stage dependence of geometric relationships and biological behaviors of radionuclides.

These calculations led to tables of gestational-stage-dependent dose factors for the embryo/fetus from several representative maternally administered radionuclides. The approaches to calculation of radiation doses and the resulting dose factors have been accepted by the radiation protection community as providing a useful format and adequate accuracy.

The approaches to calculation suggested in this report yield radiation absorbed dose. For some tabulations and comparisons, absorbed dose was multiplied by quality or radiation weighting factors to convert to dose equivalent. Periodically, suggestions are made that radiation protection needs would be best served if prenatal dose limits were stated in terms of effective dose or comparable expressions, which allow for sensitivities of individual tissues.

It is suggested that use of derived quantities should be deferred because meaningful weighting factors have not been determined for the embryo or fetus. If alternative expressions are desired for specific purposes, the dose equivalent can be multiplied by the selected factors. Further consideration should be given to suggestions that dose limits for the embryo/fetus should be stated in terms of effective dose or conceptually similar expressions. Efforts to determine weighting factors for the embryo and fetus may provide meaningful values but default numbers should be avoided.

B. Radiation Doses from Intakes Before or During Pregnancy

Generalized approaches were developed and factors calculated for use in operational radiological protection situations. This included tables of correlations and relationships, surrogate dose factors, and categorizations, as well as comparisons among estimators. Analyses determined dose factors to accommodate repeated or chronic exposures by ingestion or inhalation. These calculations were based on dividing the total activity that would enter the transfer compartment into nine increments and considering these as being administered at 30-day intervals. These dosimetric analyses of simulated chronic exposures, based on stage-related models, appear to be theoretically valid and to yield acceptable results.

Procedures were proposed for calculating dose factors that related to radionuclide intakes before pregnancy The radioactivity content of the woman was considered to be the amount that entered the transfer compartment after ingestion or inhalation immediately before the start of pregnancy. All of this activity was considered to be present in the transfer compartment and available for transfer to the embryo at the beginning of pregnancy.

This approach provides a convenient basis for operational health physics decisions, but it involves theoretical objections and practical limitations. The approach was expected to yield conservative estimates of radiation dose to the embryo/fetus.

These scenarios for dosimetry of pre-existing radionuclide burdens were not evaluated in detail and validations were not performed. A potential deficiency is that radiation dose from a gradually accessed burden would be more meaningful, and might be greater than if all activity were available at conception. Evaluations to seek improvement of approaches might be useful.

Results of calculations were made amenable for operational purposes by converting repeated or pre-existing doses to expressions of stage-related dose equivalents in terms of ALI and determinations of dose equivalent per ALI. Comparisons showed reasonable agreements among ALI-related approximations for most radionuclides. Explanations are apparent for situations where there was not reasonable agreement.

Operational predictors also employed tabulations of committed dose equivalent factors for the uterus for developing estimators for ingestion or inhalation of radionuclides that lacked biokinetic models. These uterine dose estimators were compared with directly calculated dose factors and usually showed acceptable agreement. More detailed analysis and enhancements and amplifications of approach are needed.

C. Additional Considerations

1. Residual Activity at Term

There is interest in the radiation doses during postnatal life that would result from radioactivity that was present at birth. The fractions of prenatally acquired radionuclide burdens that are retained at birth were thought to provide a useful baseline for such evaluations. Accordingly, gestational-stage-related information, which was tabulated as fractional retention values at 270 days of gestation in tables of deposition and retention, was assembled into an overall summary.

In addition to providing the needed data, the summary reinforces general patterns that were seen in the evaluations. There are marked differences among radionuclides in the fractions present in the term fetus after injection into a pregnant woman. Stage of gestation at the time of maternal administration plays a major role in deposition and retention.

2. Radiation Dose during Postnatal Life

Despite interest in the lifetime radiation doses that would be received from this residual radioactivity at birth, methodologies have not been defined for calculations of meaningful values. Approximations were attempted on the basis of ICRP models and tables of effective dose for intakes of radioactivity by the 3-month infant. Values of effective dose through age 70 (converted and expressed as rem per μCi intake) were combined with the corresponding age-dependent values for fractional absorption from the gastrointestinal tract, the above-indicated values of frac tional retention at birth, and the nominal 1 μCi of radioactivity that was considered to be introduced into the woman's transfer compartment.

The results for postnatal doses (in rem per μCi injected into the woman) roughly correspond to effective dose equivalent or effective dose, as used in ICRP Publications 56 and 67. The large number of assumptions and far-reaching extrapolations required for these calculations suggest that such efforts toward postnatal dose may be premature. These concepts should be evaluated further so that the calculation of useful approximations is improved.

3. Implications of Localized Deposition

The importance of localized deposition of radioactivity in the embryo/fetus was demonstrated relative to the dynamics of placental transfer. These considerations pertain especially to radioiodine in the thyroid and to radionuclides that deposit in fetal bone. The ratio of concentration in developing bone relative to that in soft tissues changes with stage of gestation and these relationships differ quantitatively among radioelements that have such inhomogeneous distribution. These factors also affect dosimetric interactions with structures of the embryo/fetus and the placenta, and overall dose rates and radiation doses during postnatal and intrauterine life.

Because a primary objective of the project was to provide information and methods that would help radiological protection professionals comply with recommendations and regulations, the approach taken for all radionuclides was to provide radiation dose to the entire embryo/fetus. Inhomogeneities become especially important when there are markedly elevated concentrations in specific organs or tissues, when physical characteristics will affect the dosimetry, or when there is interest in radiation dose to specific prenatal tissues because of the possibility of effect.

Postnatal doses from many radionuclides that are retained at birth following prenatal exposure are related to deposition in specific tissues. These tissues might be of greatest interest in regard to effect although methods are not yet available for quantitative dosimetric evaluation.

However, this situation emphasizes the desirability of efforts to consider these tissues in prenatal dosimetric evaluations.

Attention also should be directed to the high localized concentrations in the developing placental structures and membranes. It is during embryonic stages that deposition in the yolk sac may result in significant radiation doses to hematopoietic and germinal stem cells and has the greatest potential for producing deleterious effects. This is an important issue that should be explored.

By way of summary, we note that values of overall radiation dose to the embryo/fetus are compatible with usual statements of dose limitation. However, nonuniform radiation doses could be meaningful to the dosimetry of an individual medical or accidental radionuclide intake by a pregnant woman or to epidemiologic evaluations of deterministic or stochastic effects related to specific tissues. For example, separate calculations for the fetal thyroid gland found radiation doses that were orders of magnitude

greater than average embryo/fetus dose or dose to the remainder of the fetus for some isotopes and gestational ages.

Nonuniform radiation doses, likewise, would be especially meaningful for radionuclides that localize in developing skeleton. Deposition increases during progressive ossification and calcification. Relative radiation doses from alpha or beta particles will be higher because of the greater density and mineralization. Also, the high localized concentrations of actinides and heavy metals in placental structures and membranes deserve formal consideration.

4. Relationships to External Radiations

Approaches to quantification of radiation doses to the embryo/fetus from sources external to the woman's body are incomplete. They rely on surrogate estimators such as deep dose equivalent to the woman. Moreover, regulatory requirements regarding the frequency of dosimeter reading satisfy practical needs but are incomplete from a scientific standpoint. Thus, additional efforts would provide closure to the problem of radiation dosimetry of the embryo/fetus and to operational health physics procedures regarding pregnant or potentially pregnant women.

Formal comparisons should be performed using relevant exposure scenarios, defined doses in phantoms, and readings provided by radiation dosimeters. These results would determine the validity of the use of deep dose equivalent as a component of limit statements and would also indicate the appropriate number and placement of dosimeters on the woman's body.

D. Identification of Research Needs

Several analytic and dosimetric unknowns, uncertainties, and inconsistencies were identified and discussed in the above paragraphs. The most pressing needs have been restated as follows, in order of importance:

- Nonuniform radiation doses are meaningful for many radionuclides. Their calculation and significance should receive attention relative to their biological effects.

- Consideration should be given to expression of dose limits for the embryo/fetus in terms of effective dose or conceptually similar expressions and toward determination of weighting factors for the embryo and fetus.

- Concepts and calculations of postnatal radiation doses from prenatal radionuclide deposition should be evaluated.

- The scenarios developed for dosimetry of pre-existing radionuclide burdens were not evaluated in detail and approaches need to be improveed.

- Formal comparisons of approaches to external dosimetry for pregnant and potentially pregnant women should be performed. The use of deep dose equivalent as a component of limit statements should be validated.

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Appendix A

Initially Deposited and Retained Fractions of Activity in the Embryo/Fetus and Selected Source Organs Following Introduction of Radioactivity into the Maternal Transfer Compartment

Initially Deposited and Retained Fractions of Activity in the Embryo/Fetus and Selected Source Organs Following Introduction of Radioactivity into the Maternal Transfer Compartment

The tables in Appendix A were constructed for selected radionuclides in relevant chemical forms, using the biokinetic models presented in Section V of this report. As was described, these models usually incorporate the metabolic models of ICRP Publication 30, but are supplemented with revisions in Publications 48, 53, 56, and 67. The assumptions were that pregnancy began at the time of fertilization, approximately 2 weeks after the last menses, and that gestation consisted of nine 30-day months. Separate sets of values of fractional deposition were calculated for administration at the start of gestation and at the beginning of each subsequent 30-day time period, including the assumed final day (270) of gestation.

These calculations are based on the assumption of instantaneous introduction of a bolus of nominal activity into the maternal transfer compartment. The resulting fractions of the activity that are deposited in the woman, the embryo/fetus, and other selected structures are tabulated. These are usually given at the time immediately after administration at these gestational stages, but the fractional activity that is modeled as going to immediate or early excretion is not included. However, the maximal deposited fraction is given when longer than nominal times are required to achieve this level. The fractions of the administered activity that are retained in these compartments at the beginning of each subsequent month of gestation are presented on each line.

It is noted that ICRP Publication 30 employs a metabolic model in which a fraction of activity in the transfer compartment often is assumed to go immediately to excretion. Because of the minuscule mass of the embryo at that time, the model sometimes might predict that there would be negligible activity in the embryo when administration of some materials is immediately following fertilization. The pattern of partition and clearance usually is such that there will be minimal activity in the maternal blood at later times to provide for subsequent transfer. The revised models in ICRP Publication 56 and 67 and the enhanced biokinetic models used in the present calculations circumvent this difficulty. Estimation of the fraction that is present in the embryo after maternal administration at intermediate times during the first month (0-30 days) of pregnancy can be accomplished using proportionation, by elapsed times, of the fractions given for administration at 30 days. Although it likely would result in a greater over-estimate, the residual fraction at subsequent months could be estimated by the same proportion.

Furthermore, these ICRP publications recognize that over-estimates for certain chemical forms arise through the use of generalized metabolic models that encompass multiple related forms. Incorporation of these models as part of the basis for predicting the behavior of materials in the pregnant woman, together with dynamic modeling their placental transfer and subsequent disposition by the embryo/fetus, sometimes leads to irregularities. The occasional use of stepwise transitions in the geometry of the pregnant woman and in the metabolic behavior of the embryo/fetus may interact with these irregularities to perturb the transitions that otherwise would be anticipated to be regular in fractional content or dose rate.

Table A1. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 3H, as tritiated water, into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	4.8E-10	7.6E-07	2.9E-06	2.3E-06	1.1E-06	3.1E-07	7.0E-08	1.5E-08	2.6E-09	3.8E-10
30		6.8E-06	2.3E-05	1.9E-05	9.1E-06	2.5E-06	5.6E-07	1.2E-07	2.1E-08	3.1E-09
60			1.8E-04	1.5E-04	7.3E-05	2.0E-05	4.6E-06	9.5E-07	1.7E-07	2.5E-08
90				1.2E-03	5.9E-04	1.6E-04	3.7E-05	7.7E-06	1.4E-06	2.0E-07
120					4.6E-03	1.3E-03	3.0E-04	6.2E-05	1.1E-05	1.6E-06
150						1.0E-02	2.4E-03	5.0E-04	8.9E-05	1.3E-05
180							1.8E-02	4.0E-03	7.2E-04	1.0E-04
210								3.1E-02	5.8E-03	8.4E-04
240									4.4E-02	6.7E-03
270										5.1E-02

Table A2. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of organically bound 3H, as hexose or amino acid, into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	3.1E-10	9.1E-07	1.2E-05	4.1E-05	8.7E-05	1.0E-04	1.0E-04	9.7E-05	7.7E-05	4.9E-05
30		6.3E-06	2.9E-05	8.1E-05	1.6E-04	1.9E-04	1.9E-04	1.8E-04	1.4E-04	9.0E-05
60			1.8E-04	2.3E-04	3.4E-04	3.7E-04	3.6E-04	3.3E-04	2.6E-04	1.7E-04
90				1.2E-03	1.0E-03	8.7E-04	7.5E-04	6.5E-04	5.0E-04	3.2E-04
120					4.4E-03	2.9E-03	2.0E-03	1.5E-03	1.1E-03	6.6E-04
150						9.7E-03	5.7E-03	3.7E-03	2.4E-03	1.5E-03
180							1.8E-02	1.0E-02	5.9E-03	3.4E-03
210								3.0E-02	1.6E-02	8.4E-03
240									4.3E-02	2.1E-02
270										5.0E-02

Table A3. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 14C, as carbonate, hexose, or amino acid, into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	8.5E-11	3.4E-09	5.6E-08	2.0E-07	4.3E-07	5.2E-07	5.2E-07	4.8E-07	3.8E-07	2.4E-07
30		3.1E-06	1.9E-06	1.4E-06	1.3E-06	1.2E-06	1.1E-06	9.6E-07	7.4E-07	4.7E-07
60			8.9E-05	5.2E-05	3.0E-05	1.7E-05	1.0E-05	6.3E-06	3.8E-06	2.2E-06
90				5.9E-04	3.4E-04	1.9E-04	1.1E-04	5.9E-05	3.3E-05	1.8E-05
120					2.3E-03	1.3E-03	7.2E-04	4.0E-04	2.2E-04	1.2E-04
150						5.0E-03	2.9E-03	1.6E-03	8.8E-04	4.8E-04
180							9.1E-03	5.3E-03	2.9E-03	1.6E-03
210								1.5E-02	8.9E-03	4.9E-03
240									2.2E-02	1.3E-02
270										2.6E-02

Table A4. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 32P as phosphate into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	4.3E-10	6.0E-07	1.4E-06	7.2E-07	2.2E-07	3.6E-08	5.1E-09	6.4E-10	6.9E-11	6.2E-12
30		6.1E-06	1.8E-05	9.2E-06	2.8E-06	4.7E-07	6.5E-08	8.2E-09	8.9E-10	7.9E-11
60			1.7E-04	1.2E-04	3.5E-05	6.0E-06	8.3E-07	1.0E-07	1.1E-08	1.0E-09
90				1.1E-03	4.5E-04	7.7E-05	1.1E-05	1.4E-06	1.5E-07	1.3E-08
120					4.1E-03	9.9E-04	1.4E-04	1.7E-05	1.9E-06	1.7E-07
150						8.7E-03	1.8E-03	2.2E-04	2.4E-05	2.1E-06
180							1.5E-02	2.8E-03	3.1E-04	2.7E-05
210								2.5E-02	3.9E-03	3.5E-04
240									3.4E-02	4.5E-03
270										3.9E-02

Table A5a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 51Cr as the chloride into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	8.6E-01	2.5E-01	9.8E-02	4.0E-02	1.7E-02	6.9E-03	2.9E-03	1.2E-03	4.9E-04	2.0E-04
30		8.6E-01	2.5E-01	9.8E-02	4.0E-02	1.7E-02	6.9E-03	2.9E-03	1.2E-03	4.9E-04
60			8.6E-01	2.5E-01	9.8E-02	4.0E-02	1.7E-02	6.9E-03	2.9E-03	1.2E-03
90				8.6E-01	2.5E-01	9.8E-02	4.0E-02	1.7E-02	6.9E-03	2.9E-03
120					8.6E-01	2.5E-01	9.8E-02	4.0E-02	1.7E-02	6.9E-03
150						8.6E-01	2.5E-01	9.8E-02	4.0E-02	1.7E-02
180							8.5E-01	2.5E-01	9.8E-02	4.0E-02
210								8.5E-01	2.5E-01	9.7E-02
240									8.5E-01	2.5E-01
270										8.5E-01

Table A5b. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 51Cr as the chloride into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	5.1E-11	5.7E-11	2.7E-11	1.3E-11	6.0E-12	2.8E-12	1.3E-12	6.3E-13	3.0E-13	1.4E-13
30		1.8E-06	1.2E-06	5.6E-07	2.7E-07	1.2E-07	5.9E-08	2.8E-08	1.3E-08	6.2E-09
60			5.3E-05	3.4E-05	1.6E-05	7.5E-06	3.5E-06	1.7E-06	7.8E-07	3.7E-07
90				3.5E-04	2.2E-04	1.0E-04	4.9E-05	2.3E-05	1.1E-05	5.2E-06
120					1.3E-03	8.4E-04	4.0E-04	1.9E-04	8.8E-05	4.2E-05
150						2.9E-03	1.8E-03	8.7E-04	4.1E-04	1.9E-04
180							5.3E-03	3.3E-03	1.6E-03	7.5E-04
210								9.0E-03	5.6E-03	2.7E-03
240									1.3E-02	8.1E-03
270										1.5E-02

Table A6a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 55Fe into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	1.0E+00	9.8E-01	9.6E-01	9.4E-01	9.2E-01	9.0E-01	8.8E-01	8.6E-01	8.5E-01	8.3E-01
30		1.0E+00	9.8E-01	9.6E-01	9.4E-01	9.2E-01	9.0E-01	8.8E-01	8.6E-01	8.5E-01
60			1.0E+00	9.8E-01	9.6E-01	9.4E-01	9.2E-01	9.0E-01	8.8E-01	8.6E-01
90				1.0E+00	9.8E-01	9.5E-01	9.4E-01	9.2E-01	9.0E-01	8.8E-01
120					9.9E-01	9.6E-01	9.4E-01	9.3E-01	9.1E-01	8.9E-01
150						9.7E-01	9.5E-01	9.3E-01	9.1E-01	8.9E-01
180							9.6E-01	9.4E-01	9.2E-01	9.0E-01
210								9.7E-01	9.5E-01	9.3E-01
240									9.5E-01	9.3E-01
270										9.5E-01

Table A6b. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 55Fe into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	1.2E-10	1.4E-10	1.4E-10	1.4E-10	1.3E-10	1.3E-10	1.3E-10	1.3E-10	1.2E-10	1.2E-10
30		6.1E-06	6.2E-06	6.1E-06	6.0E-06	5.8E-06	5.7E-06	5.6E-06	5.5E-06	5.4E-06
60			1.8E-04	1.8E-04	1.8E-04	1.8E-04	1.7E-04	1.7E-04	1.7E-04	1.6E-04
90				3.5E-03	3.6E-03	3.5E-03	3.4E-03	3.4E-03	3.3E-03	3.2E-03
120					1.4E-02	1.4E-02	1.4E-02	1.3E-02	1.3E-02	1.3E-02
150						3.0E-02	3.1E-02	3.0E-02	2.9E-02	2.9E-02
180							3.6E-02	3.7E-02	3.6E-02	3.5E-02
210								3.1E-02	3.1E-02	3.1E-02
240									4.4E-02	4.5E-02
270										5.2E-02

Table A7a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 59Fe into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	9.9E-01	6.3E-01	3.9E-01	2.5E-01	1.5E-01	9.7E-02	6.1E-02	3.8E-02	2.4E-02	1.5E-02
30		9.9E-01	6.3E-01	3.9E-01	2.5E-01	1.5E-01	9.7E-02	6.1E-02	3.8E-02	2.4E-02
60			9.8E-01	6.3E-01	3.9E-01	2.5E-01	1.5E-01	9.7E-02	6.1E-02	3.8E-02
90				9.8E-01	6.3E-01	3.9E-01	2.5E-01	1.5E-01	9.7E-02	6.0E-02
120					9.7E-01	6.2E-01	3.9E-01	2.4E-01	1.5E-01	9.5E-02
150						9.5E-01	6.1E-01	3.8E-01	2.4E-01	1.5E-01
180							9.5E-01	6.0E-01	3.8E-01	2.4E-01
210								9.5E-01	6.1E-01	3.8E-01
240									9.4E-01	6.0E-01
270										9.3E-01

Table A7b. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 59Fe into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	1.2E-10	9.1E-11	5.7E-11	3.6E-11	2.3E-11	1.4E-11	8.8E-12	5.5E-12	3.5E-12	2.2E-12
30		6.0E-06	4.0E-06	2.5E-06	1.6E-06	9.8E-07	6.1E-07	3.9E-07	2.4E-07	1.5E-07
60			1.8E-04	1.2E-04	7.4E-05	4.7E-05	2.9E-05	1.8E-05	1.2E-05	7.2E-06
90				3.5E-03	2.3E-03	1.4E-03	9.1E-04	5.7E-04	3.6E-04	2.2E-04
120					1.3E-02	8.9E-03	5.6E-03	3.5E-03	2.2E-03	1.4E-03
150						2.9E-02	2.0E-02	1.2E-02	7.7E-03	4.8E-03
180							3.6E-02	2.4E-02	1.5E-02	9.3E-03
210								3.0E-02	2.0E-02	1.3E-02
240									4.3E-02	2.9E-02
270										5.1E-02

Table A8a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 57Co into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	5.4E-01	1.5E-01	1.1E-01	9.1E-02	7.6E-02	6.4E-02	5.5E-02	4.7E-02	4.1E-02	3.6E-02
30		5.4E-01	1.5E-01	1.1E-01	9.1E-02	7.5E-02	6.4E-02	5.4E-02	4.6E-02	4.0E-02
60			5.4E-01	1.5E-01	1.1E-01	9.0E-02	7.5E-02	6.3E-02	5.3E-02	4.6E-02
90				5.4E-01	1.5E-01	1.1E-01	9.0E-02	7.4E-02	6.2E-02	5.3E-02
120					5.4E-01	1.5E-01	1.1E-01	8.9E-02	7.3E-02	6.1E-02
150						5.4E-01	1.5E-01	1.1E-01	8.7E-02	7.2E-02
180							5.3E-01	1.4E-01	1.1E-01	8.6E-02
210								5.3E-01	1.4E-01	1.1E-01
240									5.2E-01	1.4E-01
270										5.2E-01

Table A8b. Fraction of activity deposited in the maternal liver and fractions retained at start of subsequent 30-day periods after injection of 57Co into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	4.6E-02	1.6E-02	1.3E-02	1.0E-02	8.5E-03	7.2E-03	6.2E-03	5.4E-03	4.7E-03	4.2E-03
30		4.6E-02	1.6E-02	1.3E-02	1.0E-02	8.5E-03	7.2E-03	6.2E-03	5.4E-03	4.7E-03
60			4.6E-02	1.6E-02	1.3E-02	1.0E-02	8.5E-03	7.2E-03	6.2E-03	5.4E-03
90				4.6E-02	1.6E-02	1.3E-02	1.0E-02	8.5E-03	7.2E-03	6.2E-03
120					4.6E-02	1.6E-02	1.3E-02	1.0E-02	8.5E-03	7.2E-03
150						4.6E-02	1.6E-02	1.3E-02	1.0E-02	8.5E-03
180							4.6E-02	1.6E-02	1.3E-02	1.0E-02
210								4.6E-02	1.6E-02	1.3E-02
240									4.6E-02	1.6E-02
270										4.6E-02

Table A8c. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 57Co into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	1.2E-10	5.0E-08	4.2E-08	8.0E-09	8.7E-10	5.5E-11	2.8E-12	1.4E-13	5.5E-15	1.8E-16
30		1.8E-06	1.5E-06	2.8E-07	3.1E-08	1.9E-09	1.0E-10	4.8E-12	1.9E-13	6.5E-15
60			4.8E-05	9.9E-06	1.1E-06	6.8E-08	3.5E-09	1.7E-10	6.9E-12	2.3E-13
90				3.1E-04	3.8E-05	2.4E-06	1.2E-07	5.9E-09	2.4E-10	8.0E-12
120					1.2E-03	8.5E-05	4.4E-06	2.1E-07	8.5E-09	2.8E-10
150						2.6E-03	1.6E-04	7.4E-06	3.0E-07	1.0E-08
180							4.7E-03	2.6E-04	1.1E-05	3.5E-07
210								7.9E-03	3.8E-04	1.2E-05
240									1.1E-02	4.4E-04
270										1.3E-02

Table A9a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 58Co into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	5.5E-01	1.2E-01	7.3E-02	4.8E-02	3.2E-02	2.2E-02	1.5E-02	1.0E-02	7.2E-03	5.1E-03
30		5.5E-01	1.2E-01	7.3E-02	4.8E-02	3.2E-02	2.1E-02	1.5E-02	1.0E-02	7.1E-03
60			5.5E-01	1.2E-01	7.2E-02	4.7E-02	3.2E-02	2.1E-02	1.4E-02	1.0E-02
90				5.5E-01	1.2E-01	7.2E-02	4.7E-02	3.1E-02	2.1E-02	1.4E-02
120					5.5E-01	1.2E-01	7.2E-02	4.6E-02	3.1E-02	2.1E-02
150						5.5E-01	1.2E-01	7.1E-02	4.6E-02	3.0E-02
180							5.5E-01	1.2E-01	6.9E-02	4.5E-02
210								5.4E-01	1.1E-01	6.9E-02
240									5.4E-01	1.1E-01
270										5.4E-01

Table A9b. Fraction of activity deposited in the maternal liver and fractions retained at start of subsequent 30-day periods after injection of 58Co into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	3.7E-02	1.3E-02	8.1E-03	5.3E-03	3.6E-03	2.4E-03	1.7E-03	1.2E-03	8.4E-04	5.9E-04
30		3.7E-02	1.3E-02	8.1E-03	5.3E-03	3.6E-03	2.4E-03	1.7E-03	1.2E-03	8.4E-04
60			3.7E-02	1.3E-02	8.1E-03	5.3E-03	3.6E-03	2.4E-03	1.7E-03	1.2E-03
90				3.7E-02	1.3E-02	8.1E-03	5.3E-03	3.6E-03	2.4E-03	1.7E-03
120					3.7E-02	1.3E-02	8.1E-03	5.3E-03	3.6E-03	2.4E-03
150						3.7E-02	1.3E-02	8.1E-03	5.3E-03	3.6E-03
180							3.7E-02	1.3E-02	8.1E-03	5.3E-03
210								3.7E-02	1.3E-02	8.1E-03
240									3.7E-02	1.3E-02
270										3.7E-02

Table A9c. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 58Co into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	1.7E-10	7.4E-07	1.4E-05	5.9E-05	1.5E-04	2.3E-04	2.9E-04	3.5E-04	3.5E-04	2.9E-04
30		2.4E-06	2.3E-05	9.0E-05	2.3E-04	3.4E-04	4.2E-04	4.9E-04	5.0E-04	4.1E-04
60			6.6E-05	1.5E-04	3.5E-04	5.1E-04	6.2E-04	7.1E-04	7.1E-04	5.8E-04
90				4.3E-04	5.7E-04	7.7E-04	9.3E-04	1.0E-03	1.0E-03	8.3E-04
120					1.6E-03	1.3E-03	1.4E-03	1.5E-03	1.5E-03	1.2E-03
150						3.6E-03	2.3E-03	2.4E-03	2.2E-03	1.8E-03
180							6.5E-03	3.9E-03	3.4E-03	2.6E-03
210								1.1E-02	5.6E-03	4.0E-03
240									1.6E-02	6.6E-03
270										1.8E-02

Table A10a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 60Co into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	5.6E-01	1.6E-01	1.3E-01	1.1E-01	9.9E-02	8.9E-02	8.1E-02	7.4E-02	6.9E-02	6.5E-02
30		5.6E-01	1.6E-01	1.3E-01	1.1E-01	9.8E-02	8.8E-02	8.0E-02	7.3E-02	6.8E-02
60			5.6E-01	1.6E-01	1.3E-01	1.1E-01	9.7E-02	8.7E-02	7.9E-02	7.3E-02
90				5.6E-01	1.6E-01	1.3E-01	1.1E-01	9.6E-02	8.6E-02	7.8E-02
120					5.6E-01	1.6E-01	1.3E-01	1.1E-01	9.5E-02	8.5E-02
150						5.6E-01	1.6E-01	1.2E-01	1.1E-01	9.4E-02
180							5.5E-01	1.5E-01	1.2E-01	1.1E-01
210								5.5E-01	1.5E-01	1.2E-01
240									5.4E-01	1.5E-01
270										5.4E-01

Table A10b. Fraction of activity deposited in the maternal liver and fractions retained at start of subsequent 30-day periods after injection of 60Co into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	3.7E-02	1.8E-02	1.4E-02	1.2E-02	1.1E-02	1.0E-02	9.2E-03	8.6E-03	8.0E-03	7.6E-03
30		3.7E-02	1.8E-02	1.4E-02	1.2E-02	1.1E-02	1.0E-02	9.2E-03	8.6E-03	8.0E-03
60			3.7E-02	1.8E-02	1.4E-02	1.2E-02	1.1E-02	1.0E-02	9.2E-03	8.6E-03
90				3.7E-02	1.8E-02	1.4E-02	1.2E-02	1.1E-02	1.0E-02	9.2E-03
120					3.7E-02	1.8E-02	1.4E-02	1.2E-02	1.1E-02	1.0E-02
150						3.7E-02	1.8E-02	1.4E-02	1.2E-02	1.1E-02
180							3.7E-02	1.8E-02	1.4E-02	1.2E-02
210								3.7E-02	1.8E-02	1.4E-02
240									3.7E-02	1.8E-02
270										3.7E-02

Table A10c. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 60Co into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	1.8E-10	9.9E-07	2.4E-05	1.4E-04	4.8E-04	9.5E-04	1.6E-03	2.5E-03	3.4E-03	3.7E-03
30		2.5E-06	3.0E-05	1.6E-04	5.3E-04	1.0E-03	1.7E-03	2.7E-03	3.6E-03	4.0E-03
60			6.7E-05	2.0E-04	6.1E-04	1.2E-03	1.9E-03	2.9E-03	3.9E-03	4.2E-03
90				4.4E-04	7.6E-04	1.4E-03	2.2E-03	3.2E-03	4.2E-03	4.5E-03
120					1.7E-03	1.7E-03	2.5E-03	3.6E-03	4.7E-03	4.9E-03
150						3.6E-03	3.1E-03	4.2E-03	5.2E-03	5.5E-03
180							6.6E-03	5.2E-03	6.0E-03	6.1E-03
210								1.1E-02	7.5E-03	7.0E-03
240									1.6E-02	8.7E-03
270										1.8E-02

Table A11a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 57Co as vitamin B-12 into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	3.9E-01	2.7E-01	2.4E-01	2.1E-01	1.9E-01	1.6E-01	1.4E-01	1.3E-01	1.1E-01	9.8E-02
30		3.9E-01	2.7E-01	2.4E-01	2.1E-01	1.9E-01	1.6E-01	1.4E-01	1.3E-01	1.1E-01
60			3.9E-01	2.7E-01	2.4E-01	2.1E-01	1.8E-01	1.6E-01	1.4E-01	1.2E-01
90				3.8E-01	2.6E-01	2.3E-01	2.1E-01	1.8E-01	1.6E-01	1.4E-01
120					3.8E-01	2.6E-01	2.3E-01	2.0E-01	1.8E-01	1.6E-01
150						3.8E-01	2.6E-01	2.3E-01	2.0E-01	1.8E-01
180							3.8E-01	2.6E-01	2.3E-01	2.0E-01
210								3.7E-01	2.5E-01	2.2E-01
240									3.7E-01	2.5E-01
270										3.7E-01

Table A11b. Fraction of activity deposited in the maternal liver and fractions retained at start of subsequent 30-day periods after injection of 57Co as vitamin B-12 into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	5.7E-01	5.3E-01	4.7E-01	4.2E-01	3.7E-01	3.3E-01	2.9E-01	2.6E-01	2.3E-01	2.1E-01
30		5.7E-01	5.3E-01	4.7E-01	4.2E-01	3.7E-01	3.3E-01	2.9E-01	2.6E-01	2.3E-01
60			5.7E-01	5.3E-01	4.7E-01	4.2E-01	3.7E-01	3.3E-01	2.9E-01	2.6E-01
90				5.7E-01	5.3E-01	4.7E-01	4.2E-01	3.7E-01	3.3E-01	2.9E-01
120					5.7E-01	5.3E-01	4.7E-01	4.2E-01	3.7E-01	3.3E-01
150						5.7E-01	5.3E-01	4.7E-01	4.2E-01	3.7E-01
180							5.7E-01	5.3E-01	4.7E-01	4.2E-01
210								5.7E-01	5.3E-01	4.7E-01
240									5.7E-01	5.3E-01
270										5.7E-01

Table A11c. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 57Co as vitamin B-12 into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	1.8E-10	1.7E-06	4.4E-05	2.6E-04	8.9E-04	1.8E-03	2.9E-03	4.3E-03	5.5E-03	5.7E-03
30		2.5E-06	5.0E-05	2.9E-04	1.0E-03	2.0E-03	3.2E-03	4.8E-03	6.1E-03	6.4E-03
60			6.9E-05	3.3E-04	1.1E-03	2.2E-03	3.6E-03	5.4E-03	6.9E-03	7.2E-03
90				4.5E-04	1.3E-03	2.5E-03	4.1E-03	6.1E-03	7.8E-03	8.1E-03
120					1.7E-03	2.8E-03	4.6E-03	6.8E-03	8.8E-03	9.1E-03
150						3.7E-03	5.2E-03	7.7E-03	9.9E-03	1.0E-02
180							6.8E-03	8.7E-03	1.1E-02	1.2E-02
210								1.1E-02	1.3E-02	1.3E-02
240									1.6E-02	1.5E-02
270										1.9E-02

Table A12a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 58Co as vitamin B-12 into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	3.8E-01	2.2E-01	1.5E-01	1.1E-01	7.8E-02	5.6E-02	3.9E-02	2.8E-02	2.0E-02	1.4E-02
30		3.8E-01	2.2E-01	1.5E-01	1.1E-01	7.8E-02	5.5E-02	3.9E-02	2.7E-02	1.9E-02
60			3.8E-01	2.1E-01	1.5E-01	1.1E-01	7.7E-02	5.4E-02	3.8E-02	2.7E-02
90				3.8E-01	2.1E-01	1.5E-01	1.1E-01	7.6E-02	5.4E-02	3.8E-02
120					3.8E-01	2.1E-01	1.5E-01	1.1E-01	7.5E-02	5.3E-02
150						3.8E-01	2.1E-01	1.5E-01	1.0E-01	7.4E-02
180							3.8E-01	2.1E-01	1.5E-01	1.0E-01
210								3.7E-01	2.0E-01	1.4E-01
240									3.7E-01	2.0E-01
270										3.6E-01

Table A12b. Fraction of activity deposited in the maternal liver and fractions retained at start of subsequent 30-day periods after injection of 58Co as vitamin B-12 into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	5.7E-01	4.3E-01	3.1E-01	2.2E-01	1.6E-01	1.1E-01	8.0E-02	5.7E-02	4.1E-02	2.9E-02
30		5.7E-01	4.3E-01	3.1E-01	2.2E-01	1.6E-01	1.1E-01	8.0E-02	5.7E-02	4.1E-02
60			5.7E-01	4.3E-01	3.1E-01	2.2E-01	1.6E-01	1.1E-01	8.0E-02	5.7E-02
90				5.7E-01	4.3E-01	3.1E-01	2.2E-01	1.6E-01	1.1E-01	8.0E-02
120					5.7E-01	4.3E-01	3.1E-01	2.2E-01	1.6E-01	1.1E-01
150						5.7E-01	4.3E-01	3.1E-01	2.2E-01	1.6E-01
180							5.7E-01	4.3E-01	3.1E-01	2.2E-01
210								5.7E-01	4.3E-01	3.1E-01
240									5.7E-01	4.3E-01
270										5.7E-01

Table A12c. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 58Co as vitamin B-12 into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	1.8E-10	1.3E-06	2.9E-05	1.4E-04	3.8E-04	5.9E-04	7.8E-04	9.3E-04	9.6E-04	8.0E-04
30		2.5E-06	4.0E-05	1.9E-04	5.2E-04	8.3E-04	1.1E-03	1.3E-03	1.4E-03	1.1E-03
60			6.9E-05	2.7E-04	7.3E-04	1.2E-03	1.5E-03	1.8E-03	1.9E-03	1.6E-03
90				4.5E-04	1.0E-03	1.6E-03	2.1E-03	2.5E-03	2.6E-03	2.2E-03
120					1.7E-03	2.3E-03	3.0E-03	3.6E-03	3.7E-03	3.1E-03
150						3.7E-03	4.1E-03	5.0E-03	5.2E-03	4.3E-03
180							6.8E-03	7.0E-03	7.2E-03	6.0E-03
210								1.1E-02	1.0E-02	8.4E-03
240									1.6E-02	1.2E-02
270										1.9E-02

Table A13a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 60Co as vitamin B-12 into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	3.9E-01	2.8E-01	2.7E-01	2.6E-01	2.4E-01	2.3E-01	2.2E-01	2.0E-01	1.9E-01	1.8E-01
30		3.9E-01	2.8E-01	2.7E-01	2.5E-01	2.4E-01	2.3E-01	2.1E-01	2.0E-01	1.9E-01
60			3.9E-01	2.8E-01	2.7E-01	2.5E-01	2.4E-01	2.2E-01	2.1E-01	2.0E-01
90				3.9E-01	2.8E-01	2.7E-01	2.5E-01	2.3E-01	2.2E-01	2.1E-01
120					3.8E-01	2.8E-01	2.6E-01	2.5E-01	2.3E-01	2.2E-01
150						3.8E-01	2.8E-01	2.6E-01	2.4E-01	2.3E-01
180							3.8E-01	2.8E-01	2.6E-01	2.4E-01
210								3.8E-01	2.7E-01	2.5E-01
240									3.7E-01	2.7E-01
270										3.7E-01

Table A13b. Fraction of activity deposited in the maternal liver and fractions retained at start of subsequent 30-day periods after injection of 60Co as vitamin B-12 into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	5.8E-01	5.7E-01	5.4E-01	5.1E-01	4.9E-01	4.6E-01	4.4E-01	4.2E-01	3.9E-01	3.8E-01
30		5.8E-01	5.7E-01	5.4E-01	5.1E-01	4.9E-01	4.6E-01	4.4E-01	4.2E-01	3.9E-01
60			5.8E-01	5.7E-01	5.4E-01	5.1E-01	4.9E-01	4.6E-01	4.4E-01	4.2E-01
90				5.8E-01	5.7E-01	5.4E-01	5.1E-01	4.9E-01	4.6E-01	4.4E-01
120					5.8E-01	5.7E-01	5.4E-01	5.1E-01	4.9E-01	4.6E-01
150						5.8E-01	5.7E-01	5.4E-01	5.1E-01	4.9E-01
180							5.8E-01	5.7E-01	5.4E-01	5.1E-01
210								5.8E-01	5.7E-01	5.4E-01
240									5.8E-01	5.7E-01
270										5.8E-01

Table A13c. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 60Co as vitamin B-12 into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	1.8E-10	1.8E-06	5.1E-05	3.2E-04	1.2E-03	2.5E-03	4.2E-03	6.8E-03	9.3E-03	1.0E-02
30		2.6E-06	5.3E-05	3.3E-04	1.2E-03	2.6E-03	4.5E-03	7.1E-03	9.8E-03	1.1E-02
60			6.9E-05	3.5E-04	1.3E-03	2.7E-03	4.7E-03	7.5E-03	1.0E-02	1.1E-02
90				4.6E-04	1.4E-03	2.9E-03	5.0E-03	7.9E-03	1.1E-02	1.2E-02
120					1.7E-03	3.0E-03	5.2E-03	8.3E-03	1.1E-02	1.3E-02
150						3.8E-01	2.8E-01	2.6E-01	2.4E-01	2.3E-01
180							6.8E-03	9.3E-03	1.3E-02	1.4E-02
210								1.2E-02	1.3E-02	1.5E-02
240									1.6E-02	1.6E-02
270										1.9E-02

Table A14a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 65Zn into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	9.9E-01	7.4E-01	6.0E-01	5.1E-01	4.4E-01	3.8E-01	3.3E-01	2.8E-01	2.4E-01	2.1E-01
30		9.9E-01	7.4E-01	6.0E-01	5.1E-01	4.4E-01	3.8E-01	3.2E-01	2.8E-01	2.4E-01
60			9.9E-01	7.4E-01	6.0E-01	5.1E-01	4.4E-01	3.7E-01	3.2E-01	2.8E-01
90				9.9E-01	7.4E-01	6.0E-01	5.0E-01	4.3E-01	3.7E-01	3.2E-01
120					9.8E-01	7.3E-01	5.9E-01	5.0E-01	4.3E-01	3.7E-01
150						9.8E-01	7.3E-01	5.9E-01	4.9E-01	4.2E-01
180							9.7E-01	7.2E-01	5.8E-01	4.9E-01
210								9.6E-01	7.1E-01	5.8E-01
240									9.5E-01	7.1E-01
270										9.4E-01

Table A14b. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 65Zn into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	4.6E-10	4.0E-06	9.5E-05	5.3E-04	1.8E-03	3.4E-03	5.3E-03	7.8E-03	9.8E-03	9.9E-03
30		6.5E-06	1.2E-04	6.3E-04	2.0E-03	3.9E-03	6.1E-03	8.9E-03	1.1E-02	1.1E-02
60			1.8E-04	7.9E-04	2.4E-03	4.5E-03	7.1E-03	1.0E-02	1.3E-02	1.3E-02
90				1.2E-03	3.0E-03	5.4E-03	8.2E-03	1.2E-02	1.5E-02	1.5E-02
120					4.4E-03	6.7E-03	9.8E-03	1.4E-02	1.7E-02	1.7E-02
150						9.6E-03	1.2E-02	1.6E-02	2.0E-02	2.0E-02
180							1.7E-02	2.1E-02	2.3E-02	2.3E-02
210								2.9E-02	3.0E-02	2.7E-02
240									4.2E-02	3.4E-02
270										4.8E-02

Table A15a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 67Ga into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	7.2E-01	6.3E-04	4.8E-07	3.6E-10	2.7E-13	2.0E-16	1.5E-19	1.1E-22	8.6E-26	6.5E-29
30		7.2E-01	6.3E-04	4.8E-07	3.6E-10	2.7E-13	2.0E-16	1.5E-19	1.1E-22	8.6E-26
60			7.2E-01	6.3E-04	4.8E-07	3.6E-10	2.7E-13	2.0E-16	1.5E-19	1.1E-22
90				7.1E-01	6.3E-04	4.7E-07	3.6E-10	2.7E-13	2.0E-16	1.5E-19
120					7.0E-01	6.2E-04	4.7E-07	3.5E-10	2.6E-13	2.0E-16
150						6.9E-01	6.1E-04	4.6E-07	3.5E-10	2.6E-13
180							6.8E-01	6.0E-04	4.5E-07	3.4E-10
210								6.6E-01	5.8E-04	4.4E-07
240									6.5E-01	5.7E-04
270										6.4E-01

Table A15b. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 67Ga into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	5.9E-11	2.2E-13	3.8E-16	6.4E-19	1.1E-21	1.9E-24	3.2E-27	5.4E-30	9.1E-33	1.5E-35
30		2.9E-06	1.2E-08	2.0E-11	3.5E-14	5.9E-17	1.0E-19	1.7E-22	2.9E-25	4.9E-28
60			9.4E-05	5.9E-07	1.0E-09	1.7E-12	2.9E-15	5.0E-18	8.4E-21	1.4E-23
90				9.1E-04	1.5E-05	2.5E-08	4.3E-11	7.3E-14	1.3E-16	2.1E-19
120					2.7E-03	3.3E-05	5.7E-08	9.7E-11	1.6E-13	2.8E-16
150						5.4E-03	5.9E-05	1.0E-07	1.7E-10	2.9E-13
180							9.3E-03	9.3E-05	1.6E-07	2.7E-10
210								1.5E-02	1.3E-04	2.3E-07
240									2.0E-02	1.7E-04
270										2.3E-02

Table A16a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 86Rb into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	9.5E-01	2.1E-01	4.2E-02	8.6E-03	1.8E-03	3.6E-04	7.2E-05	1.4E-05	2.9E-06	5.9E-07
30		9.5E-01	2.1E-01	4.2E-02	8.6E-03	1.7E-03	3.5E-04	7.1E-05	1.4E-05	2.9E-06
60			9.5E-01	2.0E-01	4.2E-02	8.5E-03	1.7E-03	3.5E-04	7.0E-05	1.4E-05
90				9.5E-01	2.0E-01	4.2E-02	8.4E-03	1.7E-03	3.4E-04	6.9E-05
120					9.5E-01	2.0E-01	4.1E-02	8.3E-03	1.7E-03	3.4E-04
150						9.4E-01	2.0E-01	4.1E-02	8.2E-03	1.7E-03
180							9.4E-01	2.0E-01	4.0E-02	8.1E-03
210								9.2E-01	2.0E-01	4.0E-02
240									9.1E-01	1.9E-01
270										9.0E-01

Table A16b. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 86Rb into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	4.7E-10	1.2E-06	7.7E-06	1.0E-05	8.2E-06	3.7E-06	1.4E-06	4.8E-07	1.4E-07	3.4E-08
30		6.6E-06	3.8E-05	5.1E-05	4.0E-05	1.8E-05	6.8E-06	2.3E-06	6.9E-07	1.7E-07
60			1.8E-04	2.5E-04	2.0E-04	8.9E-05	3.3E-05	1.1E-05	3.4E-06	8.1E-07
90				1.2E-03	9.6E-04	4.3E-04	1.6E-04	5.6E-05	1.7E-05	3.9E-06
120					4.4E-03	2.1E-03	7.9E-04	2.7E-04	8.1E-05	1.9E-05
150						9.7E-03	3.9E-03	1.3E-03	3.9E-04	9.4E-05
180							1.8E-02	6.5E-03	1.9E-03	4.6E-04
210								3.0E-02	9.4E-03	2.2E-03
240									4.2E-02	1.1E-02
270										4.9E-02

Table A17a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 89Sr into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	7.1E-01	1.7E-01	1.1E-01	7.3E-02	4.8E-02	3.2E-02	2.1E-02	1.4E-02	9.3E-03	6.1E-03
30		7.1E-01	1.7E-01	1.1E-01	7.3E-02	4.8E-02	3.2E-02	2.1E-02	1.4E-02	9.3E-03
60			7.1E-01	1.7E-01	1.1E-01	7.3E-02	4.8E-02	3.2E-02	2.1E-02	1.4E-02
90				7.1E-01	1.7E-01	1.1E-01	7.3E-02	4.8E-02	3.2E-02	2.1E-02
120					7.0E-01	1.6E-01	1.1E-01	7.2E-02	4.8E-02	3.2E-02
150						7.0E-01	1.6E-01	1.1E-01	7.2E-02	4.8E-02
180							7.0E-01	1.6E-01	1.1E-01	7.1E-02
210								6.9E-01	1.6E-01	1.1E-01
240									6.8E-01	1.6E-01
270										6.8E-01

Table A17b. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 89Sr into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	3.1E-10	5.9E-08	1.5E-07	7.9E-08	2.5E-08	4.6E-09	6.9E-10	9.4E-11	1.1E-11	1.1E-12
30		4.3E-06	1.8E-06	9.6E-07	3.1E-07	5.6E-08	8.3E-09	1.1E-09	1.4E-10	1.3E-11
60			1.2E-04	1.2E-05	3.7E-06	6.8E-07	1.0E-07	1.6E-08	3.0E-09	1.0E-09
90				7.7E-04	1.2E-04	5.7E-05	3.3E-05	2.1E-05	1.4E-05	8.9E-06
120					3.0E-03	7.2E-04	4.5E-04	2.8E-04	1.8E-04	1.2E-04
150						6.5E-03	2.0E-03	1.2E-03	8.0E-04	5.2E-04
180							1.2E-02	3.9E-03	2.5E-03	1.6E-03
210								2.0E-02	6.2E-03	4.0E-03
240									2.8E-02	8.2E-03
270										3.3E-02

Table A18a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 90Sr/Y into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	7.2E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01
30		7.2E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01
60			7.2E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01
90				7.1E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01
120					7.1E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01
150						7.1E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01
180							7.1E-01	2.4E-01	2.4E-01	2.4E-01
210								7.0E-01	2.4E-01	2.4E-01
240									6.9E-01	2.4E-01
270										6.9E-01

Table A18b. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 90Sr/Y into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	3.1E-10	8.9E-08	3.3E-07	2.7E-07	1.3E-07	3.6E-08	8.0E-09	1.7E-09	3.0E-10	4.3E-11
30		4.4E-06	2.7E-06	2.2E-06	1.1E-06	2.9E-07	6.5E-08	1.3E-08	2.4E-09	3.5E-10
60			1.2E-04	1.8E-05	8.5E-06	2.3E-06	5.4E-07	1.2E-07	3.5E-08	1.9E-08
90				7.8E-04	1.7E-04	1.3E-04	1.1E-04	1.1E-04	1.0E-04	1.0E-04
120					3.0E-03	1.1E-03	1.0E-03	9.7E-04	9.5E-04	9.4E-04
150						6.6E-03	3.0E-03	2.8E-03	2.7E-03	2.7E-03
180							1.2E-02	5.9E-03	5.7E-03	5.5E-03
210								2.0E-02	9.3E-03	9.1E-03
240									2.9E-02	1.2E-02
270										3.3E-02

Table A19a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 99mTc pertechnetate into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	4.5E-02	0	0	0	0	0	0	0	0	0
30		4.5E-02	0	0	0	0	0	0	0	0
60			4.5E-02	0	0	0	0	0	0	0
90				4.5E-02	0	0	0	0	0	0
120					4.5E-02	0	0	0	0	0
150						4.5E-02	0	0	0	0
180							4.4E-02	0	0	0
210								4.4E-02	0	0
240									4.3E-02	0
270										4.3E-02

Table A19b. Fraction of activity deposited in the maternal thyroid and fractions retained at start of subsequent 30-day periods after injection of 99mTc pertechnetate into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	6.5E-04	0	0	0	0	0	0	0	0	0
30		6.5E-04	0	0	0	0	0	0	0	0
60			6.5E-04	0	0	0	0	0	0	0
90				6.5E-04	0	0	0	0	0	0
120					6.5E-04	0	0	0	0	0
150						6.3E-04	0	0	0	0
180							6.1E-04	0	0	0
210								5.9E-04	0	0
240									5.7E-04	0
270										5.6E-04

Table A19c. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 99mTc pertechnetate into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	2.7E-11	0	0	0	0	0	0	0	0	0
30		3.7E-07	0	0	0	0	0	0	0	0
60			1.0E-05	0	0	0	0	0	0	0
90				6.6E-05	0	0	0	0	0	0
120					2.5E-04	0	0	0	0	0
150						5.5E-04	0	0	0	0
180							1.0E-03	0	0	0
210								1.7E-03	0	0
240									2.4E-03	0
270										2.7E-03

Table A19d. Fraction of activity deposited in the fetal thyroid and fractions retained at start of subsequent 30-day periods after injection of 99mTc pertechnetate into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0				0	0	0	0	0	0	0
30				0	0	0	0	0	0	0
60				0	0	0	0	0	0	0
90				1.1E-06	0	0	0	0	0	0
120					7.1E-06	0	0	0	0	0
150						2.6E-05	0	0	0	0
180							4.4E-05	0	0	0
210								6.4E-05	0	0
240									8.2E- 5	0
270										9.0E-05

Table A20. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 106Ru/Rh into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	1.0E-10	1.2E-10	1.1E-10	1.0E-10	9.9E-11	9.3E-11	8.8E-11	8.3E-11	7.9E-11	7.5E-11
30		5.1E-06	5.1E-06	4.8E-06	4.6E-06	4.3E-06	4.1E-06	3.9E-06	3.6E-06	3.4E-06
60			1.5E-04	1.5E-04	1.4E-04	1.3E-04	1.2E-04	1.2E-04	1.1E-04	1.1E-04
90				1.0E-04	9.9E-05	9.3E-05	8.8E-05	8.3E-05	7.9E-05	7.4E-05
120					3.8E-04	3.8E-04	3.6E-04	3.4E-04	3.2E-04	3.0E-04
150						8.5E-04	8.4E-04	7.9E-04	7.5E-04	7.1E-04
180							1.5E-03	1.5E-03	1.4E-03	1.4E-03
210								2.6E-03	2.6E-03	2.4E-03
240									3.7E-03	3.7E-03
270										4.4E-03

Table A21a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 111In into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	7.0E-01	3.4E-04	1.6E-07	7.7E-11	3.7E-14	1.8E-17	8.5E-21	4.1E-24	2.0E-27	9.4E-31
30		7.0E-01	3.4E-04	1.6E-07	7.7E-11	3.7E-14	1.8E-17	8.5E-21	4.1E-24	2.0E-27
60			7.0E-01	3.4E-04	1.6E-07	7.7E-11	3.7E-14	1.8E-17	8.5E-21	4.1E-24
90				6.9E-01	3.3E-04	1.6E-07	7.7E-11	3.7E-14	1.8E-17	8.4E-21
120					6.9E-01	3.3E-04	1.6E-07	7.6E-11	3.6E-14	1.8E-17
150						6.8E-01	3.3E-04	1.6E-07	7.5E-11	3.6E-14
180							6.7E-01	3.2E-04	1.5E-07	7.4E-11
210								6.5E-01	3.2E-04	1.5E-07
240									6.4E-01	3.1E-04
270										6.4E-01

Table A21b. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 111In into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	4.0E-11	5.9E-14	3.8E-17	2.5E-20	1.6E-23	1.0E-26	6.6E-30	4.3E-33	2.8E-36	
30		2.0E-06	3.2E-09	2.1E-12	1.3E-15	8.6E-19	5.5E-22	3.6E-25	2.3E-28	1.5E-31
60			6.4E-05	1.6E-07	1.0E-10	6.7E-14	4.3E-17	2.8E-20	1.8E-23	1.2E-26
90				6.0E-04	4.7E-06	3.1E-09	2.0E-12	1.3E-15	8.3E-19	5.3E-22
120					1.6E-03	1.0E-05	6.7E-09	4.4E-12	2.8E-15	1.8E-18
150						3.0E-03	1.8E-05	1.2E-08	7.5E-12	4.9E-15
180							5.1E-03	2.8E-05	1.8E-08	1.2E-11
210								7.9E-03	4.0E-05	2.6E-08
240									1.1E-02	4.9E-05
270										1.2E-02

Table A22a. Maximum fraction of activity deposited in the maternal body after introduction of 123I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	1.7E-01									
30		1.7E-01								
60			1.7E-01							
90				1.6E-01						
120					1.6E-01					
150						1.6E-01				
180							1.6E-01			
210								1.5E-01		
240									1.5E-01	
270										1.5E-01

Table A22b. Maximum fraction of activity deposited in the maternal thyroid after introduction of 123I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	1.3E-01									
30		1.3E-01								
60			1.3E-01							
90				1.3E-01						
120					1.3E-01					
150						1.3E-01				
180							1.3E-01			
210								1.3E-01		
240									1.3E-01	
270										1.3E-01

Table A22c. Maximum fraction of activity deposited in the embryo/fetus after introduction of 123I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	4.5E-11									
30		1.2E-06								
60			3.6E-05							
90				2.4E-04						
120					9.1E-04					
150						2.0E-03				
180							3.6E-03			
210								5.9E-03		
240									8.4E-03	
270										9.6E-03

Table A22d. Maximum fraction of activity deposited in the fetal thyroid after introduction of 123I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0										
30										
60										
90				2.1E-04						
120					1.4E-03					
150						5.0E-03				
180							8.5E-03			
210								1.2E-02		
240									1.6E-02	
270										1.7E-02

Table A22e. Residence time in hours of 123I activity deposited in the maternal body after introduction into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	2.4E-01									
30		2.4E-01								
60			2.4E-01							
90				2.4E-01						
120					2.4E-01					
150						2.3E-01				
180							2.3E-01			
210								2.2E-01		
240									2.2E-01	
270										2.2E-01

Table A22f. Residence time in hours of 123I activity deposited in the maternal thyroid after introduction into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	1.7E-01									
30		1.7E-01								
60			1.7E-01							
90				1.7E-01						
120					1.7E-01					
150						1.7E-01				
180							1.7E-01			
210								1.6E-01		
240									1.6E-01	
270										1.6E-01

Table A22g. Residence time in hours of 123I activity deposited in the embryo/fetus after introduction into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	3.8E-11									
30		1.7E-06								
60			5.1E-05							
90				3.4E-04						
120					1.3E-03					
150						3.0E-03				
180							5.3E-03			
210								8.8E-03		
240									1.3E-02	
270										1.6E-02

Table A22h. Residence time in hours of 123I activity deposited in the fetal thyroid after introduction into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0										
30										
60										
90				2.8E-04						
120					1.8E-03					
150						6.5E-03				
180							1.1E-02			
210								1.6E-02		
240									2.0E-02	
270										2.4E-02

Table A23a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 125I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	5.2E-02	1.0E-02	6.3E-03	3.7E-03	2.2E-03	1.3E-03	7.8E-04	4.6E-04	2.7E-04	1.6E-04
30		5.2E-02	1.0E-02	6.3E-03	3.7E-03	2.2E-03	1.3E-03	7.8E-04	4.6E-04	2.7E-04
60			5.2E-02	1.0E-02	6.3E-03	3.7E-03	2.2E-03	1.3E-03	7.8E-04	4.6E-04
90				5.1E-02	1.0E-02	6.3E-03	3.7E-03	2.2E-03	1.3E-03	7.8E-04
120					5.1E-02	1.0E-02	6.3E-03	3.7E-03	2.2E-03	1.3E-03
150						4.9E-02	1.0E-02	6.3E-03	3.7E-03	2.2E-03
180							4.7E-02	1.0E-02	6.3E-03	3.7E-03
210								4.5E-02	1.0E-02	6.3E-03
240									4.3E-02	1.0E-02
270										4.3E-02

Table A23b. Fraction of activity deposited in the maternal thyroid and fractions retained at start of subsequent 30-day periods after injection of 125I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	2.9E-01	1.9E-01	1.1E-01	6.5E-02	3.9E-02	2.3E-02	1.4E-02	8.1E-03	4.8E-03	2.9E-03
30		2.9E-01	1.9E-01	1.1E-01	6.5E-02	3.9E-02	2.3E-02	1.4E-02	8.1E-03	4.8E-03
60			2.9E-01	1.9E-01	1.1E-01	6.5E-02	3.9E-02	2.3E-02	1.4E-02	8.1E-03
90				2.9E-01	1.9E-01	1.1E-01	6.5E-02	3.9E-02	2.3E-02	1.4E-02
120					2.9E-01	1.9E-01	1.1E-01	6.5E-02	3.9E-02	2.3E-02
150						2.9E-01	1.8E-01	1.1E-01	6.5E-02	3.9E-02
180							2.9E-01	1.8E-01	1.1E-01	6.5E-02
210								2.9E-01	1.8E-01	1.1E-01
240									2.8E-01	1.8E-01
270										2.8E-01

Table A23c. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 125I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	2.9E-11	3.9E-09	7.1E-08	4.0E-07	1.4E-06	2.9E-06	3.8E-06	3.7E-06	3.1E-06	2.3E-06
30		4.1E-07	1.2E-07	6.8E-07	2.4E-06	4.9E-06	6.4E-06	6.3E-06	5.3E-06	3.8E-06
60			1.1E-05	1.1E-06	4.1E-06	8.2E-06	1.1E-05	1.0E-05	8.9E-06	6.4E-06
90				8.5E-05	1.3E-05	1.5E-05	1.8E-05	1.8E-05	1.5E-05	1.1E-05
120					3.5E-04	6.6E-05	3.8E-05	3.1E-05	2.5E-05	1.8E-05
150						8.6E-04	2.1E-04	7.9E-05	4.8E-05	3.1E-05
180							1.5E-03	3.4E-04	1.2E-04	6.0E-05
210								2.4E-03	5.0E-04	1.6E-04
240									3.2E-03	6.3E-04
270										3.6E-03

Table A23d. Fraction of activity deposited in the fetal thyroid and fractions retained at start of subsequent 30-day periods after injection of 125I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0				2.1E-06	1.3E-05	3.3E-05	4.4E-05	4.3E-05	3.6E-05	2.6E-05
30				3.6E-06	2.2E-05	5.5E-05	7.5E-05	7.2E-05	6.0E-05	4.3E-05
60				5.9E-06	3.6E-05	9.2E-05	1.3E-04	1.2E-04	1.0E-04	7.3E-05
90				4.9E-04	1.5E-04	1.7E-04	2.1E-04	2.0E-04	1.7E-04	1.2E-04
120					3.2E-03	8.5E-04	4.6E-04	3.6E-04	2.9E-04	2.1E-04
150						1.1E-02	2.7E-03	9.7E-04	5.5E-04	3.6E-04
180							1.9E-02	4.5E-03	1.5E-03	7.1E-04
210								2.8E-02	6.6E-03	2.0E-03
240									3.5E-02	8.3E-03
270										3.8E-02

Table A24a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 131I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	4.8E-02	1.1E-03	7.1E-05	4.5E-06	2.8E-07	1.8E-08	1.1E-09	7.1E-11	4.5E-12	2.8E-13
30		4.8E-02	1.1E-03	7.1E-05	4.5E-06	2.8E-07	1.8E-08	1.1E-09	7.1E-11	4.5E-12
60			4.8E-02	1.1E-03	7.1E-05	4.5E-06	2.8E-07	1.8E-08	1.1E-09	7.1E-11
90				4.8E-02	1.1E-03	7.1E-05	4.5E-06	2.8E-07	1.8E-08	1.1E-09
120					4.7E-02	1.1E-03	7.1E-05	4.5E-06	2.8E-07	1.8E-08
150						4.5E-02	1.1E-03	7.1E-05	4.5E-06	2.8E-07
180							4.4E-02	1.1E-03	7.1E-05	4.5E-06
210								4.2E-02	1.1E-03	7.1E-05
240									4.0E-02	1.1E-03
270										3.9E-02

Table A24b. Fraction of activity deposited in the maternal thyroid and fractions retained at start of subsequent 30-day periods after injection of 131I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	2.7E-01	2.0E-02	1.2E-03	7.9E-05	5.0E-06	3.1E-07	2.0E-08	1.2E-09	7.9E-11	5.0E-12
30		2.7E-01	2.0E-02	1.2E-03	7.9E-05	5.0E-06	3.1E-07	2.0E-08	1.2E-09	7.9E-11
60			2.7E-01	2.0E-02	1.2E-03	7.9E-05	5.0E-06	3.1E-07	2.0E-08	1.2E-09
90				2.7E-01	2.0E-02	1.2E-03	7.9E-05	5.0E-06	3.1E-07	2.0E-08
120					2.7E-01	2.0E-02	1.2E-03	7.9E-05	5.0E-06	3.1E-07
150						2.7E-01	2.0E-02	1.2E-03	7.9E-05	5.0E-06
180							2.7E-01	2.0E-02	1.2E-03	7.9E-05
210								2.7E-01	2.0E-02	1.2E-03
240									2.6E-01	1.9E-02
270										2.6E-01

Table A24c. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 131I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	2.7E-11	4.2E-10	8.1E-10	4.8E-10	1.8E-10	4.0E-11	5.5E-12	5.8E-13	5.1E-14	4.0E-15
30		3.8E-07	1.3E-08	7.6E-09	2.9E-09	6.3E-10	8.8E-11	9.1E-12	8.1E-13	6.2E-14
60			1.0E-05	1.2E-07	4.6E-08	9.9E-09	1.4E-09	1.4E-10	1.3E-11	9.9E-13
90				7.9E-05	1.4E-06	1.7E-07	2.2E-08	2.3E-09	2.0E-10	1.6E-11
120					3.3E-04	7.0E-06	4.3E-07	3.8E-08	3.3E-09	2.5E-10
150						8.0E-04	2.2E-05	8.9E-07	5.7E-08	4.0E-09
180							1.4E-03	3.6E-05	1.4E-06	7.3E-08
210								2.2E-03	5.3E-05	1.8E-06
240									3.0E-03	6.7E-05
270										3.3E-03

Table A24d. Fraction of activity deposited in the fetal thyroid and fractions retained at start of subsequent 30-day periods after injection of 131I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0				2.5E-09	1.7E-09	4.4E-10	6.4E-11	6.6E-12	5.8E-13	4.5E-14
30				4.0E-08	2.6E-08	7.0E-09	1.0E-09	1.0E-10	9.2E-12	7.1E-13
60				6.2E-07	4.1E-07	1.1E-07	1.6E-08	1.7E-09	1.5E-10	1.1E-11
90				4.6E-04	1.6E-05	1.9E-06	2.6E-07	2.6E-08	2.3E-09	1.8E-10
120					2.9E-03	9.1E-05	5.2E-06	4.4E-07	3.7E-08	2.8E-09
150						1.1E-02	2.9E-04	1.1E-05	6.7E-07	4.6E-08
180							1.8E-02	4.8E-04	1.7E-05	8.5E-07
210								2.6E-02	7.0E-04	2.2E-05
240									3.3E-02	8.9E-04
270										3.6E-02

Table A25a. Maximum fraction of activity deposited in the maternal body after introduction of 132I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	2.2E-01									
30		2.2E-01								
60			2.2E-01							
90				2.2E-01						
120					2.2E-01					
150						2.1E-01				
180							2.1E-01			
210								2.1E-01		
240									2.0E-01	
270										2.0E-01

Table A25b. Maximum Fraction of activity deposited in the maternal thyroid after introduction of 132I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	3.1E-02									
30		3.1E-02								
60			3.1E-02							
90				3.1E-02						
120					3.1E-02					
150						2.9E-02				
180							3.1E-02			
210								3.1E-02		
240									3.1E-02	
270										3.1E-02

Table A25c. Maximum Fraction of activity deposited in the embryo/fetus after introduction of 132I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	2.4E-11									
30		1.5E-06								
60			4.6E-05							
90				3.0E-04						
120					1.2E-03					
150						2.6E-03				
180							4.7E-03			
210								7.8E-03		
240									1.1E-02	
270										1.3E-02

Table A25d. Maximum Fraction of activity deposited in the fetal thyroid after introduction of 132I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0										
30										
60										
90				5.1E-05						
120					3.4E-04					
150						1.2E-03				
180							2.1E-03			
210								3.0E-03		
240									3.9E-03	
270										4.3E-03

Table A25e. Residence time in hours of 132I activity deposited in the maternal body after introduction into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	8.8E-02									
30		8.8E-02								
60			8.8E-02							
90				8.8E-02						
120					8.8E-02					
150						8.7E-02				
180							8.6E-02			
210								8.4E-02		
240									8.3E-02	
270										8.1E-02

Table A25f. Residence time in hours of 132I activity deposited in the maternal thyroid after introduction into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	9.7E-03									
30		9.7E-03								
60			9.7E-03							
90				9.7E-03						
120					9.7E-03					
150						9.7E-03				
180							9.7E-03			
210								9.6E-03		
240									9.6E-03	
270										9.6E-03

Table A25g. Residence time in hours of 132I activity deposited in the embryo/fetus after introduction into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	7.7E-12									
30		6.3E-07								
60			1.9E-05							
90				1.2E-04						
120					4.8E-04					
150						1.0E-03				
180							1.9E-03			
210								3.2E-03		
240									4.6E-03	
270										6.0E-03

Table A25h. Residence time in hours of 132I activity deposited in the fetal thyroid after introduction into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0										
30										
60										
90				1.6E-05						
120					1.1E-04					
150						3.8E-04				
180							6.4E-04			
210								9.4E-04		
240									1.2E-03	
270										1.5E-03

Table A26a. Maximum fraction of activity deposited in the maternal body after introduction of 133I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	1.3E-01									
30		1.3E-01								
60			1.3E-01							
90				1.3E-01						
120					1.3E-01					
150						1.2E-01				
180							1.2E-01			
210								1.2E-01		
240									1.1E-01	
270										1.1E-01

Table A26b. Maximum fraction of activity deposited in the maternal thyroid after introduction of 133I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	1.6E-01									
30		1.6E-01								
60			1.6E-01							
90				1.6E-01						
120					1.6E-01					
150						1.6E-01				
180							1.6E-01			
210								1.6E-01		
240									1.6E-01	
270										1.6E-01

Table A26c. Maximum fraction of activity deposited in the embryo/fetus after introduction of 133I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	4.3E-11									
30		9.8E-07								
60			2.8E-05							
90				1.8E-04						
120					7.1E-04					
150						1.6E-03				
180							2.8E-03			
210								4.6E-03		
240									6.5E-03	
270										7.4E-03

Table A26d. Maximum fraction of activity deposited in the fetal thyroid after introduction of 133I into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0										
30										
60										
90				2.7E-04						
120					1.8E-03					
150						6.3E-03				
180							1.0E-02			
210								1.5E-02		
240									2.0E-02	
270										2.2E-02

Table A26e. Residence time in hours of 133I activity deposited in the maternal body after introduction into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	2.7E-01									
30		2.7E-01								
60			2.7E-01							
90				2.7E-01						
120					2.7E-01					
150						2.6E-01				
180							2.6E-01			
210								2.5E-01		
240									2.5E-01	
270										2.4E-01

Table A26f. Residence time in hours of 133I activity deposited in the maternal thyroid after introduction into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	3.0E-01									
30		3.0E-01								
60			3.0E-01							
90				3.0E-01						
120					3.0E-01					
150						3.0E-01				
180							2.9E-01			
210								2.9E-01		
240									2.9E-01	
270										2.9E-01

Table A26g. Residence time in hours of 133I activity deposited in the embryo/fetus after introduction into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	4.8E-11									
30		2.0E-06								
60			5.7E-05							
90				3.9E-04						
120					1.5E-03					
150						3.5E-03				
180							6.3E-03			
210								1.0E-02		
240									1.5E-02	
270										1.9E-02

Table A26h. Residence time in hours of 133I activity deposited in the fetal thyroid after introduction into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0										
30										
60										
90				4.9E-04						
120					3.2E-03					
150						1.1E-02				
180							1.9E-02			
210								2.8E-02		
240									3.5E-02	
270										4.3E-02

Table A27a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 134Cs into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	9.9E-01	7.6E-01	5.8E-01	4.4E-01	3.3E-01	2.5E-01	1.8E-01	1.2E-01	7.8E-02	4.9E-02
30		9.9E-01	7.6E-01	5.8E-01	4.4E-01	3.3E-01	2.4E-01	1.6E-01	1.0E-01	6.5E-02
60			9.9E-01	7.6E-01	5.7E-01	4.3E-01	3.2E-01	2.1E-01	1.3E-01	8.6E-02
90				9.9E-01	7.6E-01	5.7E-01	4.2E-01	2.8E-01	1.8E-01	1.1E-01
120					9.9E-01	7.5E-01	5.5E-01	3.7E-01	2.3E-01	1.5E-01
150						9.8E-01	7.3E-01	4.9E-01	3.1E-01	2.0E-01
180							9.7E-01	6.6E-01	4.2E-01	2.6E-01
210								9.5E-01	6.1E-01	3.9E-01
240									9.4E-01	6.1E-01
270										9.3E-01

Table A27b. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 134Cs into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	5.5E-10	5.0E-06	1.2E-04	5.8E-04	1.7E-03	2.9E-03	3.9E-03	4.4E-03	4.1E-03	3.0E-03
30		7.8E-06	1.5E-04	7.6E-04	2.2E-03	3.8E-03	5.1E-03	5.8E-03	5.4E-03	4.0E-03
60			2.1E-04	1.0E-03	3.0E-03	5.0E-03	6.7E-03	7.7E-03	7.1E-03	5.3E-03
90				1.4E-03	3.9E-03	6.5E-03	8.8E-03	1.0E-02	9.3E-03	7.0E-03
120					5.3E-03	8.6E-03	1.2E-02	1.3E-02	1.2E-02	9.2E-03
150						1.1E-02	1.5E-02	1.8E-02	1.6E-02	1.2E-02
180							2.1E-02	2.4E-02	2.2E-02	1.6E-02
210								3.5E-02	3.2E-02	2.4E-02
240									5.0E-02	3.7E-02
270										5.7E-02

Table A28a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 137Cs into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	9.9E-01	7.8E-01	6.1E-01	4.7E-01	3.7E-01	2.8E-01	2.1E-01	1.5E-01	9.6E-02	6.2E-02
30		9.9E-01	7.8E-01	6.1E-01	4.7E-01	3.7E-01	2.8E-01	1.9E-01	1.2E-01	8.0E-02
60			9.9E-01	7.8E-01	6.1E-01	4.7E-01	3.5E-01	2.4E-01	1.6E-01	1.0E-01
90				9.9E-01	7.8E-01	6.0E-01	4.5E-01	3.1E-01	2.0E-01	1.3E-01
120					9.9E-01	7.7E-01	5.8E-01	4.0E-01	2.6E-01	1.7E-01
150						9.8E-01	7.5E-01	5.1E-01	3.3E-01	2.2E-01
180							9.7E-01	6.8E-01	4.4E-01	2.9E-01
210								9.5E-01	6.3E-01	4.1E-01
240									9.4E-01	6.2E-01
270										9.3E-01

Table A28b. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 137Cs into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	5.5E-10	5.2E-06	1.2E-04	6.3E-04	1.9E-03	3.3E-03	4.5E-03	5.3E-03	5.0E-03	3.8E-03
30		7.8E-06	1.6E-04	8.0E-04	2.4E-03	4.2E-03	5.8E-03	6.8E-03	6.4E-03	4.9E-03
60			2.1E-04	1.0E-03	3.1E-03	5.4E-03	7.4E-03	8.7E-03	8.2E-03	6.3E-03
90				1.4E-03	4.0E-03	6.9E-03	9.5E-03	1.1E-02	1.1E-02	8.1E-03
120					5.3E-03	8.8E-03	1.2E-02	1.4E-02	1.4E-02	1.0E-02
150						1.2E-02	1.6E-02	1.8E-02	1.7E-02	1.3E-02
180							2.1E-02	2.4E-02	2.3E-02	1.8E-02
210								3.5E-02	3.3E-02	2.5E-02
240									5.0E-02	3.8E-02
270										5.7E-02

Table A29a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 141Ce into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	9.8E-01	5.2E-01	2.8E-01	1.4E-01	7.6E-02	4.0E-02	2.1E-02	1.1E-02	5.7E-03	3.0E-03
30		9.8E-01	5.2E-01	2.8E-01	1.4E-01	7.6E-02	4.0E-02	2.1E-02	1.1E-02	5.7E-03
60			9.8E-01	5.2E-01	2.8E-01	1.4E-01	7.6E-02	4.0E-02	2.1E-02	1.1E-02
90				9.8E-01	5.2E-01	2.8E-01	1.4E-01	7.6E-02	4.0E-02	2.1E-02
120					9.8E-01	5.2E-01	2.8E-01	1.4E-01	7.5E-02	4.0E-02
150						9.8E-01	5.2E-01	2.8E-01	1.4E-01	7.5E-02
180							9.8E-01	5.2E-01	2.8E-01	1.4E-01
210								9.8E-01	5.2E-01	2.8E-01
240									9.8E-01	5.2E-01
270										9.8E-01

Table A29b. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 141Ce into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	2.7E-12	1.8E-12	9.3E-13	4.9E-13	2.6E-13	1.4E-13	7.2E-14	3.8E-14	2.0E-14	1.1E-14
30		1.4E-07	7.7E-08	4.1E-08	2.2E-08	1.1E-08	6.0E-09	3.2E-09	1.7E-09	8.7E-10
60			4.0E-06	2.3E-06	1.2E-06	6.3E-07	3.3E-07	1.7E-07	9.2E-08	4.9E-08
90				2.6E-05	1.5E-05	7.8E-06	4.1E-06	2.2E-06	1.2E-06	6.1E-07
120					1.0E-04	5.7E-05	3.0E-05	1.6E-05	8.4E-06	4.4E-06
150						2.2E-04	1.3E-04	6.6E-05	3.5E-05	1.8E-05
180							4.1E-04	2.3E-04	1.2E-04	6.4E-05
210								6.8E-04	3.8E-04	2.0E-04
240									9.8E-04	5.5E-04
270										1.1E-03

Table A30a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 144Ce into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	1.0E+00	9.2E-01	8.5E-01	7.9E-01	7.3E-01	6.7E-01	6.2E-01	5.7E-01	5.3E-01	4.9E-01
30		1.0E+00	9.2E-01	8.5E-01	7.9E-01	7.3E-01	6.7E-01	6.2E-01	5.7E-01	5.3E-01
60			1.0E+00	9.2E-01	8.5E-01	7.9E-01	7.3E-01	6.7E-01	6.2E-01	5.7E-01
90				1.0E+00	9.2E-01	8.5E-01	7.9E-01	7.3E-01	6.7E-01	6.2E-01
120					1.0E+00	9.2E-01	8.5E-01	7.9E-01	7.3E-01	6.7E-01
150						1.0E+00	9.2E-01	8.5E-01	7.9E-01	7.3E-01
180							1.0E+00	9.2E-01	8.5E-01	7.9E-01
210								1.0E+00	9.2E-01	8.5E-01
240									1.0E+00	9.2E-01
270										1.0E+00

Table A30b. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 144Ce into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	2.8E-12	3.1E-12	2.9E-12	2.7E-12	2.5E-12	2.3E-12	2.2E-12	2.0E-12	1.9E-12	1.7E-12
30		1.4E-07	1.4E-07	1.3E-07	1.2E-07	1.1E-07	1.0E-07	9.4E-08	8.8E-08	8.1E-08
60			4.1E-06	4.0E-06	3.7E-06	3.4E-06	3.2E-06	3.0E-06	2.8E-06	2.6E-06
90				2.7E-05	2.6E-05	2.4E-05	2.3E-05	2.1E-05	2.0E-05	1.8E-05
120					1.0E-04	1.0E-04	9.4E-05	8.7E-05	8.1E-05	7.5E-05
150						2.3E-04	2.2E-04	2.1E-04	1.9E-04	1.8E-04
180							4.2E-04	4.0E-04	3.8E-04	3.5E-04
210								7.0E-04	6.8E-04	6.3E-04
240									1.0E-03	9.7E-04
270										1.2E-03

Table A31a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 191Os into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	7.3E-01	5.0E-02	9.0E-03	2.1E-03	4.8E-04	1.1E-04	2.6E-05	6.1E-06	1.4E-06	3.3E-07
30		7.3E-01	5.0E-02	9.0E-03	2.1E-03	4.8E-04	1.1E-04	2.6E-05	6.1E-06	1.4E-06
60			7.3E-01	5.0E-02	9.0E-03	2.1E-03	4.8E-04	1.1E-04	2.6E-05	6.1E-06
90				7.3E-01	5.0E-02	9.0E-03	2.1E-03	4.8E-04	1.1E-04	2.6E-05
120					7.3E-01	5.0E-02	9.0E-03	2.0E-03	4.8E-04	1.1E-04
150						7.3E-01	5.0E-02	9.0E-03	2.0E-03	4.8E-04
180							7.3E-01	5.0E-02	9.0E-03	2.0E-03
210								7.3E-01	5.0E-02	9.0E-03
240									7.3E-01	5.0E-02
270										7.3E-01

Table A31b. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 191Os into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	6.2E-11	2.0E-11	5.3E-12	1.4E-12	3.5E-13	9.2E-14	2.4E-14	6.2E-15	1.6E-15	4.1E-16
30		3.1E-06	8.9E-07	2.3E-07	6.0E-08	1.5E-08	4.0E-09	1.0E-09	2.7E-10	7.0E-11
60			9.1E-05	2.6E-05	6.7E-06	1.7E-06	4.5E-07	1.2E-07	3.0E-08	7.8E-09
90				1.8E-05	5.2E-06	1.3E-06	3.5E-07	9.0E-08	2.3E-08	6.0E-09
120					7.0E-05	2.0E-05	5.1E-06	1.3E-06	3.4E-07	8.9E-08
150						1.6E-04	4.4E-05	1.1E-05	2.9E-06	7.6E-07
180							2.8E-04	8.0E-05	2.1E-05	5.3E-06
210								4.7E-04	1.3E-04	3.5E-05
240									6.8E-04	1.9E-04
270										8.0E-04

Table A32a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 192Ir into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	7.8E-01	4.4E-01	3.0E-01	2.0E-01	1.4E-01	9.4E-02	6.4E-02	4.3E-02	2.9E-02	2.0E-02
30		7.8E-01	4.4E-01	3.0E-01	2.0E-01	1.4E-01	9.4E-02	6.4E-02	4.3E-02	2.9E-02
60			7.8E-01	4.4E-01	3.0E-01	2.0E-01	1.4E-01	9.3E-02	6.4E-02	4.3E-02
90				7.8E-01	4.4E-01	3.0E-01	2.0E-01	1.4E-01	9.3E-02	6.4E-02
120					7.8E-01	4.4E-01	3.0E-01	2.0E-01	1.4E-01	9.3E-02
150						7.8E-01	4.4E-01	3.0E-01	2.0E-01	1.4E-01
180							7.8E-01	4.4E-01	3.0E-01	2.0E-01
210								7.8E-01	4.4E-01	3.0E-01
240									7.8E-01	4.4E-01
270										7.8E-01

Table A32b. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 192Ir into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	6.5E-11	5.9E-11	4.5E-11	3.4E-11	2.6E-11	1.9E-11	1.5E-11	1.1E-11	8.3E-12	6.3E-12
30		3.2E-06	2.6E-06	2.0E-06	1.5E-06	1.1E-06	8.4E-07	6.4E-07	4.8E-07	3.6E-07
60			9.5E-05	7.5E-05	5.7E-05	4.3E-05	3.2E-05	2.4E-05	1.8E-05	1.4E-05
90				3.1E-05	2.5E-05	1.9E-05	1.4E-05	1.1E-05	8.1E-06	6.1E-06
120					1.2E-04	9.6E-05	7.3E-05	5.5E-05	4.1E-05	3.1E-05
150						2.7E-04	2.1E-04	1.6E-04	1.2E-04	9.1E-05
180							4.9E-04	3.9E-04	2.9E-04	2.2E-04
210								8.2E-04	6.5E-04	4.9E-04
240									1.2E-03	9.4E-04
270										1.4E-03

Table A33a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 201Tl into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	7.5E-01	1.3E-04	1.8E-08	2.4E-12	3.2E-16	4.3E-20	5.8E-24	7.7E-28	1.0E-31	1.4E-35
30		7.5E-01	1.3E-04	1.8E-08	2.4E-12	3.2E-16	4.3E-20	5.7E-24	7.6E-28	1.0E-31
60			7.5E-01	1.3E-04	1.8E-08	2.4E-12	3.2E-16	4.3E-20	5.7E-24	7.6E-28
90				7.5E-01	1.3E-04	1.8E-08	2.4E-12	3.2E-16	4.2E-20	5.7E-24
120					7.5E-01	1.3E-04	1.8E-08	2.4E-12	3.2E-16	4.2E-20
150						7.4E-01	1.3E-04	1.8E-08	2.4E-12	3.2E-16
180							7.4E-01	1.3E-04	1.8E-08	2.4E-12
210								7.4E-01	1.3E-04	1.8E-08
240									7.3E-01	1.3E-04
270										7.3E-01

Table A33b. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 201Tl into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	3.8E-10	8.2E-10	3.3E-12	1.5E-15	7.6E-19	2.2E-22	5.5E-26	1.2E-29	2.4E-33	3.8E-37
30		5.4E-06	2.5E-08	1.1E-11	5.6E-15	1.7E-18	4.1E-22	9.2E-26	1.8E-29	2.8E-33
60			1.4E-04	8.1E-08	4.2E-11	1.2E-14	3.1E-18	6.9E-22	1.3E-25	2.1E-29
90				4.8E-04	3.1E-07	9.3E-11	2.3E-14	5.2E-18	9.9E-22	1.6E-25
120					1.8E-03	7.0E-07	1.7E-10	3.8E-14	7.4E-18	1.2E-21
150						3.9E-03	1.3E-06	2.9E-10	5.5E-14	8.7E-18
180							7.2E-03	2.1E-06	4.1E-10	6.5E-14
210								1.2E-02	3.1E-06	4.8E-10
240									1.7E-02	3.6E-06
270										2.0E-02

Table A34a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 210Pb into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	4.7E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.4E-01
30		4.7E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01
60			4.7E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01
90				4.7E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01
120					4.7E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01
150						4.7E-01	2.5E-01	2.5E-01	2.5E-01	2.5E-01
180							4.7E-01	2.5E-01	2.4E-01	2.4E-01
210								4.6E-01	2.4E-01	2.4E-01
240									4.6E-01	2.4E-01
270										4.6E-01

Table A34b. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 210Pb into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	1.8E-10	3.6E-07	3.8E-06	9.3E-06	1.3E-05	1.1E-05	7.3E-06	4.5E-06	2.4E-06	1.0E-06
30		2.6E-06	1.1E-05	2.5E-05	3.6E-05	2.9E-05	2.0E-05	1.2E-05	6.5E-06	2.8E-06
60			7.0E-05	7.2E-05	9.7E-05	7.9E-05	5.3E-05	3.3E-05	1.8E-05	7.6E-06
90				4.6E-04	3.8E-04	3.2E-04	2.5E-04	2.0E-04	1.5E-04	1.2E-04
120					1.8E-03	1.6E-03	1.4E-03	1.2E-03	1.1E-03	9.9E-04
150						4.0E-03	3.8E-03	3.4E-03	3.1E-03	2.8E-03
180							7.3E-03	7.3E-03	6.5E-03	5.9E-03
210								1.2E-02	1.1E-02	1.0E-02
240									1.8E-02	1.5E-02
270										2.1E-02

Table A35. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 210Bi into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	3.8E-11	8.3E-13	1.3E-14	2.1E-16	3.3E-18	5.2E-20	8.2E-22	1.3E-23	2.0E-25	3.2E-27
30		1.9E-06	3.6E-08	5.7E-10	9.1E-12	1.4E-13	2.3E-15	3.6E-17	5.6E-19	8.9E-21
60			5.6E-05	1.1E-06	1.7E-08	2.6E-10	4.2E-12	6.6E-14	1.0E-15	1.6E-17
90				3.7E-04	7.0E-06	1.1E-07	1.7E-09	2.7E-11	4.3E-13	6.9E-15
120					1.4E-03	2.7E-05	4.2E-07	6.7E-09	1.1E-10	1.7E-12
150						3.1E-03	5.9E-05	9.4E-07	1.5E-08	2.3E-10
180							5.7E-03	1.1E-04	1.7E-06	2.7E-08
210								9.6E-03	1.8E-04	2.8E-06
240									1.4E-02	2.6E-04
270										1.6E-02

Table A36. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 210Po into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	1.7E-11	1.5E-11	1.3E-11	1.1E-11	9.4E-12	8.1E-12	7.0E-12	6.0E-12	5.2E-12	4.5E-12
30		6.0E-06	5.2E-06	4.5E-06	3.9E-06	3.3E-06	2.9E-06	2.5E-06	2.1E-06	1.8E-06
60			1.8E-04	1.6E-04	1.3E-04	1.2E-04	1.0E-04	8.6E-05	7.4E-05	6.4E-05
90				1.2E-04	1.0E-04	8.9E-05	7.7E-05	6.6E-05	5.7E-05	4.9E-05
120					4.6E-04	4.0E-04	3.5E-04	3.0E-04	2.6E-04	2.2E-04
150						1.0E-03	8.9E-04	7.7E-04	6.6E-04	5.7E-04
180							1.9E-03	1.6E-03	1.4E-03	1.2E-03
210								3.2E-03	2.7E-03	2.3E-03
240									4.6E-03	3.9E-03
270										5.3E-03

Table A37. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 224Ra into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	2.0E-10	3.6E-09	1.3E-10	1.0E-12	4.9E-15	1.3E-17	2.9E-20	5.8E-23	1.0E-25	1.4E-28
30		2.8E-06	1.1E-07	8.7E-10	4.1E-12	1.1E-14	2.4E-17	4.8E-20	8.3E-23	1.2E-25
60			7.5E-05	7.3E-07	3.4E-09	9.0E-12	2.0E-14	4.0E-17	6.9E-20	9.6E-23
90				5.0E-04	3.2E-06	8.8E-09	2.1E-11	4.8E-14	1.1E-16	2.4E-19
120					1.9E-03	9.4E-06	2.5E-08	6.6E-11	1.8E-13	5.0E-16
150						4.2E-03	2.0E-05	5.5E-08	1.5E-10	4.2E-13
180							7.6E-03	3.7E-05	9.8E-08	2.7E-10
210								1.3E-02	5.6E-05	1.4E-07
240									1.8E-02	7.1E-05
270										2.1E-02

Table A38. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 226Ra into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	2.4E-10	1.1E-06	1.1E-05	2.7E-05	3.6E-05	2.8E-05	1.8E-05	1.1E-05	5.5E-06	2.2E-06
30		3.3E-06	3.2E-05	7.5E-05	1.0E-04	8.0E-05	5.2E-05	3.0E-05	1.5E-05	6.4E-06
60			9.0E-05	2.1E-04	2.9E-04	2.3E-04	1.5E-04	8.6E-05	4.4E-05	1.8E-05
90				6.0E-04	9.3E-04	7.5E-04	5.2E-04	3.5E-04	2.3E-04	1.6E-04
120					2.3E-03	2.8E-03	2.2E-03	1.7E-03	1.3E-03	1.1E-03
150						5.1E-03	6.0E-03	4.7E-03	3.7E-03	3.1E-03
180							9.2E-03	1.1E-02	8.4E-03	6.7E-03
210								1.5E-02	1.6E-02	1.2E-02
240									2.2E-02	2.1E-02
270										2.5E-02

Table A39. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 227Th into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	2.6E-11	2.0E-11	6.7E-12	2.2E-12	7.2E-13	2.4E-13	7.8E-14	2.6E-14	8.5E-15	2.8E-15
30		9.1E-07	4.2E-07	1.4E-07	4.6E-08	1.5E-08	5.0E-09	1.6E-09	5.4E-10	1.8E-10
60			2.6E-05	1.2E-05	3.8E-06	1.3E-06	4.1E-07	1.4E-07	4.5E-08	1.5E-08
90				8.7E-06	3.9E-06	1.3E-06	4.2E-07	1.4E-07	4.6E-08	1.5E-08
120					3.3E-05	1.5E-05	4.9E-06	1.6E-06	5.3E-07	1.7E-07
150						7.3E-05	3.3E-05	1.1E-05	3.5E-06	1.2E-06
180							1.3E-04	5.9E-05	1.9E-05	6.4E-06
210								2.2E-04	9.9E-05	3.3E-05
240									3.2E-04	1.4E-04
270										3.7E-04

Table A40. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 230Th ot 232Th into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	2.7E-11	6.1E-11	6.1E-11	6.1E-11	6.1E-11	6.1E-11	6.1E-11	6.1E-11	6.1E-11	6.1E-11
30		9.4E-07	1.3E-06	1.3E-06	1.3E-06	1.3E-06	1.3E-06	1.3E-06	1.3E-06	1.3E-06
60			2.7E-05	3.5E-05	3.5E-05	3.5E-05	3.5E-05	3.5E-05	3.5E-05	3.5E-05
90				9.0E-06	1.2E-05	1.2E-05	1.2E-05	1.2E-05	1.2E-05	1.2E-05
120					3.5E-05	4.5E-05	4.5E-05	4.5E-05	4.5E-05	4.5E-05
150						7.6E-05	9.9E-05	9.9E-05	9.9E-05	9.9E-05
180							1.4E-04	1.8E-04	1.8E-04	1.8E-04
210								2.3E-04	3.0E-04	3.0E-04
240									3.3E-04	4.3E-04
270										3.9E-04

Table A41a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 234Th into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	8.7E-01	3.6E-01	1.5E-01	6.1E-02	2.5E-02	1.0E-02	4.4E-03	1.8E-03	7.6E-04	3.2E-04
30		8.7E-01	3.6E-01	1.5E-01	6.1E-02	2.5E-02	1.0E-02	4.4E-03	1.8E-03	7.6E-04
60			8.7E-01	3.6E-01	1.5E-01	6.1E-02	2.5E-02	1.0E-02	4.4E-03	1.8E-03
90				8.7E-01	3.6E-01	1.5E-01	6.1E-02	2.5E-02	1.0E-02	4.4E-03
120					8.7E-01	3.6E-01	1.5E-01	6.1E-02	2.5E-02	1.0E-02
150						8.7E-01	3.5E-01	1.5E-01	6.1E-02	2.5E-02
180							8.7E-01	3.5E-01	1.5E-01	6.1E-02
210								8.7E-01	3.5E-01	1.5E-01
240									8.7E-01	3.5E-01
270										8.7E-01

Table A41b. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 234Th into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	2.6E-11	2.6E-11	1.1E-11	4.6E-12	2.0E-12	8.2E-13	3.5E-13	1.5E-13	6.2E-14	2.6E-14
30		9.2E-07	5.4E-07	2.3E-07	9.7E-08	4.1E-08	1.7E-08	7.3E-09	3.1E-09	1.3E-09
60			2.6E-05	1.5E-05	6.3E-06	2.6E-06	1.1E-06	4.7E-07	2.0E-07	8.4E-08
90				8.8E-06	5.0E-06	2.1E-06	8.9E-07	3.8E-07	1.6E-07	6.7E-08
120					3.4E-05	1.9E-05	8.1E-06	3.4E-06	1.4E-06	6.1E-07
150						7.4E-05	4.2E-05	1.8E-05	7.4E-06	3.1E-06
180							1.3E-04	7.6E-05	3.2E-05	1.4E-05
210								2.3E-04	1.3E-04	5.4E-05
240									3.2E-04	1.8E-04
270										3.8E-04

Table A42. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 234U, 235U, or 238U into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	4.7E-14	6.1E-14	6.1E-14	6.1E-14	6.1E-14	6.1E-14	6.1E-14	6.0E-14	6.0E-14	6.0E-14
30		6.9E-07	7.3E-07	7.3E-07	7.2E-07	7.2E-07	7.2E-07	7.2E-07	7.2E-07	7.2E-07
60			1.6E-05	1.7E-05	1.7E-05	1.7E-05	1.7E-05	1.7E-05	1.7E-05	1.7E-05
90				1.3E-04	1.4E-04	1.4E-04	1.4E-04	1.4E-04	1.4E-04	1.4E-04
120					5.7E-04	5.9E-04	5.9E-04	5.9E-04	5.9E-04	5.9E-04
150						1.6E-03	1.7E-03	1.7E-03	1.7E-03	1.7E-03
180							4.5E-03	4.7E-03	4.7E-03	4.7E-03
210								9.0E-03	9.4E-03	9.4E-03
240									1.3E-02	1.4E-02
270										1.7E-02

Table A43. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 237Np into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period)									
	0	30	60	90	120	150	180	210	240	270
0	4.1E-14	5.4E-14	5.4E-14	5.3E-14	5.3E-14	5.3E-14	5.3E-14	5.3E-14	5.3E-14	5.3E-14
30		5.5E-07	5.7E-07	5.7E-07	5.7E-07	5.7E-07	5.7E-07	5.7E-07	5.7E-07	5.7E-07
60			1.1E-05	1.2E-05	1.2E-05	1.2E-05	1.2E-05	1.2E-05	1.2E-05	1.2E-05
90				1.0E-04	1.0E-04	1.0E-04	1.0E-04	1.0E-04	1.0E-04	1.0E-04
120					5.4E-04	5.6E-04	5.6E-04	5.6E-04	5.6E-04	5.5E-04
150						1.6E-03	1.7E-03	1.7E-03	1.7E-03	1.7E-03
180							4.6E-03	4.8E-03	4.8E-03	4.7E-03
210								9.8E-03	1.0E-02	1.0E-02
240									1.5E-02	1.5E-02
270										1.8E-02

Table A44. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 238Pu or 239Pu into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	5.8E-14	7.5E-14	7.5E-14	7.5E-14	7.5E-14	7.5E-14	7.5E-14	7.5E-14	7.5E-14	7.5E-14
30		1.0E-06	1.1E-06	1.1E-06	1.1E-06	1.0E-06	1.0E-06	1.0E-06	1.0E-06	1.0E-06
60			2.8E-05	2.9E-05	2.9E-05	2.9E-05	2.9E-05	2.9E-05	2.9E-05	2.9E-05
90				2.9E-04	3.0E-04	3.0E-04	3.0E-04	3.0E-04	3.0E-04	3.0E-04
120					1.3E-03	1.4E-03	1.4E-03	1.4E-03	1.4E-03	1.4E-03
150						3.4E-03	3.5E-03	3.5E-03	3.5E-03	3.5E-03
180							7.6E-03	7.8E-03	7.8E-03	7.8E-03
210								1.5E-02	1.6E-02	1.5E-02
240									2.3E-02	2.4E-02
270										2.8E-02

Table A45. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 241Am into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	3.6E-14	4.7E-14	4.7E-14	4.7E-14	4.7E-14	4.7E-14	4.6E-14	4.6E-14	4.6E-14	4.6E-14
30		4.1E-07	4.3E-07	4.3E-07	4.3E-07	4.3E-07	4.3E-07	4.3E-07	4.3E-07	4.3E-07
60			7.1E-06	7.4E-06	7.4E-06	7.4E-06	7.4E-06	7.3E-06	7.3E-06	7.3E-06
90				6.5E-05	6.7E-05	6.7E-05	6.7E-05	6.7E-05	6.7E-05	6.7E-05
120					3.1E-04	3.2E-04	3.2E-04	3.2E-04	3.2E-04	3.2E-04
150						7.7E-04	8.0E-04	8.0E-04	8.0E-04	8.0E-04
180							1.8E-03	1.8E-03	1.8E-03	1.8E-03
210								3.3E-03	3.5E-03	3.5E-03
240									4.9E-03	5.1E-03
270										6.1E-03

Appendix B

Radiation Absorbed Dose Rates and Doses to the Embryo/Fetus Following Introduction of Specified Radionuclides and Chemical Forms into the Maternal Transfer Compartment

Radiation Absorbed Dose Rates and Doses to the Embryo/Fetus Following Introduction of Specified Radionuclides and Chemical Forms into the Maternal Transfer Compartment

The entries in the tables presented in this appendix, for selected radionuclides and chemical forms, were calculated from the corresponding fractional activities given in Appendix A and the dosimetric models presented in Section V. They are based on the operational methodology given in Section III. It was assumed that 1μCi of activity was introduced into the maternal transfer compartment and the tabulated values represent the dose rates or doses that would be obtained using the approaches described. The fractional depositions in the embryo/fetus (Appendix A) were determined using the methodologies presented in Section IV, and the associated methodologies were employed for calculating the dose factors. Pregnancy was assumed to begin at the time of fertilization, roughly 2 weeks after menses, and gestation was considered to consist of nine 30-day months.

Radiation absorbed dose rates were calculated from the initial fraction that was present after a single administration at the start of each of these months or on the assumed final day (270) of gestation. Monthly doses were determined by integrating under the curve relating the fraction of the activity in the embryo/fetus at the start of each month after administration and the fraction at the beginning of the subsequent month of gestation. They are shown for the inclusive periods, expressed in days.

Doses to the embryo/fetus from radionuclides in maternal organs were calculated; when appropriate, these are included to provide total radiation absorbed doses. Values of cumulated doses were determined as the sum of the monthly doses and are tabulated as the right-most column of each line of doses.

As was noted, because of the minuscule mass of the conceptus soon after fertilization, the biokinetic model predicts that there would be negligible deposited activity of some materials in the embryo after administration at that time, and that there would be minimal activity at later times. As a consequence, the dose rate and doses also could be negligible but the values, as calculated, are tabulated. Because radiation doses to fetal thyroid are of special interest, they were calculated and are given for ^{99m}Tc and for the iodine isotopes. In these instances, no entries were made for the first 90 days of pregnancy, prior to significant thyroid function.

When it is desired to know the dose rates or doses to the embryo/fetus after intakes during the first month (0-30 days) of pregnancy, these may be estimated by expressing time of intake as a fraction of 30 days (e.g., 15 days/30 days or 1/2) and multiplying this by the corresponding dose rate or monthly dose presented for administration at 30 days.

Table B1. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 3H, as tritiated water, injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	2.0E-07	2.6E-08	3.2E-09	4.0E-10	4.9E-11	6.1E-12	7.5E-13	9.1E-14	1.1E-14	1.3E-15
30		2.0E-07	2.6E-08	3.2E-09	4.0E-10	4.9E-11	6.0E-12	7.3E-13	8.9E-14	1.1E-14
60			2.0E-07	2.6E-08	3.2E-09	3.9E-10	4.8E-11	5.9E-12	7.1E-13	8.6E-14
90				2.0E-07	2.6E-08	3.2E-09	3.9E-10	4.8E-11	5.8E-12	6.9E-13
120					1.9E-07	2.5E-08	3.1E-09	3.8E-10	4.6E-11	5.6E-12
150						1.9E-07	2.5E-08	3.1E-09	3.7E-10	4.5E-11
180							1.9E-07	2.5E-08	3.0E-09	3.6E-10
210								1.9E-07	2.4E-08	2.9E-09
240									1.8E-07	2.3E-08
270										1.8E-07

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	5.9E-05	7.9E-06	9.8E-07	1.2E-07	1.5E-08	1.8E-09	2.2E-10	2.7E-11	3.3E-12	6.8E-05
30		5.9E-05	7.9E-06	9.7E-07	1.2E-07	1.5E-08	1.8E-09	2.2E-10	2.7E-11	6.8E-05
60			5.8E-05	7.8E-06	9.6E-07	1.2E-07	1.5E-08	1.8E-09	2.1E-10	6.7E-05
90				5.8E-05	7.8E-06	9.6E-07	1.2E-07	1.4E-08	1.7E-09	6.7E-05
120					5.8E-05	7.7E-06	9.4E-07	1.1E-07	1.4E-08	6.7E-05
150						5.7E-05	7.6E-06	9.2E-07	1.1E-07	6.6E-05
180							5.6E-05	7.4E-06	9.0E-07	6.5E-05
210								5.5E-05	7.2E-06	6.3E-05
240									5.4E-05	5.4E-05

Table B2. Radiation dose rates and doses to the embryo/fetus from 1 μCi of organically bound 3H, as hexose or amino acid, injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	1.3E-07	3.1E-08	1.4E-08	7.1E-09	3.8E-09	2.1E-09	1.1E-09	6.0E-10	3.2E-10	1.7E-10
30		1.8E-07	3.3E-08	1.4E-08	7.1E-09	3.8E-09	2.0E-09	1.1E-09	5.9E-10	3.1E-10
60			1.9E-07	4.0E-08	1.5E-08	7.3E-09	3.8E-09	2.0E-09	1.1E-09	5.7E-10
90				1.9E-07	4.6E-08	1.7E-08	8.0E-09	4.0E-09	2.1E-09	1.1E-09
120					1.9E-07	5.6E-08	2.1E-08	9.2E-09	4.5E-09	2.3E-09
150						1.9E-07	6.1E-08	2.3E-08	1.0E-08	5.1E-09
180							1.8E-07	6.2E-08	2.5E-08	1.2E-08
210								1.8E-07	6.6E-08	2.9E-08
240									1.8E-07	7.2E-08
270										1.7E-07

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	4.2E-05	1.5E-05	7.2E-06	3.8E-06	2.0E-06	1.1E-06	6.0E-07	3.2E-07	1.7E-07	7.2E-05
30		5.3E-05	1.5E-05	7.2E-06	3.8E-06	2.0E-06	1.1E-06	5.9E-07	3.1E-07	8.4E-05
60			6.5E-05	1.8E-05	7.5E-06	3.9E-06	2.0E-06	1.1E-06	5.8E-07	9.8E-05
90				6.9E-05	2.0E-05	8.5E-06	4.1E-06	2.1E-06	1.1E-06	1.1E-04
120					7.5E-05	2.5E-05	1.0E-05	4.7E-06	2.3E-06	1.2E-04
150						7.9E-05	2.7E-05	1.1E-05	5.3E-06	1.2E-04
180							7.9E-05	2.9E-05	1.2E-05	1.2E-04
210								8.0E-05	3.2E-05	1.1E-04
240									8.1E-05	8.1E-05

Table B3. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 14C, as carbonate, hexose or amino acid, injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	3.0E-07	1.0E-09	5.5E-10	3.0E-10	1.6E-10	8.9E-11	4.8E-11	2.6E-11	1.4E-11	7.4E-12
30		7.8E-07	1.9E-08	2.0E-09	5.0E-10	2.1E-10	1.0E-10	5.2E-11	2.7E-11	1.4E-11
60			8.3E-07	7.8E-08	1.1E-08	3.0E-09	9.5E-10	3.4E-10	1.4E-10	6.7E-11
90				8.3E-07	1.3E-07	3.2E-08	9.8E-09	3.2E-09	1.2E-09	5.6E-10
120					8.3E-07	2.3E-07	6.7E-08	2.2E-08	8.1E-09	3.7E-09
150						8.4E-07	2.7E-07	8.6E-08	3.2E-08	1.5E-08
180							8.3E-07	2.9E-07	1.1E-07	4.8E-08
210								8.1E-07	3.2E-07	1.5E-07
240									8.0E-07	3.9E-07
270										7.8E-07

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	1.7E-05	5.4E-07	3.0E-07	1.6E-07	8.8E-08	4.8E-08	2.6E-08	1.4E-08	7.4E-09	1.8E-05
30		1.2E-04	5.1E-06	7.4E-07	2.4E-07	1.1E-07	5.3E-08	2.8E-08	1.4E-08	1.3E-04
60			2.2E-04	2.4E-05	4.3E-06	1.3E-06	4.2E-07	1.6E-07	7.0E-08	2.5E-04
90				2.6E-04	4.9E-05	1.4E-05	4.2E-06	1.5E-06	5.9E-07	3.3E-04
120					3.2E-04	9.4E-05	2.8E-05	9.9E-06	3.9E-06	4.5E-04
150						3.5E-04	1.1E-04	3.9E-05	1.6E-05	5.2E-04
180							3.6E-04	1.3E-04	5.1E-05	5.4E-04
210								3.8E-04	1.6E-04	5.3E-04
240									3.9E-04	3.9E-04

Table B4. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 32P as phosphate injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	2.2E-05	2.5E-06	1.9E-07	1.5E-08	1.2E-09	8.8E-11	6.6E-12	4.9E-13	3.6E-14	2.6E-15
30		2.2E-05	2.5E-06	1.9E-07	1.5E-08	1.1E-09	8.4E-11	6.2E-12	4.6E-13	3.4E-14
60			2.1E-05	2.5E-06	1.9E-07	1.4E-08	1.1E-09	8.0E-11	5.9E-12	4.3E-13
90				2.1E-05	2.4E-06	1.8E-07	1.4E-08	1.0E-09	7.5E-11	5.5E-12
120					2.1E-05	2.4E-06	1.8E-07	1.3E-08	9.6E-10	7.1E-11
150						2.0E-05	2.3E-06	1.7E-07	1.2E-08	9.1E-10
180							2.0E-05	2.2E-06	1.6E-07	1.2E-08
210								1.8E-05	2.0E-06	1.5E-07
240									1.7E-05	1.9E-06
270										1.6E-05

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	7.5E-03	6.5E-04	5.0E-05	3.9E-06	3.0E-07	2.3E-08	1.7E-09	1.2E-10	9.1E-12	8.2E-03
30		7.5E-03	6.5E-04	5.0E-05	3.8E-06	2.9E-07	2.2E-08	1.6E-09	1.2E-10	8.2E-03
60			7.4E-03	6.4E-04	4.9E-05	3.7E-06	2.8E-07	2.0E-08	1.5E-09	8.1E-03
90				7.3E-03	6.3E-04	4.8E-05	3.5E-06	2.6E-07	1.9E-08	8.0E-03
120					7.2E-03	6.1E-04	4.6E-05	3.4E-06	2.5E-07	7.8E-03
150						7.0E-03	5.8E-04	4.3E-05	3.1E-06	7.6E-03
180							6.7E-03	5.5E-04	4.0E-05	7.3E-03
210								6.3E-03	5.2E-04	6.8E-03
240									5.9E-03	5.9E-03

Table B5. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 51Cr as chloride injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	7.4E-07	1.8E-07	3.8E-08	1.6E-08	6.4E-09	2.2E-09	9.2E-10	3.8E-10	1.3E-10	5.3E-11
30		7.4E-07	9.6E-08	3.8E-08	1.6E-08	5.4E-09	2.2E-09	9.2E-10	3.1E-10	1.3E-10
60			3.9E-07	9.7E-08	3.9E-08	1.3E-08	5.4E-09	2.3E-09	7.5E-10	3.1E-10
90				3.9E-07	1.0E-07	3.3E-08	1.4E-08	5.7E-09	1.9E-09	7.9E-10
120					3.9E-07	9.2E-08	3.7E-08	1.6E-08	5.1E-09	2.1E-09
150						3.2E-07	1.1E-07	4.4E-08	1.4E-08	6.0E-09
180							3.2E-07	1.3E-07	3.9E-08	1.7E-08
210								3.2E-07	1.1E-07	4.8E-08
240									2.6E-07	1.3E-07
270										3.5E-07

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	2.5E-04	8.5E-05	1.8E-05	7.5E-06	2.9E-06	1.1E-06	4.4E-07	1.7E-07	6.1E-08	3.6E-04
30		2.5E-04	4.5E-05	1.8E-05	7.0E-06	2.6E-06	1.1E-06	4.1E-07	1.5E-07	3.3E-04
60			1.3E-04	4.5E-05	1.7E-05	6.3E-06	2.6E-06	9.9E-07	3.6E-07	2.0E-04
90				1.4E-04	4.5E-05	1.6E-05	6.6E-06	2.5E-06	9.1E-07	2.1E-04
120					1.5E-04	4.3E-05	1.8E-05	6.8E-06	2.5E-06	2.2E-04
150						1.3E-04	5.0E-05	1.9E-05	6.8E-06	2.1E-04
180							1.5E-04	5.4E-05	1.9E-05	2.3E-04
210								1.7E-04	5.4E-05	2.2E-04
240									1.6E-04	1.6E-04

Table B6. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 55Fe injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	2.2E-07	2.2E-07	3.8E-15	3.8E-15	3.7E-15	9.8E-16	9.5E-16	9.4E-16	5.2E-16	5.1E-16
30		2.2E-07	1.7E-10	1.7E-10	1.6E-10	4.4E-11	4.3E-11	4.2E-11	2.3E-11	2.3E-11
60				5.1E-09	5.0E-09	1.3E-09	1.3E-09	1.3E-09	7.1E-10	6.9E-10
90					9.9E-08	2.6E-08	2.6E-08	2.5E-08	1.4E-08	1.4E-08
120						1.0E-07	1.0E-07	9.9E-08	5.5E-08	5.4E-08
150							2.3E-07	2.2E-07	1.2E-07	1.2E-07
180								2.8E-07	1.5E-07	1.5E-07
210									1.3E-07	1.3E-07
240										1.9E-07
270										2.2E-07

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	1.6E-04	1.5E-04	2.7E-12	2.7E-12	1.6E-12	7.0E-13	6.8E-13	5.2E-13	3.7E-13	3.1E-04
30		1.8E-04	1.2E-07	1.2E-07	7.3E-08	3.1E-08	3.0E-08	2.3E-08	1.7E-08	1.8E-04
60			3.6E-06	3.6E-06	2.2E-06	9.4E-07	9.3E-07	7.0E-07	5.0E-07	1.2E-05
90				6.9E-05	4.4E-05	1.9E-05	1.8E-05	1.4E-05	1.0E-05	1.7E-04
120					1.6E-04	7.4E-05	7.2E-05	5.5E-05	3.9E-05	4.0E-04
150						1.6E-04	1.6E-04	1.2E-04	8.8E-05	5.3E-04
180							1.9E-04	1.5E-04	1.1E-04	4.6E-04
210								1.3E-04	9.4E-05	2.2E-04
240									1.3E-04	1.3E-04

Table B7. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 59Fe injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	2.3E-05	1.4E-05	5.0E-06	3.1E-06	1.9E-06	1.0E-06	6.3E-07	4.0E-07	2.0E-07	1.2E-07
30		2.3E-05	7.9E-06	5.0E-06	3.1E-06	1.6E-06	1.0E-06	6.3E-07	3.2E-07	2.0E-07
60			1.3E-05	8.0E-06	5.0E-06	2.6E-06	1.6E-06	1.0E-06	5.1E-07	3.2E-07
90				1.3E-05	1.0E-05	4.6E-06	2.9E-06	1.8E-06	8.9E-07	5.6E-07
120					1.3E-05	9.9E-06	6.2E-06	3.9E-06	1.8E-06	1.1E-06
150						1.0E-05	1.4E-05	8.7E-06	3.8E-06	2.4E-06
180							1.0E-05	1.5E-05	6.7E-06	4.2E-06
210								1.0E-05	9.8E-06	6.1E-06
240									8.3E-06	1.2E-05
270										2.0E-05

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	1.3E-02	8.1E-03	2.8E-03	1.8E-03	1.0E-03	5.8E-04	3.6E-04	2.1E-04	1.1E-04	2.8E-02
30		1.4E-02	4.5E-03	2.8E-03	1.6E-03	9.2E-04	5.8E-04	3.3E-04	1.8E-04	2.5E-02
60			7.4E-03	4.6E-03	2.7E-03	1.5E-03	9.3E-04	5.3E-04	2.9E-04	1.8E-02
90				9.6E-03	5.2E-03	2.7E-03	1.7E-03	9.4E-04	5.1E-04	2.1E-02
120					1.3E-02	5.7E-03	3.6E-03	2.0E-03	1.0E-03	2.5E-02
150						1.3E-02	8.0E-03	4.3E-03	2.2E-03	2.7E-02
180							1.4E-02	7.6E-03	3.8E-03	2.5E-02
210								1.1E-02	5.6E-03	1.7E-02
240									1.1E-02	1.1E-02
270										

Table B8. Radiation dose rates and doses to the embryo/fetus from 1 μCi of inorganic 57Co injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	3.1E-06	4.6E-07	2.9E-07	2.4E-07	2.0E-07	9.6E-08	8.2E-08	7.1E-08	5.1E-08	4.5E-08
30		3.1E-06	3.9E-07	2.9E-07	2.4E-07	1.1E-07	9.6E-08	8.1E-08	5.8E-08	5.1E-08
60			2.6E-06	3.9E-07	2.9E-07	1.4E-07	1.1E-07	9.4E-08	6.7E-08	5.8E-08
90				2.6E-06	3.9E-07	1.7E-07	1.4E-07	1.1E-07	7.8E-08	6.6E-08
120					2.6E-06	2.2E-07	1.7E-07	1.3E-07	9.1E-08	7.7E-08
150						1.4E-06	2.2E-07	1.6E-07	1.1E-07	9.1E-08
180							1.4E-06	2.2E-07	1.3E-07	1.1E-07
210								1.4E-06	1.8E-07	1.3E-07
240									1.1E-06	1.8E-07
270										6.3E-07

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	5.6E-04	2.9E-04	1.9E-04	1.6E-04	1.0E-04	6.4E-05	5.5E-05	4.3E-05	3.4E-05	1.5E-03
30		5.6E-04	2.4E-04	1.9E-04	1.2E-04	7.5E-05	6.3E-05	5.0E-05	3.9E-05	1.3E-03
60			4.7E-04	2.4E-04	1.5E-04	8.9E-05	7.4E-05	5.7E-05	4.5E-05	1.1E-03
90				4.7E-04	1.9E-04	1.1E-04	8.8E-05	6.7E-05	5.2E-05	9.8E-04
120					4.0E-04	1.4E-04	1.1E-04	8.0E-05	6.0E-05	7.8E-04
150						2.7E-04	1.3E-04	9.7E-05	7.2E-05	5.7E-04
180							2.6E-04	1.2E-04	8.7E-05	4.7E-04
210								2.4E-04	1.1E-04	3.5E-04
240									2.1E-04	2.1E-04

Table B9. Radiation dose rates and doses to the embryo/fetus from 1 μCi of inorganic 58Co injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	1.7E-05	2.1E-06	8.4E-07	5.5E-07	3.7E-07	2.1E-07	1.5E-07	1.0E-07	5.9E-08	4.2E-08
30		1.7E-05	1.4E-06	8.4E-07	5.5E-07	3.1E-07	2.1E-07	1.5E-07	8.3E-08	5.9E-08
60			1.1E-05	1.4E-06	8.3E-07	4.7E-07	3.1E-07	2.1E-07	1.2E-07	8.3E-08
90				1.1E-05	1.4E-06	7.1E-07	4.6E-07	3.1E-07	1.7E-07	1.2E-07
120					1.1E-05	1.2E-06	7.1E-07	4.6E-07	2.5E-07	1.7E-07
150						9.0E-06	1.2E-06	7.0E-07	3.8E-07	2.5E-07
180							9.0E-06	1.2E-06	5.7E-07	3.7E-07
210								9.0E-06	9.4E-07	5.7E-07
240									7.2E-06	9.3E-07
270										4.2E-06

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	3.0E-03	1.2E-03	4.9E-04	3.2E-04	2.0E-04	1.3E-04	8.9E-05	5.7E-05	3.6E-05	5.5E-03
30		3.0E-03	7.7E-04	4.9E-04	3.0E-04	1.9E-04	1.3E-04	8.1E-05	5.1E-05	5.0E-03
60			1.9E-03	7.7E-04	4.6E-04	2.8E-04	1.9E-04	1.2E-04	7.2E-05	3.8E-03
90				1.9E-03	7.2E-04	4.2E-04	2.7E-04	1.7E-04	1.0E-04	3.6E-03
120					1.8E-03	6.5E-04	4.1E-04	2.5E-04	1.5E-04	3.3E-03
150						1.6E-03	6.5E-04	3.8E-04	2.2E-04	2.9E-03
180							1.6E-03	5.9E-04	3.3E-04	2.5E-03
210								1.5E-03	5.2E-04	2.0E-03
240									1.3E-03	1.3E-03

Table B10. Radiation dose rates and doses to the embryo/fetus from 1 μCi of inorganic 60Co injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	4.1E-05	6.8E-06	3.6E-06	3.1E-06	2.8E-06	2.1E-06	1.9E-06	1.8E-06	1.4E-06	1.3E-06
30		4.1E-05	4.4E-06	3.6E-06	3.1E-06	2.3E-06	2.1E-06	1.9E-06	1.5E-06	1.4E-06
60			2.6E-05	4.4E-06	3.6E-06	2.6E-06	2.3E-06	2.1E-06	1.6E-06	1.5E-06
90				2.6E-05	4.4E-06	3.0E-06	2.6E-06	2.3E-06	1.7E-06	1.6E-06
120					2.6E-05	3.8E-06	3.0E-06	2.6E-06	1.9E-06	1.7E-06
150						2.2E-05	3.7E-06	3.0E-06	2.1E-06	1.9E-06
180							2.2E-05	3.7E-06	2.4E-06	2.1E-06
210								2.2E-05	3.0E-06	2.4E-06
240									1.7E-05	3.0E-06
270										1.0E-05

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	8.0E-03	4.3E-03	2.4E-03	2.1E-03	1.7E-03	1.5E-03	1.3E-03	1.1E-03	9.6E-04	2.3E-02
30		8.0E-03	2.8E-03	2.4E-03	1.9E-03	1.6E-03	1.4E-03	1.2E-03	1.0E-03	2.0E-02
60			5.2E-03	2.8E-03	2.2E-03	1.8E-03	1.6E-03	1.3E-03	1.1E-03	1.6E-02
90				5.2E-03	2.6E-03	2.0E-03	1.8E-03	1.4E-03	1.2E-03	1.4E-02
120					4.9E-03	2.4E-03	2.0E-03	1.6E-03	1.3E-03	1.2E-02
150						4.4E-03	2.4E-03	1.8E-03	1.4E-03	1.0E-02
180							4.3E-03	2.1E-03	1.6E-03	8.1E-03
210								4.0E-03	1.9E-03	5.9E-03
240									3.5E-03	3.5E-03

Table B11. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 65Zn injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	9.3E-06	7.1E-06	3.8E-06	3.4E-06	3.3E-06	2.4E-06	2.4E-06	2.5E-06	1.8E-06	1.7E-06
30		9.3E-06	4.7E-06	4.0E-06	3.9E-06	2.8E-06	2.7E-06	2.8E-06	2.1E-06	1.9E-06
60			6.3E-06	4.9E-06	4.6E-06	3.2E-06	3.1E-06	3.2E-06	2.4E-06	2.2E-06
90				6.3E-06	5.6E-06	3.8E-06	3.6E-06	3.7E-06	2.7E-06	2.5E-06
120					6.3E-06	4.6E-06	4.3E-06	4.3E-06	3.2E-06	2.9E-06
150						5.1E-06	5.3E-06	5.1E-06	3.7E-06	3.4E-06
180							5.1E-06	6.4E-06	4.3E-06	3.9E-06
210								5.1E-06	5.4E-06	4.6E-06
240									4.1E-06	5.8E-06
270										7.8E-06

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	5.8E-03	4.7E-03	2.6E-03	2.4E-03	2.1E-03	1.7E-03	1.7E-03	1.5E-03	1.3E-03	2.4E-02
30		6.0E-03	3.1E-03	2.8E-03	2.4E-03	2.0E-03	2.0E-03	1.8E-03	1.5E-03	2.1E-02
60			3.9E-03	3.4E-03	2.8E-03	2.3E-03	2.3E-03	2.0E-03	1.7E-03	1.8E-02
90				4.3E-03	3.4E-03	2.6E-03	2.7E-03	2.3E-03	1.9E-03	1.7E-02
120					4.4E-03	3.2E-03	3.1E-03	2.7E-03	2.2E-03	1.6E-02
150						4.1E-03	3.7E-03	3.1E-03	2.6E-03	1.4E-02
180							4.8E-03	3.8E-03	3.0E-03	1.2E-02
210								4.9E-03	3.6E-03	8.5E-03
240									4.7E-03	4.7E-03

Table B12. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 86Rb injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	2.6E-05	8.4E-06	6.7E-08	4.2E-08	2.8E-08	3.6E-09	1.3E-09	4.3E-10	7.1E-11	1.7E-11
30		2.6E-05	3.3E-07	2.0E-07	1.4E-07	1.8E-08	6.3E-09	2.1E-09	3.5E-10	8.3E-11
60			1.0E-06	9.9E-07	6.6E-07	8.6E-08	3.1E-08	1.0E-08	1.7E-09	4.1E-10
90				1.0E-06	3.2E-06	4.2E-07	1.5E-07	5.1E-08	8.4E-09	2.0E-09
120					1.0E-06	2.1E-06	7.4E-07	2.5E-07	4.1E-08	9.7E-09
150						8.4E-07	3.6E-06	1.2E-06	2.0E-07	4.8E-08
180							8.4E-07	5.9E-06	9.8E-07	2.3E-07
210								8.4E-07	4.8E-06	1.1E-06
240									6.7E-07	5.6E-06
270										2.5E-05

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	1.3E-02	3.4E-03	3.6E-05	2.5E-05	1.0E-05	1.6E-06	5.7E-07	1.5E-07	2.8E-08	1.6E-02
30		1.6E-02	1.8E-04	1.2E-04	4.9E-05	7.9E-06	2.8E-06	7.4E-07	1.4E-07	1.7E-02
60			8.6E-04	6.0E-04	2.4E-04	3.9E-05	1.4E-05	3.6E-06	6.7E-07	1.8E-03
90				2.9E-03	1.2E-03	1.9E-04	6.7E-05	1.8E-05	3.3E-06	4.3E-03
120					5.6E-03	9.2E-04	3.3E-04	8.7E-05	1.6E-05	6.9E-03
150						4.4E-03	1.6E-03	4.2E-04	7.8E-05	6.5E-03
180							7.6E-03	2.1E-03	3.8E-04	1.0E-02
210								9.8E-03	1.9E-03	1.2E-02
240									8.9E-03	8.9E-03

Table B13. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 89Sr injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	2.2E-05	3.8E-06	5.0E-10	2.8E-10	1.1E-10	2.8E-11	1.7E-11	1.1E-11	5.7E-12	3.8E-12
30		2.2E-05	5.0E-09	2.7E-09	9.0E-10	7.9E-11	3.1E-11	1.7E-11	8.6E-12	5.7E-12
60			9.3E-10	3.2E-08	1.0E-08	5.7E-10	1.2E-10	3.7E-11	1.4E-11	9.0E-12
90				9.3E-10	3.1E-07	4.3E-08	2.5E-08	1.6E-08	5.7E-09	3.7E-09
120					9.3E-10	5.5E-07	3.4E-07	2.2E-07	7.7E-08	5.1E-08
150						7.7E-10	1.5E-06	9.5E-07	3.4E-07	2.2E-07
180							7.7E-10	3.0E-06	1.1E-06	6.8E-07
210								7.7E-10	2.6E-06	1.7E-06
240									6.1E-10	3.5E-06
270										1.4E-05

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	4.8E-03	2.1E-03	2.8E-07	1.4E-07	4.3E-08	1.6E-08	9.7E-09	5.8E-09	3.4E-09	6.9E-03
30		5.2E-03	2.7E-06	1.2E-06	2.7E-07	3.5E-08	1.6E-08	8.9E-09	5.1E-09	5.3E-03
60			5.7E-05	1.4E-05	2.9E-06	2.0E-07	4.8E-08	1.7E-08	8.2E-09	7.4E-05
90				4.4E-04	1.1E-04	2.4E-05	1.4E-05	7.3E-06	3.3E-06	6.0E-04
120					1.5E-03	3.1E-04	2.0E-04	1.0E-04	4.5E-05	2.2E-03
150						1.4E-03	8.6E-04	4.4E-04	2.0E-04	2.9E-03
180							2.8E-03	1.4E-03	6.1E-04	4.8E-03
210								3.6E-03	1.5E-03	5.2E-03
240									3.4E-03	3.4E-03

Table B14. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 90Sr/Y injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	4.2E-05	1.1E-05	1.7E-09	1.4E-09	6.8E-10	5.2E-11	1.2E-11	2.7E-12	4.7E-13	2.7E-13
30		4.2E-05	1.4E-08	1.2E-08	5.5E-09	4.2E-10	9.5E-11	2.0E-11	2.2E-12	5.1E-13
60			1.0E-11	9.3E-08	4.5E-08	3.4E-09	7.9E-10	1.8E-10	2.9E-11	1.5E-11
90				1.0E-11	9.1E-07	1.9E-07	1.7E-07	1.6E-07	8.5E-08	8.5E-08
120					1.0E-11	1.6E-06	1.5E-06	1.4E-06	7.7E-07	7.6E-07
150						1.1E-12	4.3E-06	4.1E-06	2.2E-06	2.2E-06
180							1.1E-12	8.6E-06	4.6E-06	4.5E-06
210								1.1E-12	7.6E-06	7.4E-06
240									9.4E-13	1.0E-05
270										2.7E-05

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	1.0E-02	7.6E-03	1.2E-06	7.5E-07	2.1E-07	2.0E-08	4.5E-09	9.1E-10	2.4E-10	1.8E-02
30		1.2E-02	9.4E-06	6.1E-06	1.7E-06	1.6E-07	3.5E-08	6.0E-09	8.0E-10	1.2E-02
60			1.3E-04	4.9E-05	1.4E-05	1.3E-06	3.0E-07	6.0E-08	1.5E-08	1.9E-04
90				9.9E-04	3.7E-04	1.3E-04	1.2E-04	8.6E-05	6.1E-05	1.8E-03
120					3.3E-03	1.1E-03	1.0E-03	7.8E-04	5.5E-04	6.8E-03
150						3.4E-03	3.1E-03	2.3E-03	1.6E-03	1.0E-02
180							6.5E-03	4.7E-03	3.3E-03	1.4E-02
210								8.2E-03	5.4E-03	1.4E-02
240									7.9E-03	7.9E-03
270										

Table B15a. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 99mTc-pertechnetate injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	2.9E-06									
30		2.9E-06								
60			2.9E-06							
90				1.6E-06						
120					1.6E-06					
150						1.4E-06				
180							1.4E-06			
210								1.4E-06		
240									1.1E-06	
270										1.4E-07

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	3.8E-05									3.8E-05
30		3.8E-05								3.8E-05
60			3.8E-05							3.8E-05
90				2.2E-05						2.2E-05
120					2.3E-05					2.3E-05
150						1.9E-05				1.9E-05
180							2.0E-05			2.0E-05
210								2.1E-05		2.1E-05
240									1.7E-05	1.7E-05

Table B15b. Radiation dose rates and doses to the fetal thyroid from 1 μCi of 99mTc-pertechnetate injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the fetal thyroid at indicated gestational periods (days)									
	0	30	60	90	120	150	180	210	240	270
0										
30										
60										
90				1.6E-06						
120					1.6E-06					
150						1.4E-06				
180							1.4E-06			
210								1.4E-06		
240									1.1E-06	
270										2.1E-06

Days of Gestation at Introduction	Dose (rad) to the fetal thyroid during indicated gestation periods (days)									Cumulated dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0										
30										
60										
90				5.9E-05						5.9E-05
120					1.0E-04					1.0E-04
150						1.5E-04				1.5E-04
180							1.3E-04			1.3E-04
210								1.1E-04		1.1E-04
240									8.5E-05	8.5E-05

Table B16. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 106Ru/Rh injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	1.2E-05	1.1E-09	3.6E-11	5.1E-12	1.2E-12	5.2E-13	2.7E-13	1.5E-13	9.5E-14	7.4E-14
30		4.2E-05	1.6E-06	2.3E-07	5.7E-08	2.4E-08	1.2E-08	6.8E-09	4.4E-09	3.4E-09
60			4.5E-05	7.2E-06	1.8E-06	7.4E-07	3.8E-07	2.1E-07	1.3E-07	1.1E-07
90				4.6E-06	1.2E-06	5.2E-07	2.7E-07	1.5E-07	9.4E-08	7.4E-08
120					4.6E-06	2.1E-06	1.1E-06	6.0E-07	3.8E-07	3.0E-07
150						4.6E-06	2.5E-06	1.4E-06	8.9E-07	7.0E-07
180							4.6E-06	2.7E-06	1.7E-06	1.3E-06
210								4.5E-06	3.1E-06	2.4E-06
240									4.4E-06	3.7E-06
270										4.3E-06

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	7.0E-04	1.9E-07	1.1E-08	1.9E-09	5.7E-10	2.7E-10	1.4E-10	8.6E-11	5.9E-11	7.0E-04
30		7.4E-03	5.1E-04	8.7E-05	2.6E-05	1.3E-05	6.6E-06	3.9E-06	2.7E-06	8.0E-03
60			1.5E-02	2.7E-03	8.1E-04	3.9E-04	2.0E-04	1.2E-04	8.3E-05	1.9E-02
90				1.8E-03	5.7E-04	2.7E-04	1.4E-04	8.5E-05	5.8E-05	2.9E-03
120					2.2E-03	1.1E-03	5.8E-04	3.5E-04	2.4E-04	4.5E-03
150						2.5E-03	1.4E-03	8.1E-04	5.6E-04	5.2E-03
180							2.5E-03	1.6E-03	1.1E-03	5.1E-03
210								2.7E-03	1.9E-03	4.6E-03
240									2.8E-03	2.8E-03

Table B17a. Maximum radiation dose rates and doses to the embryo/fetus from 1 μCi of 123I injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	7.3E-07									
30		7.3E-07								
60			7.8E-07							
90				4.9E-07						
120					9.9E-07					
150						1.2E-06				
180							1.8E-06			
210								2.5E-06		
240									1.6E-06	
270										1.7E-06

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	1.1E-06									1.1E-06
30		1.1E-06								1.1E-06
60			1.1E-06							1.1E-06
90				7.0E-07						7.0E-07
120					1.4E-06					1.4E-06
150						1.6E-06				1.6E-06
180							2.4E-06			2.4E-06
210								3.4E-06		3.4E-06
240									2.1E-06	2.1E-06

Table B17b. Maximum radiation dose rates and doses to the fetal thyroid from 1 μCi of 123I injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the fetal thyroid at indicated gestational periods (days)									
	0	30	60	90	120	150	180	210	240	270
0										
30										
60										
90				5.3E-04						
120					1.2E-03					
150						1.8E-03				
180							1.5E-03			
210								1.2E-03		
240									9.6E-04	
270										6.8E-04

Days of Gestation at Introduction	Dose (rad) to the fetal thyroid during indicated gestation periods (days)									Cumulated dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0										
30										
60										
90				6.9E-04						6.9E-04
120					1.5E-03					1.5E-03
150						2.3E-03				2.3E-03
180							1.9E-03			1.9E-03
210								1.6E-03		1.6E-03
240									1.2E-03	1.2E-03

Table B18a. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 125I injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	2.0E-06	2.1E-08	1.3E-08	2.8E-09	4.1E-09	3.5E-09	4.5E-09	4.2E-09	1.3E-09	9.6E-10
30		2.0E-06	2.1E-08	4.7E-09	6.9E-09	5.9E-09	7.5E-09	7.1E-09	2.2E-09	1.6E-09
60			2.0E-06	7.9E-09	1.2E-08	1.0E-08	1.3E-08	1.2E-08	3.8E-09	2.7E-09
90				6.3E-07	3.8E-08	1.8E-08	2.2E-08	2.0E-08	6.4E-09	4.6E-09
120					6.3E-07	8.4E-08	4.6E-08	3.6E-08	1.1E-08	7.7E-09
150						3.2E-07	2.6E-07	9.4E-08	2.1E-08	1.3E-08
180							3.2E-07	4.3E-07	5.4E-08	2.6E-08
210								3.5E-06	2.4E-07	7.2E-08
240									2.1E-07	3.0E-07
270										1.4E-06

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	4.2E-05	1.2E-05	5.0E-06	2.4E-06	2.8E-06	3.0E-06	3.2E-06	1.9E-06	8.3E-07	7.3E-05
30		4.2E-05	8.4E-06	4.0E-06	4.7E-06	5.1E-06	5.3E-06	3.3E-06	1.4E-06	7.4E-05
60			3.7E-05	6.6E-06	7.9E-06	8.6E-06	9.0E-06	5.5E-06	2.3E-06	7.6E-05
90				5.3E-05	1.9E-05	1.5E-05	1.5E-05	9.3E-06	4.0E-06	1.1E-04
120					2.1E-04	4.3E-05	2.9E-05	1.6E-05	6.7E-06	3.1E-04
150						4.2E-04	1.1E-04	3.7E-05	1.2E-05	5.8E-04
180							6.9E-04	1.4E-04	2.7E-05	8.6E-04
210								8.3E-04	9.6E-05	9.3E-04
240									4.8E-04	4.8E-04

Table B18b. Radiation dose rates and doses to the fetal thyroid from 1 μCi of 125I injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the fetal thyroid at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0				3.7E-06	7.5E-06	8.2E-06	5.6E-06	3.0E-06	1.5E-06	6.9E-07
30				6.2E-06	1.3E-05	1.4E-05	9.4E-06	5.0E-06	2.5E-06	1.2E-06
60				1.0E-05	2.1E-05	2.3E-05	1.6E-05	8.5E-06	4.2E-06	2.0E-06
90				6.3E-07	8.9E-05	4.3E-05	2.7E-05	1.4E-05	7.1E-06	3.3E-06
120					6.3E-07	2.1E-04	5.8E-05	2.5E-05	1.2E-05	5.6E-06
150						3.2E-07	3.5E-04	6.8E-05	2.3E-05	9.7E-06
180							3.2E-07	3.2E-04	6.2E-05	1.9E-05
210								3.5E-06	2.8E-04	5.3E-05
240									2.1E-07	2.2E-04
270										1.0E-03

Days of Gestation at Introduction	Dose (rad) to the fetal thyroid during indicated gestation periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0				4.4E-03	5.8E-03	5.2E-03	3.0E-03	1.6E-03	7.6E-04	2.1E-02
30				7.4E-03	9.8E-03	8.7E-03	5.1E-03	2.6E-03	1.3E-03	3.5E-02
60				1.2E-02	1.6E-02	1.5E-02	8.5E-03	4.4E-03	2.1E-03	5.8E-02
90				2.3E-01	4.1E-02	2.6E-02	1.4E-02	7.4E-03	3.6E-03	3.2E-01
120					5.2E-01	8.1E-02	2.8E-02	1.3E-02	6.1E-03	6.5E-01
150						8.4E-01	1.2E-01	2.9E-02	1.1E-02	1.0E+00
180							7.3E-01	1.1E-01	2.5E-02	8.6E-01
210								6.1E-01	9.4E-02	7.0E-01
240									4.8E-01	4.8E-01

Table B19a. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 131I injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	1.4E-05	1.6E-08	1.0E-09	2.8E-11	3.6E-12	3.4E-13	4.2E-14	4.1E-15	1.5E-16	1.1E-17
30		1.4E-05	1.6E-08	4.4E-10	5.6E-11	5.4E-12	6.7E-13	6.5E-14	2.3E-15	1.7E-16
60			1.4E-05	6.9E-09	8.9E-10	8.5E-11	1.1E-11	1.0E-12	3.6E-14	2.7E-15
90				4.5E-06	2.5E-08	1.5E-09	1.7E-10	1.6E-11	5.7E-13	4.3E-14
120					4.5E-06	5.7E-08	3.3E-09	2.7E-10	9.2E-12	6.9E-13
150						3.7E-06	1.7E-07	6.6E-09	1.6E-10	1.1E-11
180							3.7E-06	2.8E-07	3.8E-09	2.0E-10
210								3.7E-06	1.5E-07	5.1E-09
240									3.0E-06	1.9E-07
270										7.8E-06

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	2.2E-04	4.0E-06	2.2E-07	8.2E-09	1.0E-09	1.1E-10	1.2E-11	9.5E-13	3.8E-14	2.2E-04
30		2.2E-04	3.5E-06	1.3E-07	1.7E-08	1.7E-09	1.9E-10	1.5E-11	6.0E-13	2.2E-04
60			2.1E-04	2.0E-06	2.6E-07	2.7E-08	3.0E-09	2.4E-10	9.4E-12	2.1E-04
90				1.9E-04	6.0E-06	4.4E-07	4.7E-08	3.8E-09	1.5E-10	1.9E-04
120					7.2E-04	1.3E-05	8.7E-07	6.2E-08	2.4E-09	7.3E-04
150						1.3E-03	3.5E-05	1.4E-06	4.1E-08	1.3E-03
180							2.1E-03	5.0E-05	8.8E-07	2.1E-03
210								2.7E-03	3.1E-05	2.8E-03
240									1.5E-03	1.5E-03

Table B19b. Radiation dose rates and doses to the fetal thyroid from 1 μCi of 131I injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the fetal thyroid at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0				3.6E-08	8.0E-09	9.3E-10	6.9E-11	4.0E-12	2.2E-13	1.1E-14
30				5.6E-07	1.3E-07	1.5E-08	1.1E-09	6.3E-11	3.4E-12	1.7E-13
60				8.7E-06	2.0E-06	2.3E-07	1.7E-08	1.0E-09	5.4E-11	2.7E-12
90				4.5E-06	7.8E-05	4.1E-06	2.8E-07	1.6E-08	8.5E-10	4.3E-11
120					4.5E-06	1.9E-04	5.6E-06	2.6E-07	1.4E-08	6.8E-10
150						3.7E-06	3.1E-04	6.7E-06	2.5E-07	1.1E-08
180							3.7E-06	2.9E-04	6.1E-06	2.0E-07
210								3.7E-06	2.6E-04	5.3E-06
240									3.0E-06	2.1E-04
270										8.5E-03

Days of Gestation at Introduction	Dose (rad) to the fetal thyroid during indicated gestation periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0				1.5E-05	2.4E-06	2.5E-07	1.7E-08	9.4E-10	5.0E-11	1.8E-05
30				2.4E-04	3.8E-05	4.0E-06	2.6E-07	1.5E-08	7.8E-10	2.8E-04
60				3.7E-03	6.0E-04	6.3E-05	4.1E-06	2.3E-07	1.2E-08	4.4E-03
90				1.0E+00	1.6E-02	1.1E-03	6.6E-05	3.7E-06	2.0E-07	1.0E+00
120					2.3E+00	3.6E-02	1.2E-03	6.1E-05	3.1E-06	2.4E+00
150						3.8E+00	5.5E-02	1.4E-03	5.4E-05	3.9E+00
180							3.3E+00	5.2E-02	1.2E-03	3.4E+00
210								2.8E+00	4.6E-02	2.8E+00
240									2.2E+00	2.2E+00

Table B20a. Maximum radiation dose rates and doses to the embryo/fetus from 1 μCi of 132I injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	1.1E-05									
30		1.1E-05								
60			1.2E-05							
90				6.4E-06						
120					1.0E-05					
150						9.1E-06				
180							1.3E-05			
210								1.8E-05		
240									1.3E-05	
270										1.5E-05

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	4.7E-06									4.7E-06
30		4.7E-06								4.7E-06
60			5.0E-06							5.0E-06
90				2.6E-06						2.6E-06
120					4.1E-06					4.1E-06
150						3.5E-06				3.5E-06
180							4.9E-06			4.9E-06
210								6.8E-06		6.8E-06
240									5.3E-06	5.3E-06

Table B20b. Maximum radiation dose rates and doses to the fetal thyroid from 1 μCi of 132I injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the fetal thyroid at indicated gestational periods (days)									
	0	30	60	90	120	150	180	210	240	270
0										
30										
60										
90				1.2E-03						
120					2.9E-03					
150						5.0E-03				
180							4.6E-03			
210								4.0E-03		
240									3.3E-03	
270										2.5E-03

Days of Gestation at Introduction	Dose (rad) to the fetal thyroid during indicated gestation periods (days)									Cumulated dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0										
30										
60										
90				3.7E-04						3.7E-04
120					9.2E-04					9.2E-04
150						1.6E-03				1.6E-03
180							1.4E-03			1.4E-03
210								1.3E-03		1.3E-03
240									1.0E-03	1.0E-03

Table B21a. Maximum radiation dose rates and doses to the embryo/fetus from 1 μCi of 133I injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	3.2E-06									
30		3.2E-06								
60			3.6E-06							
90				1.9E-06						
120					6.4E-06					
150						8.4E-06				
180							1.4E-05			
210								2.0E-05		
240									1.0E-05	
270										1.1E-05

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	6.9E-06									6.9E-06
30		6.9E-06								6.9E-06
60			7.6E-06							7.6E-06
90				3.9E-06						3.9E-06
120					1.2E-05					1.2E-05
150						1.6E-05				1.6E-05
180							2.6E-05			2.6E-05
210								3.7E-05		3.7E-05
240									2.0E-05	2.0E-05

Table B21b. Maximum radiation dose rates and doses to the fetal thyroid from 1 μCi of 133I injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the fetal thyroid at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0										
30										
60										
90				6.1E-03						
120					1.5E-02					
150						2.4E-02				
180							2.1E-02			
210								1.8E-02		
240									1.5E-02	
270										1.1E-02

Days of Gestation at Introduction	Dose (rad) to the fetal thyroid during indicated gestation periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0										
30										
60										
90				1.1E-02						1.1E-02
120					2.6E-02					2.6E-02
150						4.4E-02				4.4E-02
180							3.8E-02			3.8E-02
210								3.3E-02		3.3E-02
240									2.6E-02	2.6E-02

Table B22. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 134Cs injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	3.1E-05	2.8E-05	1.0E-05	8.6E-06	8.5E-06	5.2E-06	4.8E-06	4.2E-06	2.3E-06	1.6E-06
30		3.1E-05	1.4E-05	1.1E-05	1.1E-05	6.8E-06	6.3E-06	5.5E-06	3.0E-06	2.1E-06
60			1.8E-05	1.5E-05	1.5E-05	9.0E-06	8.3E-06	7.3E-06	3.9E-06	2.8E-06
90				1.8E-05	1.9E-05	1.2E-05	1.1E-05	9.6E-06	5.2E-06	3.7E-06
120					1.8E-05	1.6E-05	1.4E-05	1.3E-05	6.9E-06	4.8E-06
150						1.4E-05	1.9E-05	1.7E-05	9.0E-06	6.4E-06
180							1.4E-05	2.2E-05	1.2E-05	8.6E-06
210								1.4E-05	1.8E-05	1.3E-05
240									1.2E-05	2.0E-05
270										3.0E-05

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	2.3E-02	1.8E-02	6.7E-03	6.1E-03	5.0E-03	3.6E-03	3.3E-03	2.3E-03	1.4E-03	7.0E-02
30		2.4E-02	8.9E-03	8.0E-03	6.6E-03	4.7E-03	4.3E-03	3.0E-03	1.8E-03	6.2E-02
60			1.2E-02	1.1E-02	8.7E-03	6.2E-03	5.7E-03	4.0E-03	2.4E-03	4.9E-02
90				1.4E-02	1.1E-02	8.2E-03	7.5E-03	5.2E-03	3.2E-03	4.9E-02
120					1.5E-02	1.1E-02	9.8E-03	6.9E-03	4.2E-03	4.7E-02
150						1.4E-02	1.3E-02	9.1E-03	5.6E-03	4.2E-02
180							1.7E-02	1.2E-02	7.5E-03	3.7E-02
210								1.8E-02	1.1E-02	2.9E-02
240									1.7E-02	1.7E-02

Table B23. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 137Cs injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	1.9E-05	2.1E-05	4.1E-06	4.0E-06	5.1E-06	3.0E-06	3.1E-06	3.1E-06	1.7E-06	1.3E-06
30		1.9E-05	5.2E-06	5.1E-06	6.6E-06	3.8E-06	4.0E-06	4.0E-06	2.2E-06	1.6E-06
60			6.4E-06	6.5E-06	8.4E-06	4.9E-06	5.2E-06	5.2E-06	2.8E-06	2.1E-06
90				6.4E-06	1.1E-05	6.3E-06	6.7E-06	6.7E-06	3.6E-06	2.7E-06
120					6.4E-06	8.0E-06	8.5E-06	8.5E-06	4.6E-06	3.4E-06
150						5.3E-06	1.1E-05	1.1E-05	5.9E-06	4.4E-06
180							5.3E-06	1.4E-05	7.8E-06	5.8E-06
210								5.3E-06	1.1E-05	8.3E-06
240									4.2E-06	1.3E-05
270										1.9E-05

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	1.6E-02	1.4E-02	2.8E-03	3.2E-03	3.0E-03	2.2E-03	2.3E-03	1.7E-03	1.1E-03	4.6E-02
30		1.8E-02	3.6E-03	4.1E-03	3.9E-03	2.8E-03	2.9E-03	2.2E-03	1.4E-03	3.9E-02
60			4.6E-03	5.2E-03	5.0E-03	3.6E-03	3.8E-03	2.8E-03	1.8E-03	2.7E-02
90				6.7E-03	6.4E-03	4.6E-03	4.9E-03	3.6E-03	2.3E-03	2.8E-02
120					8.1E-03	5.9E-03	6.2E-03	4.7E-03	2.9E-03	2.8E-02
150						7.6E-03	8.0E-03	6.0E-03	3.8E-03	2.5E-02
180							1.0E-02	7.9E-03	5.0E-03	2.3E-02
210								1.1E-02	7.1E-03	1.8E-02
240									1.1E-02	1.1E-02

Table B24. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 141Ce injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	7.8E-06	4.1E-06	2.8E-07	1.5E-07	7.7E-08	3.3E-08	1.8E-08	9.2E-09	3.8E-09	2.0E-09
30		7.8E-06	5.3E-07	2.8E-07	1.5E-07	6.4E-08	3.3E-08	1.8E-08	7.3E-09	3.8E-09
60			1.0E-06	5.4E-07	2.8E-07	1.2E-07	6.4E-08	3.4E-08	1.4E-08	7.3E-09
90				1.0E-06	5.5E-07	2.3E-07	1.2E-07	6.4E-08	2.7E-08	1.4E-08
120					1.0E-06	4.6E-07	2.4E-07	1.3E-07	5.2E-08	2.7E-08
150						8.4E-07	4.7E-07	2.5E-07	1.0E-07	5.3E-08
180							8.4E-07	5.0E-07	2.0E-07	1.1E-07
210								8.4E-07	4.0E-07	2.1E-07
240									6.7E-07	4.3E-07
270										8.1E-07

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	4.1E-03	2.1E-03	1.5E-04	7.8E-05	3.8E-05	1.8E-05	9.3E-06	4.4E-06	2.0E-06	6.6E-03
30		4.1E-03	2.8E-04	1.5E-04	7.2E-05	3.4E-05	1.8E-05	8.5E-06	3.9E-06	4.7E-03
60			5.4E-04	2.8E-04	1.4E-04	6.5E-05	3.4E-05	1.6E-05	7.4E-06	1.1E-03
90				5.5E-04	2.7E-04	1.2E-04	6.5E-05	3.1E-05	1.4E-05	1.1E-03
120					5.3E-04	2.4E-04	1.3E-04	6.0E-05	2.7E-05	9.9E-04
150						4.8E-04	2.5E-04	1.2E-04	5.4E-05	9.0E-04
180							5.0E-04	2.4E-04	1.1E-04	8.5E-04
210								4.8E-04	2.1E-04	7.0E-04
240									4.3E-04	4.3E-04

Table B25. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 144Ce injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	4.2E-07	3.9E-07	2.5E-07	2.3E-07	2.1E-07	1.6E-07	1.4E-07	1.3E-07	9.6E-08	8.9E-08
30		4.2E-07	2.7E-07	2.5E-07	2.3E-07	1.7E-07	1.6E-07	1.4E-07	1.0E-07	9.6E-08
60			2.9E-07	2.8E-07	2.5E-07	1.8E-07	1.7E-07	1.6E-07	1.1E-07	1.0E-07
90				2.9E-07	2.9E-07	2.1E-07	1.9E-07	1.7E-07	1.2E-07	1.1E-07
120					2.9E-07	2.5E-07	2.2E-07	1.9E-07	1.4E-07	1.3E-07
150						2.3E-07	2.5E-07	2.2E-07	1.6E-07	1.4E-07
180							2.3E-07	2.6E-07	1.8E-07	1.6E-07
210								2.3E-07	2.2E-07	1.9E-07
240									1.8E-07	2.3E-07
270										2.5E-07

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	2.9E-04	2.7E-04	1.7E-04	1.6E-04	1.3E-04	1.1E-04	1.0E-04	8.2E-05	6.7E-05	1.4E-03
30		3.0E-04	1.9E-04	1.7E-04	1.4E-04	1.2E-04	1.1E-04	8.9E-05	7.2E-05	1.2E-03
60			2.2E-04	1.9E-04	1.6E-04	1.3E-04	1.2E-04	9.7E-05	7.8E-05	9.9E-04
90				2.3E-04	1.8E-04	1.4E-04	1.3E-04	1.1E-04	8.5E-05	8.7E-04
120					2.2E-04	1.7E-04	1.5E-04	1.2E-04	9.5E-05	7.4E-04
150						2.0E-04	1.7E-04	1.3E-04	1.1E-04	6.1E-04
180							2.0E-04	1.6E-04	1.2E-04	4.8E-04
210								1.9E-04	1.5E-04	3.3E-04
240									1.7E-04	1.7E-04

Table B26. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 191Os injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	6.5E-06	3.3E-07	9.4E-09	2.2E-09	5.0E-10	9.6E-11	2.3E-11	5.3E-12	9.6E-13	2.2E-13
30		6.5E-06	5.3E-08	9.6E-09	2.2E-09	4.2E-10	9.7E-11	2.3E-11	4.1E-12	9.7E-13
60			1.1E-06	7.0E-08	1.4E-08	2.1E-09	5.0E-10	1.2E-10	2.1E-11	5.0E-12
90				1.1E-06	5.6E-08	8.1E-09	1.9E-09	4.3E-10	7.8E-11	1.8E-11
120					1.1E-06	4.7E-08	8.8E-09	2.0E-09	3.6E-10	8.5E-11
150						8.7E-07	5.2E-08	1.0E-08	1.7E-09	4.1E-10
180							8.7E-07	5.9E-08	8.4E-09	2.0E-09
210								8.7E-07	4.9E-08	1.0E-08
240									6.8E-07	5.6E-08
270										5.8E-07

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	1.2E-03	1.1E-04	3.5E-06	8.1E-07	1.8E-07	3.7E-08	8.6E-09	1.9E-09	3.6E-10	1.3E-03
30		1.5E-03	1.8E-05	3.6E-06	7.8E-07	1.6E-07	3.7E-08	8.0E-09	1.6E-09	1.5E-03
60			2.2E-04	2.4E-05	4.7E-06	8.1E-07	1.9E-07	4.2E-08	8.0E-09	2.5E-04
90				2.0E-04	1.7E-05	3.0E-06	7.0E-07	1.5E-07	3.0E-08	2.2E-04
120					2.0E-04	1.6E-05	3.3E-06	7.1E-07	1.4E-07	2.2E-04
150						1.7E-04	1.8E-05	3.5E-06	6.5E-07	1.9E-04
180							1.8E-04	1.9E-05	3.2E-06	2.0E-04
210								1.8E-04	1.7E-05	2.0E-04
240									1.5E-04	1.5E-04
270										

Table B27. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 192Ir injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	2.2E-05	9.7E-06	2.8E-06	1.9E-06	1.3E-06	7.4E-07	5.1E-07	3.4E-07	1.9E-07	1.3E-07
30		2.2E-05	4.3E-06	2.8E-06	1.9E-06	1.1E-06	7.4E-07	5.1E-07	2.8E-07	1.9E-07
60			9.6E-06	4.4E-06	2.9E-06	1.6E-06	1.1E-06	7.5E-07	4.1E-07	2.8E-07
90				9.6E-06	4.3E-06	2.4E-06	1.6E-06	1.1E-06	6.0E-07	4.1E-07
120					9.6E-06	3.6E-06	2.4E-06	1.6E-06	8.9E-07	6.1E-07
150						8.0E-06	3.6E-06	2.4E-06	1.3E-06	9.0E-07
180							8.0E-06	3.7E-06	2.0E-06	1.4E-06
210								8.0E-06	3.0E-06	2.0E-06
240									6.4E-06	3.1E-06
270										5.4E-06

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	9.3E-03	5.7E-03	1.7E-03	1.2E-03	7.2E-04	4.4E-04	3.0E-04	1.9E-04	1.1E-04	2.0E-02
30		9.8E-03	2.5E-03	1.7E-03	1.1E-03	6.5E-04	4.4E-04	2.7E-04	1.7E-04	1.7E-02
60			4.2E-03	2.6E-03	1.6E-03	9.7E-04	6.6E-04	4.1E-04	2.5E-04	1.1E-02
90				4.1E-03	2.3E-03	1.4E-03	9.6E-04	6.0E-04	3.6E-04	9.8E-03
120					3.8E-03	2.1E-03	1.4E-03	8.8E-04	5.3E-04	8.8E-03
150						3.5E-03	2.2E-03	1.3E-03	7.9E-04	7.7E-03
180							3.5E-03	2.0E-03	1.2E-03	6.7E-03
210								3.3E-03	1.8E-03	5.1E-03
240									2.9E-03	2.9E-03

Table B28. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 201Tl injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	3.4E-06	6.3E-10	2.5E-14	3.6E-18	6.3E-22	6.6E-26	1.1E-29	1.9E-33	2.1E-37	0
30		3.4E-06	1.9E-10	2.7E-14	4.7E-18	5.0E-22	8.1E-26	1.4E-29	1.5E-33	2.3E-37
60			1.3E-06	2.0E-10	3.5E-14	3.7E-18	6.1E-22	1.0E-25	1.1E-29	1.7E-33
90				1.3E-06	2.6E-10	2.8E-14	4.5E-18	7.8E-22	8.6E-26	1.3E-29
120					1.3E-06	2.1E-10	3.4E-14	5.8E-18	6.4E-22	9.4E-26
150						1.1E-06	2.5E-10	4.3E-14	4.8E-18	7.0E-22
180							1.1E-06	3.2E-10	3.6E-14	5.2E-18
210								1.1E-06	2.7E-10	3.9E-14
240									8.5E-07	2.9E-10
270										1.6E-06

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	3.7E-04	5.2E-08	2.1E-12	3.0E-16						3.7E-04
30		3.7E-04	1.5E-08	2.2E-12	3.9E-16					3.7E-04
60			1.1E-04	1.7E-08	2.9E-12	3.1E-16				1.1E-04
90				1.2E-04	2.2E-08	2.3E-12	3.8E-16			1.2E-04
120					1.6E-04	1.7E-08	2.8E-12	4.8E-16		1.6E-04
150						1.2E-04	2.1E-08	3.6E-12	3.9E-16	1.2E-04
180							1.5E-04	2.7E-08	3.0E-12	1.5E-04
210								1.9E-04	2.2E-08	1.9E-04
240									1.5E-04	1.5E-04

Table B29. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 210Pb injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	1.4E-07	1.2E-07	4.2E-08	2.4E-08	1.8E-08	1.1E-08	9.6E-09	9.3E-09	6.9E-09	6.9E-09
30		1.4E-07	9.7E-08	4.3E-08	2.4E-08	1.3E-08	1.1E-08	9.6E-09	7.1E-09	6.9E-09
60			5.5E-08	9.7E-08	4.3E-08	2.0E-08	1.3E-08	1.1E-08	7.4E-09	7.1E-09
90				5.5E-08	1.3E-07	5.3E-08	2.8E-08	1.8E-08	1.2E-08	1.0E-08
120					5.5E-08	2.2E-07	1.1E-07	6.3E-08	3.9E-08	3.2E-08
150						3.7E-08	2.9E-07	1.6E-07	1.0E-07	7.9E-08
180							3.7E-08	3.4E-07	2.0E-07	1.6E-07
210								3.7E-08	3.5E-07	2.6E-07
240									2.8E-08	3.8E-07
270										5.3E-07

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	1.8E-04	6.1E-05	2.3E-05	1.5E-05	9.9E-06	7.2E-06	6.8E-06	5.8E-06	5.0E-06	3.1E-04
30		1.8E-04	4.6E-05	2.3E-05	1.3E-05	8.4E-06	7.2E-06	6.0E-06	5.0E-06	2.9E-04
60			1.6E-04	4.7E-05	2.2E-05	1.1E-05	8.4E-06	6.4E-06	5.2E-06	2.6E-04
90				1.9E-04	6.1E-05	2.8E-05	1.6E-05	1.0E-05	7.6E-06	3.1E-04
120					2.5E-04	1.1E-04	6.0E-05	3.6E-05	2.5E-05	4.9E-04
150						2.9E-04	1.6E-04	9.3E-05	6.2E-05	6.0E-04
180							3.1E-04	1.9E-04	1.3E-04	6.3E-04
210								3.2E-04	2.1E-04	5.3E-04
240									3.1E-04	3.1E-04

Table B30. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 210Bi injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	1.1E-06	2.0E-12	1.0E-15	2.4E-18	9.8E-21	7.0E-23	5.9E-25	5.5E-27	5.9E-29	7.6E-31
30		3.8E-06	2.8E-09	6.7E-12	2.7E-14	1.9E-16	1.6E-18	1.5E-20	1.6E-22	2.1E-24
60			4.1E-06	1.2E-08	5.0E-11	3.6E-13	3.0E-15	2.8E-17	3.0E-19	3.9E-21
90				4.1E-06	2.1E-08	1.5E-10	1.3E-12	1.2E-14	1.3E-16	1.6E-18
120					4.1E-06	3.6E-08	3.1E-10	2.9E-12	3.0E-14	4.0E-16
150						4.1E-06	4.3E-08	4.0E-10	4.3E-12	5.5E-14
180							4.1E-06	4.6E-08	4.9E-10	6.4E-12
210								4.0E-06	5.2E-08	6.8E-10
240									3.9E-06	6.2E-08
270										3.8E-06

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	4.8E-05	1.6E-10	1.2E-13	3.1E-16						4.8E-05
30		3.3E-04	3.3E-07	8.5E-10	3.8E-12	2.9E-14	2.5E-16	6.3E-19		3.3E-04
60			5.0E-04	1.6E-06	7.0E-09	5.3E-11	4.6E-13	4.4E-15	4.7E-17	5.0E-04
90				5.4E-04	2.9E-06	2.2E-08	1.9E-10	1.8E-12	2.0E-14	5.5E-04
120					6.0E-04	5.4E-06	4.7E-08	4.5E-10	4.9E-12	6.0E-04
150						6.4E-04	6.5E-06	6.2E-08	6.8E-10	6.5E-04
180							6.4E-04	7.2E-06	7.8E-08	6.4E-04
210								6.5E-04	8.3E-06	6.6E-04
240									6.5E-04	6.5E-04

Table B31. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 210Po injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	6.7E-06	4.8E-10	1.4E-11	1.8E-12	3.9E-13	1.5E-13	7.1E-14	3.6E-14	2.1E-14	1.5E-14
30		1.7E-04	5.6E-06	7.3E-07	1.6E-07	6.2E-08	2.9E-08	1.5E-08	8.5E-09	6.0E-09
60			1.8E-04	2.5E-05	5.6E-06	2.2E-06	1.0E-06	5.1E-07	3.0E-07	2.1E-07
90				1.8E-05	4.3E-06	1.7E-06	7.8E-07	3.9E-07	2.3E-07	1.6E-07
120					1.9E-05	7.5E-06	3.5E-06	1.8E-06	1.0E-06	7.3E-07
150						1.9E-05	9.0E-06	4.5E-06	2.6E-06	1.9E-06
180							1.9E-05	9.6E-06	5.6E-06	4.0E-06
210								1.8E-05	1.1E-05	7.8E-06
240									1.8E-05	1.3E-05
270										1.8E-05

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	3.4E-04	7.7E-08	4.1E-09	6.4E-10	1.7E-10	7.6E-11	3.6E-11	2.0E-11	1.2E-11	3.4E-04
30		2.7E-02	1.7E-03	2.6E-04	7.1E-05	3.1E-05	1.5E-05	8.1E-06	5.0E-06	2.9E-02
60			5.5E-02	9.1E-03	2.5E-03	1.1E-03	5.2E-04	2.8E-04	1.8E-04	6.9E-02
90				6.6E-03	1.9E-03	8.4E-04	4.0E-04	2.2E-04	1.4E-04	1.0E-02
120					8.2E-03	3.8E-03	1.8E-03	9.7E-04	6.1E-04	1.5E-02
150						9.2E-03	4.6E-03	2.5E-03	1.6E-03	1.8E-02
180							9.3E-03	5.3E-03	3.3E-03	1.8E-02
210								1.0E-02	6.5E-03	1.6E-02
240									1.0E-02	1.0E-02

Table B32. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 224Ra injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	8.2E-05	1.3E-07	1.5E-10	1.8E-13	2.2E-16	2.6E-19	3.1E-22	3.6E-25	4.3E-28	4.9E-31
30		8.1E-05	1.3E-07	1.5E-10	1.8E-13	2.2E-16	2.6E-19	3.0E-22	3.5E-25	4.1E-28
60			8.1E-05	1.3E-07	1.5E-10	1.8E-13	2.1E-16	2.5E-19	2.9E-22	3.4E-25
90				8.1E-05	1.4E-07	1.7E-10	2.2E-13	3.0E-16	4.5E-19	8.6E-22
120					8.2E-05	1.9E-07	2.7E-10	4.2E-13	7.5E-16	1.8E-18
150						8.2E-05	2.2E-07	3.5E-10	6.3E-13	1.5E-15
180							8.1E-05	2.4E-07	4.2E-10	9.4E-13
210								8.0E-05	2.4E-07	5.1E-10
240									7.7E-05	2.5E-07
270										7.5E-05

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	9.1E-03	1.4E-05	1.6E-08	2.0E-11	2.3E-14	2.7E-17				9.1E-03
30		9.0E-03	1.4E-05	1.6E-08	1.9E-11	2.3E-14	2.6E-17			9.0E-03
60			9.0E-03	1.4E-05	1.6E-08	1.9E-11	2.3E-14	2.6E-17		9.0E-03
90				9.5E-03	1.5E-05	1.9E-08	2.4E-11	3.3E-14	5.0E-17	9.5E-03
120					1.0E-02	2.1E-05	3.0E-08	4.7E-11	8.8E-14	1.0E-02
150						1.1E-02	2.5E-05	3.9E-08	7.4E-11	1.1E-02
180							1.1E-02	2.7E-05	4.8E-08	1.1E-02
210								1.1E-02	2.8E-05	1.1E-02
240									1.0E-02	1.0E-02

Table B33. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 226Ra injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	8.3E-05	3.1E-05	1.1E-05	3.9E-06	1.4E-06	4.7E-07	1.7E-07	5.7E-08	2.0E-08	6.7E-09
30		8.2E-05	3.1E-05	1.1E-05	3.9E-06	1.3E-06	4.7E-07	1.6E-07	5.6E-08	1.9E-08
60			8.2E-05	3.1E-05	1.1E-05	3.8E-06	1.3E-06	4.6E-07	1.6E-07	5.4E-08
90				8.3E-05	3.5E-05	1.3E-05	4.7E-06	1.9E-06	8.3E-07	4.6E-07
120					8.3E-05	4.6E-05	2.0E-05	8.8E-06	4.7E-06	3.2E-06
150						8.3E-05	5.4E-05	2.5E-05	1.3E-05	9.3E-06
180							8.2E-05	5.8E-05	3.0E-05	2.0E-05
210								8.1E-05	5.9E-05	3.7E-05
240									7.8E-05	6.2E-05
270										7.6E-05

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	3.8E-02	1.4E-02	4.9E-03	1.7E-03	6.1E-04	2.1E-04	7.3E-05	2.5E-05	8.7E-06	5.9E-02
30		3.8E-02	1.4E-02	4.9E-03	1.7E-03	6.0E-04	2.1E-04	7.2E-05	2.5E-05	5.9E-02
60			3.7E-02	1.4E-02	4.9E-03	1.7E-03	5.9E-04	2.0E-04	7.0E-05	5.9E-02
90				4.1E-02	1.6E-02	5.8E-03	2.2E-03	9.1E-04	4.4E-04	6.6E-02
120					4.8E-02	2.2E-02	9.6E-03	4.7E-03	2.7E-03	8.7E-02
150						5.2E-02	2.7E-02	1.3E-02	7.8E-03	1.0E-01
180							5.4E-02	3.1E-02	1.7E-02	1.0E-01
210								5.3E-02	3.3E-02	8.6E-02
240									5.2E-02	5.2E-02

Table B34. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 227Th injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	1.1E-05	7.3E-10	7.9E-12	3.9E-13	3.3E-14	4.9E-15	8.7E-16	1.7E-16	3.7E-17	1.0E-17
30		2.8E-05	5.0E-07	2.5E-08	2.1E-09	3.1E-10	5.5E-11	1.1E-11	2.4E-12	6.5E-13
60			2.9E-05	2.1E-06	1.8E-07	2.6E-08	4.6E-09	8.9E-10	2.0E-10	5.4E-11
90				1.5E-06	1.8E-07	2.6E-08	4.7E-09	9.0E-10	2.0E-10	5.5E-11
120					1.5E-06	3.1E-07	5.4E-08	1.0E-08	2.3E-09	6.4E-10
150						1.5E-06	3.6E-07	7.0E-08	1.6E-08	4.2E-09
180							1.5E-06	3.8E-07	8.6E-08	2.3E-08
210								1.4E-06	4.4E-07	1.2E-07
240									1.4E-06	5.2E-07
270										1.4E-06

Days of Gestation at v Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	9.5E-04	9.4E-08	1.8E-09	1.0E-10	1.0E-11	1.7E-12	3.0E-13	6.2E-14	1.5E-14	9.5E-04
30		4.8E-03	1.1E-04	6.4E-06	6.5E-07	1.1E-07	1.9E-08	4.0E-09	9.3E-10	4.9E-03
60			8.3E-03	5.4E-04	5.4E-05	8.9E-06	1.6E-06	3.3E-07	7.8E-08	8.9E-03
90				4.9E-04	5.5E-05	9.0E-06	1.6E-06	3.4E-07	7.9E-08	5.5E-04
120					5.8E-04	1.0E-04	1.9E-05	3.9E-06	9.2E-07	7.1E-04
150						6.4E-04	1.3E-04	2.6E-05	6.1E-06	8.0E-04
180							6.4E-04	1.4E-04	3.4E-05	8.2E-04
210								6.7E-04	1.7E-04	8.4E-04
240									6.9E-04	6.9E-04

Table B35. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 230Th injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days)									
	0	30	60	90	120	150	180	210	240	270
0	9.0E-06	1.8E-09	5.8E-11	8.7E-12	2.2E-12	1.0E-12	5.4E-13	3.2E-13	2.2E-13	1.8E-13
30		2.3E-05	1.2E-06	1.8E-07	4.7E-08	2.1E-08	1.1E-08	6.7E-09	4.5E-09	3.7E-09
60			2.4E-05	5.0E-06	1.3E-06	5.8E-07	3.1E-07	1.8E-07	1.2E-07	1.0E-07
90				1.2E-06	4.3E-07	1.9E-07	1.0E-07	6.1E-08	4.1E-08	3.4E-08
120					1.2E-06	7.4E-07	4.0E-07	2.3E-07	1.6E-07	1.3E-07
150						1.2E-06	8.8E-07	5.1E-07	3.5E-07	2.9E-07
180							1.2E-06	9.3E-07	6.3E-07	5.2E-07
210								1.2E-06	1.1E-06	8.7E-07
240									1.2E-06	1.3E-06
270										1.1E-06

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestation periods (days)									Cumulated dose
	0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	0-270
0	8.6E-04	2.9E-07	1.8E-08	3.3E-09	1.1E-09	5.4E-10	3.0E-10	1.9E-10	1.4E-10	8.6E-04
30		5.1E-03	3.9E-04	7.0E-05	2.2E-05	1.1E-05	6.3E-06	4.0E-06	2.9E-06	5.6E-03
60			9.7E-03	1.9E-03	6.1E-04	3.1E-04	1.7E-04	1.1E-04	7.9E-05	1.3E-02
90				5.9E-04	2.0E-04	1.0E-04	5.7E-05	3.6E-05	2.6E-05	1.0E-03
120					7.4E-04	4.0E-04	2.2E-04	1.4E-04	1.0E-04	1.6E-03
150						8.2E-04	4.8E-04	3.0E-04	2.2E-04	1.8E-03
180							8.3E-04	5.5E-04	4.0E-04	1.8E-03
210								8.8E-04	6.7E-04	1.6E-03
240									9.2E-04	9.2E-04

Table B36. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 232Th injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	7.8E-06	1.5E-09	5.0E-11	7.5E-12	1.9E-12	8.6E-13	4.7E-13	2.7E-13	1.8E-13	1.5E-13
30		2.0E-05	1.0E-06	1.6E-07	4.1E-08	1.8E-08	9.8E-09	5.7E-09	3.9E-09	3.2E-09
60			2.1E-05	4.3E-06	1.1E-06	5.0E-07	2.7E-07	1.6E-07	1.1E-07	8.8E-08
90				1.0E-06	3.7E-07	1.7E-07	9.0E-08	5.2E-08	3.6E-08	2.9E-08
120					1.0E-06	6.4E-07	3.4E-07	2.0E-07	1.4E-07	1.1E-07
150						1.0E-06	7.5E-07	4.4E-07	3.0E-07	2.5E-07
180							1.0E-06	8.0E-07	5.4E-07	4.5E-07
210								1.0E-06	9.1E-07	7.5E-07
240									9.9E-07	1.1E-06
270										9.6E-07

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestation periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	7.4E-04	2.5E-07	1.6E-08	2.8E-09	9.1E-10	4.6E-10	2.6E-10	1.6E-10	1.2E-10	7.4E-04
30		4.4E-03	3.3E-04	6.0E-05	1.9E-05	9.7E-06	5.4E-06	3.4E-06	2.5E-06	4.8E-03
60			8.3E-03	1.6E-03	5.2E-04	2.7E-04	1.5E-04	9.3E-05	6.8E-05	1.1E-02
90				5.1E-04	1.8E-04	8.9E-05	4.9E-05	3.1E-05	2.3E-05	8.8E-04
120					6.3E-04	3.4E-04	1.9E-04	1.2E-04	8.7E-05	1.4E-03
150						7.1E-04	4.1E-04	2.6E-04	1.9E-04	1.6E-03
180							7.1E-04	4.8E-04	3.5E-04	1.5E-03
210								7.6E-04	5.8E-04	1.3E-03
240									7.9E-04	7.9E-04

Table B37. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 234Th injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	2.1E-07	7.6E-08	1.9E-08	7.7E-09	3.2E-09	1.0E-09	4.3E-10	1.8E-10	5.8E-11	2.4E-11
30		2.1E-07	5.1E-08	1.9E-08	7.7E-09	2.5E-09	1.0E-09	4.3E-10	1.4E-10	5.8E-11
60			1.3E-07	7.1E-08	2.1E-08	6.6E-09	2.6E-09	1.1E-09	3.4E-10	1.4E-10
90				1.3E-07	4.7E-08	1.5E-08	6.1E-09	2.5E-09	8.1E-10	3.4E-10
120					1.3E-07	3.9E-08	1.5E-08	6.3E-09	2.0E-09	8.3E-10
150						9.9E-08	4.0E-08	1.6E-08	5.0E-09	2.1E-09
180							9.9E-08	4.0E-08	1.3E-08	5.2E-09
210								9.9E-08	3.3E-08	1.3E-08
240									7.7E-08	3.4E-08
270										8.1E-08

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	1.0E-04	3.6E-05	8.9E-06	3.7E-06	1.4E-06	5.0E-07	2.1E-07	7.9E-08	2.8E-08	1.5E-04
30		1.4E-04	2.3E-05	9.0E-06	3.4E-06	1.2E-06	5.0E-07	1.9E-07	6.7E-08	1.8E-04
60			1.5E-04	2.9E-05	9.1E-06	3.1E-06	1.2E-06	4.7E-07	1.7E-07	1.9E-04
90				5.8E-05	2.0E-05	7.1E-06	2.9E-06	1.1E-06	3.9E-07	9.0E-05
120					5.4E-05	1.8E-05	7.3E-06	2.7E-06	9.6E-07	8.4E-05
150						4.8E-05	1.9E-05	6.8E-06	2.4E-06	7.6E-05
180							4.9E-05	1.7E-05	6.1E-06	7.2E-05
210								4.5E-05	1.6E-05	6.1E-05
240									4.0E-05	4.0E-05

Table B38. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 234U injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	1.6E-08	1.8E-12	5.9E-14	8.8E-15	2.3E-15	1.0E-15	5.5E-16	3.2E-16	2.2E-16	1.8E-16
30		1.7E-05	7.0E-07	1.1E-07	2.7E-08	1.2E-08	6.5E-09	3.8E-09	2.6E-09	2.1E-09
60			1.5E-05	2.5E-06	6.3E-07	2.8E-07	1.5E-07	8.9E-08	6.0E-08	5.0E-08
90				1.8E-05	5.1E-06	2.3E-06	1.2E-06	7.2E-07	4.9E-07	4.0E-07
120					2.0E-05	9.9E-06	5.3E-06	3.1E-06	2.1E-06	1.7E-06
150						2.7E-05	1.5E-05	8.9E-06	6.0E-06	5.0E-06
180							4.0E-05	2.5E-05	1.7E-05	1.4E-05
210								4.7E-05	3.4E-05	2.8E-05
240									4.8E-05	4.1E-05
270										5.1E-05

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	1.0E-06	2.9E-10	1.9E-11	3.4E-12	1.1E-12	5.4E-13	3.0E-13	1.9E-13	1.4E-13	1.0E-06
30		3.0E-03	2.2E-04	4.0E-05	1.3E-05	6.5E-06	3.6E-06	2.3E-06	1.6E-06	3.3E-03
60			4.8E-03	9.3E-04	3.0E-04	1.5E-04	8.4E-05	5.3E-05	3.8E-05	6.4E-03
90				7.1E-03	2.4E-03	1.2E-03	6.8E-04	4.3E-04	3.1E-04	1.2E-02
120					9.9E-03	5.3E-03	2.9E-03	1.9E-03	1.3E-03	2.1E-02
150						1.5E-02	8.4E-03	5.3E-03	3.9E-03	3.2E-02
180							2.2E-02	1.5E-02	1.1E-02	4.7E-02
210								2.8E-02	2.1E-02	5.0E-02
240									3.1E-02	3.1E-02

Table B39. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 235U injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	1.5E-08	1.6E-12	5.4E-14	8.2E-15	2.1E-15	9.4E-16	5.1E-16	3.0E-16	2.0E-16	1.7E-16
30		1.6E-05	6.5E-07	9.7E-08	2.5E-08	1.1E-08	6.0E-09	3.5E-09	2.4E-09	2.0E-09
60			1.4E-05	2.3E-06	5.8E-07	2.6E-07	1.4E-07	8.3E-08	5.6E-08	4.6E-08
90				1.7E-05	4.7E-06	2.1E-06	1.1E-06	6.6E-07	4.5E-07	3.7E-07
120					1.9E-05	9.1E-06	4.9E-06	2.9E-06	1.9E-06	1.6E-06
150						2.5E-05	1.4E-05	8.3E-06	5.6E-06	4.6E-06
180							3.7E-05	2.3E-05	1.5E-05	1.3E-05
210								4.3E-05	3.1E-05	2.6E-05
240									4.4E-05	3.8E-05
270										4.7E-05

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	9.4E-07	2.7E-10	1.7E-11	3.1E-12	9.9E-13	5.0E-13	2.8E-13	1.8E-13	1.3E-13	9.4E-07
30		2.8E-03	2.1E-04	3.7E-05	1.2E-05	6.0E-06	3.3E-06	2.1E-06	1.5E-06	3.0E-03
60			4.5E-03	8.6E-04	2.8E-04	1.4E-04	7.8E-05	4.9E-05	3.5E-05	5.9E-03
90				6.5E-03	2.2E-03	1.1E-03	6.3E-04	4.0E-04	2.9E-04	1.1E-02
120					9.1E-03	4.9E-03	2.7E-03	1.7E-03	1.2E-03	2.0E-02
150						1.3E-02	7.8E-03	4.9E-03	3.6E-03	3.0E-02
180							2.0E-02	1.4E-02	9.8E-03	4.4E-02
210								2.6E-02	2.0E-02	4.6E-02
240									2.8E-02	2.8E-02

Table B40. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 238U injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	1.4E-08	1.6E-12	5.2E-14	7.8E-15	2.0E-15	8.9E-16	4.8E-16	2.8E-16	1.9E-16	1.6E-16
30		1.5E-05	6.1E-07	9.3E-08	2.4E-08	1.1E-08	5.7E-09	3.4E-09	2.3E-09	1.9E-09
60			1.3E-05	2.2E-06	5.6E-07	2.5E-07	1.3E-07	7.9E-08	5.3E-08	4.4E-08
90				1.6E-05	4.5E-06	2.0E-06	1.1E-06	6.3E-07	4.3E-07	3.5E-07
120					1.8E-05	8.7E-06	4.7E-06	2.7E-06	1.9E-06	1.5E-06
150						2.3E-05	1.3E-05	7.9E-06	5.3E-06	4.4E-06
180							3.5E-05	2.2E-05	1.5E-05	1.2E-05
210								4.1E-05	3.0E-05	2.4E-05
240									4.2E-05	3.7E-05
270										4.5E-05

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	8.9E-07	2.6E-10	1.6E-11	3.0E-12	9.4E-13	4.8E-13	2.6E-13	1.7E-13	1.2E-13	8.9E-07
30		2.6E-03	2.0E-04	3.5E-05	1.1E-05	5.7E-06	3.2E-06	2.0E-06	1.4E-06	2.9E-03
60			4.2E-03	8.2E-04	2.6E-04	1.3E-04	7.4E-05	4.7E-05	3.4E-05	5.6E-03
90				6.2E-03	2.1E-03	1.1E-03	6.0E-04	3.8E-04	2.7E-04	1.1E-02
120					8.7E-03	4.7E-03	2.6E-03	1.6E-03	1.2E-03	1.9E-02
150						1.3E-02	7.4E-03	4.7E-03	3.4E-03	2.8E-02
180							2.0E-02	1.3E-02	9.4E-03	4.2E-02
210								2.5E-02	1.9E-02	4.4E-02
240									2.7E-02	2.7E-02

Table B41. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 237Np injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	1.4E-08	1.6E-12	5.2E-14	7.8E-15	2.0E-15	8.9E-16	4.8E-16	2.8E-16	1.9E-16	1.6E-16
30		1.4E-05	5.5E-07	8.3E-08	2.1E-08	9.6E-09	5.2E-09	3.0E-09	2.0E-09	1.7E-09
60			1.0E-05	1.7E-06	4.4E-07	2.0E-07	1.1E-07	6.2E-08	4.2E-08	3.5E-08
90				1.4E-05	3.9E-06	1.7E-06	9.3E-07	5.4E-07	3.7E-07	3.1E-07
120					1.9E-05	9.3E-06	5.0E-06	2.9E-06	2.0E-06	1.6E-06
150						2.6E-05	1.5E-05	8.8E-06	5.9E-06	4.9E-06
180							4.1E-05	2.5E-05	1.7E-05	1.4E-05
210								5.1E-05	3.6E-05	3.0E-05
240									5.2E-05	4.5E-05
270										5.5E-05

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	8.9E-07	2.6E-10	1.6E-11	2.9E-12	9.4E-13	4.8E-13	2.6E-13	1.7E-13	1.2E-13	8.9E-07
30		2.4E-03	1.8E-04	3.2E-05	1.0E-05	5.1E-06	2.8E-06	1.8E-06	1.3E-06	2.6E-03
60			3.3E-03	6.5E-04	2.1E-04	1.1E-04	5.9E-05	3.7E-05	2.7E-05	4.4E-03
90				5.4E-03	1.8E-03	9.3E-04	5.1E-04	3.2E-04	2.4E-04	9.2E-03
120					9.3E-03	5.0E-03	2.8E-03	1.7E-03	1.3E-03	2.0E-02
150						1.4E-02	8.2E-03	5.2E-03	3.8E-03	3.2E-02
180							2.3E-02	1.5E-02	1.1E-02	4.8E-02
210								3.1E-02	2.3E-02	5.4E-02
240									3.4E-02	3.4E-02

Table B42. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 238Pu injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	2.3E-08	2.5E-12	8.4E-14	1.3E-14	3.2E-15	1.4E-15	7.8E-16	4.6E-16	3.1E-16	2.5E-16
30		2.8E-05	1.2E-06	1.8E-07	4.5E-08	2.0E-08	1.1E-08	6.3E-09	4.3E-09	3.6E-09
60			2.9E-05	4.9E-06	1.2E-06	5.6E-07	3.0E-07	1.8E-07	1.2E-07	9.8E-08
90				4.6E-05	1.3E-05	5.8E-06	3.1E-06	1.8E-06	1.2E-06	1.0E-06
120					5.4E-05	2.6E-05	1.4E-05	8.3E-06	5.6E-06	4.6E-06
150						6.4E-05	3.7E-05	2.2E-05	1.5E-05	1.2E-05
180							7.7E-05	4.8E-05	3.2E-05	2.7E-05
210								9.0E-05	6.4E-05	5.3E-05
240									9.4E-05	8.2E-05
270										9.7E-05

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	1.4E-06	4.2E-10	2.7E-11	4.8E-12	1.5E-12	7.8E-13	4.3E-13	2.7E-13	2.0E-13	1.4E-06
30		5.0E-03	3.7E-04	6.7E-05	2.1E-05	1.1E-05	6.0E-06	3.8E-06	2.7E-06	5.5E-03
60			9.5E-03	1.8E-03	5.9E-04	3.0E-04	1.7E-04	1.0E-04	7.6E-05	1.3E-02
90				1.8E-02	6.1E-03	3.1E-03	1.7E-03	1.1E-03	7.9E-04	3.1E-02
120					2.6E-02	1.4E-02	7.8E-03	4.9E-03	3.6E-03	5.7E-02
150						3.5E-02	2.0E-02	1.3E-02	9.3E-03	7.7E-02
180							4.3E-02	2.8E-02	2.1E-02	9.2E-02
210								5.4E-02	4.1E-02	9.5E-02
240									6.1E-02	6.1E-02
270										

Table B43. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 239Pu injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	2.2E-08	2.4E-12	7.8E-14	1.2E-14	3.0E-15	1.4E-15	7.3E-16	4.3E-16	2.9E-16	2.4E-16
30		2.7E-05	1.1E-06	1.6E-07	4.2E-08	1.9E-08	1.0E-08	5.9E-09	4.0E-09	3.3E-09
60			2.7E-05	4.6E-06	1.2E-06	5.2E-07	2.8E-07	1.6E-07	1.1E-07	9.2E-08
90				4.3E-05	1.2E-05	5.4E-06	2.9E-06	1.7E-06	1.2E-06	9.5E-07
120					5.1E-05	2.5E-05	1.3E-05	7.8E-06	5.3E-06	4.4E-06
150						6.0E-05	3.5E-05	2.0E-05	1.4E-05	1.1E-05
180							7.3E-05	4.5E-05	3.0E-05	2.5E-05
210								8.4E-05	6.0E-05	5.0E-05
240									8.8E-05	7.7E-05
270										9.1E-05

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	1.4E-06	3.9E-10	2.5E-11	4.5E-12	1.4E-12	7.3E-13	4.0E-13	2.5E-13	1.8E-13	1.4E-06
30		4.7E-03	3.5E-04	6.3E-05	2.0E-05	1.0E-05	5.6E-06	3.5E-06	2.6E-06	5.2E-03
60			8.9E-03	1.7E-03	5.5E-04	2.8E-04	1.6E-04	9.8E-05	7.1E-05	1.2E-02
90				1.7E-02	5.7E-03	2.9E-03	1.6E-03	1.0E-03	7.4E-04	2.9E-02
120					2.5E-02	1.3E-02	7.3E-03	4.6E-03	3.4E-03	5.3E-02
150						3.3E-02	1.9E-02	1.2E-02	8.7E-03	7.3E-02
180							4.0E-02	2.7E-02	1.9E-02	8.6E-02
210								5.1E-02	3.8E-02	8.9E-02
240									5.7E-02	5.7E-02

Table B44. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 241Am injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	1.4E-08	1.6E-12	5.2E-14	7.8E-15	2.0E-15	8.9E-16	4.8E-16	2.8E-16	1.9E-16	1.6E-16
30		1.2E-05	4.8E-07	7.2E-08	1.8E-08	8.3E-09	4.5E-09	2.6E-09	1.8E-09	1.5E-09
60			7.4E-06	1.2E-06	3.2E-07	1.4E-07	7.6E-08	4.5E-08	3.0E-08	2.5E-08
90				1.0E-05	2.9E-06	1.3E-06	7.0E-07	4.1E-07	2.8E-07	2.3E-07
120					1.3E-05	6.2E-06	3.4E-06	2.0E-06	1.3E-06	1.1E-06
150						1.5E-05	8.4E-06	4.9E-06	3.3E-06	2.7E-06
180							1.8E-05	1.1E-05	7.5E-06	6.2E-06
210								2.0E-05	1.4E-05	1.2E-05
240									2.0E-05	1.7E-05
270										2.1E-05

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	8.9E-07	2.6E-10	1.6E-11	3.0E-12	9.4E-13	4.8E-13	2.7E-13	1.7E-13	1.2E-13	8.9E-07
30		2.1E-03	1.5E-04	2.7E-05	8.7E-06	4.4E-06	2.5E-06	1.6E-06	1.1E-06	2.3E-03
60			2.4E-03	4.7E-04	1.5E-04	7.6E-05	4.2E-05	2.7E-05	1.9E-05	3.2E-03
90				4.0E-03	1.4E-03	6.9E-04	3.8E-04	2.4E-04	1.8E-04	6.9E-03
120					6.2E-03	3.3E-03	1.8E-03	1.2E-03	8.5E-04	1.3E-02
150						7.9E-03	4.6E-03	2.9E-03	2.1E-03	1.8E-02
180							1.0E-02	6.6E-03	4.8E-03	2.1E-02
210								1.2E-02	9.2E-03	2.1E-02
240									1.3E-02	1.3E-02

Appendix C

Fractions of Activity in the Embryo/Fetus and Radiation Dose Factors Following Introduction of 1 μCi Activity of Selected Radiopharmaceuticals into the Maternal Transfer Compartment

Fractions of Activity in the Embryo/Fetus and Radiation Dose Factors Following Introduction of 1 μCi Activity of Selected Radiopharmaceuticals into the Maternal Transfer Compartment

The tables in this appendix were constructed for selected radionuclides in chemical forms relevant to their use as radiopharmaceuticals. They are arranged in order of ascending atomic number of the radioelement. Calculations of deposition are based on the biokinetic models presented in Sections V and VII of this report.

The entries in the dose factor tables were calculated from the corresponding fractional activities given in this appendix or in Appendix A. Dose calculations are based on the operational methodology given in Section III. It was assumed that 1 μCi of activity was introduced into the maternal transfer compartment and the tabulated values represent the dose rates or doses that would be obtained using the approaches described.

Pregnancy was assumed to begin at the time of fertilization, roughly 2 weeks after menses, and gestation was considered to consist of nine 30-day months. Radiation absorbed dose rates were calculated from the initial fraction that was present after a single administration at the start of each of these months or on the assumed final day (270) of gestation. Monthly doses were determined by integrating under the curve relating the fraction of the activity in the embryo/fetus at the start of each month after administration and the fraction at the beginning of the subsequent month of gestation, and are shown for the inclusive periods, expressed in days. Doses to the embryo/fetus from radionuclides in maternal organs were calculated and are included, when appropriate, to provide total radiation absorbed doses.

Tables of radiation dose to the embryo/fetus from more complex radiopharmaceutical forms were prepared from calculations and publications of other investigators. These tables, which are presented in Section VII. Radiopharmaceuticals, summarize radiation dose factors or doses and are usually presented by trimester of gestation.

The tables are:

Table 6. Radioiodine: human serum albumin or hippuran
Table 7. Technetium-99m: relevant labeled pharmaceuticals
Table 8. Chromium-51: labeled erythrocytes or leukocytes
Table 9. Radioiron: residence times and doses
Table 10. Radiocobalt: vitamin B-12
Table 11. Radiogallium

Table C1. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 57Co as vitamin B-12 injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestation periods (days) 0	30	60	90	120	150	180	210	240	270
0	3.1E-06	1.1E-06	9.1E-07	8.1E-07	7.2E-07	5.9E-07	5.3E-07	4.7E-07	4.3E-07	3.8E-07
30		3.1E-06	1.0E-06	9.1E-07	8.1E-07	6.7E-07	5.9E-07	5.2E-07	4.9E-07	4.3E-07
60			2.6E-06	1.0E-06	9.1E-07	7.5E-07	6.7E-07	5.9E-07	5.5E-07	4.9E-07
90				2.6E-06	1.0E-06	8.5E-07	7.5E-07	6.6E-07	6.2E-07	5.5E-07
120					2.6E-06	9.6E-07	8.5E-07	7.5E-07	7.0E-07	6.2E-07
150						1.4E-06	9.5E-07	8.4E-07	7.9E-07	7.0E-07
180							1.4E-06	9.5E-07	8.8E-07	7.8E-07
210								1.4E-06	9.9E-07	8.8E-07
240									1.1E-06	9.9E-07
270										1.2E-06

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestation periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	9.0E-04	7.7E-04	6.2E-04	5.5E-04	4.7E-04	4.0E-04	3.6E-04	3.2E-04	2.9E-04	4.7E-03
30		9.0E-04	7.0E-04	6.2E-04	5.3E-04	4.5E-04	4.0E-04	3.6E-04	3.3E-04	4.3E-03
60			8.1E-04	7.0E-04	6.0E-04	5.1E-04	4.5E-04	4.1E-04	3.7E-04	3.9E-03
90				8.1E-04	6.7E-04	5.8E-04	5.1E-04	4.6E-04	4.2E-04	3.4E-03
120					7.8E-04	6.5E-04	5.7E-04	5.2E-04	4.7E-04	3.0E-03
150						7.4E-04	6.5E-04	5.9E-04	5.3E-04	2.5E-03
180							7.3E-04	6.6E-04	6.0E-04	2.0E-03
210								7.5E-04	6.7E-04	1.4E-03
240									7.6E-04	7.6E-04

Table C2. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 58Co as vitamin B-12 injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestation periods (days) 0	30	60	90	120	150	180	210	240	270
0	1.7E-05	6.1E-06	3.3E-06	2.4E-06	1.7E-06	1.4E-06	9.9E-07	7.0E-07	5.1E-07	3.6E-07
30		1.7E-05	4.6E-06	3.3E-06	2.4E-06	1.9E-06	1.4E-06	9.8E-07	7.1E-07	5.1E-07
60			1.1E-05	4.6E-06	3.3E-06	2.7E-06	1.9E-06	1.4E-06	9.9E-07	7.1E-07
90				1.1E-05	4.6E-06	3.8E-06	2.7E-06	1.9E-06	1.4E-06	9.9E-07
120					1.1E-05	5.3E-06	3.8E-06	2.7E-06	1.9E-06	1.4E-06
150						9.0E-06	5.3E-06	3.8E-06	2.7E-06	1.9E-06
180							9.0E-06	5.3E-06	3.8E-06	2.7E-06
210								9.0E-06	5.3E-06	3.8E-06
240									7.2E-06	5.3E-06
270										7.7E-06

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestation periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	5.4E-03	3.7E-03	2.0E-03	1.5E-03	1.1E-03	8.5E-04	6.0E-04	4.3E-04	3.1E-04	1.6E-02
30		5.4E-03	2.8E-03	2.0E-03	1.5E-03	1.2E-03	8.4E-04	6.0E-04	4.3E-04	1.5E-02
60			4.1E-03	2.8E-03	2.2E-03	1.7E-03	1.2E-03	8.4E-04	6.1E-04	1.3E-02
90				4.1E-03	3.0E-03	2.3E-03	1.7E-03	1.2E-03	8.5E-04	1.3E-02
120					4.3E-03	3.2E-03	2.3E-03	1.7E-03	1.2E-03	1.3E-02
150						4.6E-03	3.2E-03	2.3E-03	1.7E-03	1.2E-02
180							4.6E-03	3.2E-03	2.3E-03	1.0E-02
210								4.6E-03	3.2E-03	7.8E-03
240									4.5E-03	4.5E-03

Table C3. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 60Co as vitamin B-12 injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestation periods (days) 0	30	60	90	120	150	180	210	240	270
0	4.1E-05	2.0E-05	1.5E-05	1.4E-05	1.3E-05	1.4E-05	1.3E-05	1.2E-05	1.2E-05	1.1E-05
30		4.1E-05	1.5E-05	1.5E-05	1.4E-05	1.5E-05	1.4E-05	1.3E-05	1.2E-05	1.2E-05
60			2.6E-05	1.5E-05	1.5E-05	1.5E-05	1.5E-05	1.4E-05	1.3E-05	1.2E-05
90				2.6E-05	1.5E-05	1.6E-05	1.5E-05	1.5E-05	1.4E-05	1.3E-05
120					2.6E-05	1.7E-05	1.6E-05	1.5E-05	1.5E-05	1.4E-05
150						2.2E-05	1.7E-05	1.6E-05	1.5E-05	1.5E-05
180							2.2E-05	1.7E-05	1.6E-05	1.5E-05
210								2.2E-05	1.7E-05	1.6E-05
240									1.7E-05	1.7E-05
270										1.9E-05

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestation periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	1.5E-02	1.4E-02	1.0E-02	9.7E-03	9.8E-03	9.8E-03	9.2E-03	8.7E-03	8.3E-03	9.5E-02
30		1.5E-02	1.1E-02	1.0E-02	1.0E-02	1.0E-02	9.7E-03	9.2E-03	8.7E-03	8.5E-02
60			1.2E-02	1.1E-02	1.1E-02	1.1E-02	1.0E-02	9.7E-03	9.2E-03	7.3E-02
90				1.2E-02	1.1E-02	1.1E-02	1.1E-02	1.0E-02	9.7E-03	6.5E-02
120					1.2E-02	1.2E-02	1.1E-02	1.1E-02	1.0E-02	5.7E-02
150						1.3E-02	1.2E-02	1.1E-02	1.1E-02	4.7E-02
180							1.3E-02	1.2E-02	1.1E-02	3.6E-02
210								1.3E-02	1.2E-02	2.5E-02
240									1.3E-02	1.3E-02

Table C4a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 66Ga into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	1.5E-01	3.3E-24								
30		1.5E-01	3.3E-24							
60			1.5E-01	3.3E-24						
90				1.5E-01	3.3E-24					
120					1.5E-01	3.2E-24				
150						1.5E-01	3.2E-24			
180							1.4E-01	3.1E-24		
210								1.4E-01	3.0E-24	
240									1.4E-01	3.0E-24
270										1.3E-01

Table C4b. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 66Ga into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	1.2E-11	1.2E-33								
30		6.2E-07	6.2E-29							
60			2.0E-05	3.1E-27						
90				1.9E-04	7.7E-26					
120					5.6E-04	1.7E-25				
150						1.1E-03	3.1E-25			
180							2.0E-03	4.8E-25		
210								3.1E-03	7.0E-25	
240									4.3E-03	8.8E-25
270										4.9E-03

Table C4c. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 66Ga injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestation periods (days) 0	30	60	90	120	150	180	210	240	270
0	7.1E-05	2.3E-28								
30		7.1E-05	8.0E-29							
60			2.4E-05	9.7E-29						
90				2.4E-05	5.1E-28					
120					2.4E-05	2.7E-28				
150						2.0E-05	4.2E-28			
180							2.0E-05	6.3E-28		
210								2.0E-05	7.4E-28	
240									1.6E-05	9.2E-28
270										7.0E-06

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestation periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	1.2E-03									1.2E-03
30		1.2E-03								1.2E-03
60			4.0E-04							4.0E-04
90				4.3E-04						4.3E-04
120					5.0E-04					5.0E-04
150						3.7E-04				3.7E-04
180							4.0E-04			4.0E-04
210								4.4E-04		4.4E-04
240									3.9E-04	3.9E-04

Table C5a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 67Ga into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	7.2E-01	6.3E-04	4.8E-07	3.6E-10	2.7E-13	2.0E-16	1.5E-19	1.1E-22	8.6E-26	6.5E-29
30		7.2E-01	6.3E-04	4.8E-07	3.6E-10	2.7E-13	2.0E-16	1.5E-19	1.1E-22	8.6E-26
60			7.2E-01	6.3E-04	4.8E-07	3.6E-10	2.7E-13	2.0E-16	1.5E-19	1.1E-22
90				7.1E-01	6.3E-04	4.7E-07	3.6E-10	2.7E-13	2.0E-16	1.5E-19
120					7.0E-01	6.2E-04	4.7E-07	3.5E-10	2.6E-13	2.0E-16
150						6.9E-01	6.1E-04	4.6E-07	3.5E-10	2.6E-13
180							6.8E-01	6.0E-04	4.5E-07	3.4E-10
210								6.6E-01	5.8E-04	4.4E-07
240									6.5E-01	5.7E-04
270										6.4E-01

Table C5b. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 67Ga into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	5.9E-11	2.2E-13	3.8E-16	6.4E-19	1.1E-21	1.9E-24	3.2E-27	5.4E-30	9.1E-33	1.5E-35
30		2.9E-06	1.2E-08	2.0E-11	3.5E-14	5.9E-17	1.0E-19	1.7E-22	2.9E-25	4.9E-28
60			9.4E-05	5.9E-07	1.0E-09	1.7E-12	2.9E-15	5.0E-18	8.4E-21	1.4E-23
90				9.1E-04	1.5E-05	2.5E-08	4.3E-11	7.3E-14	1.3E-16	2.1E-19
120					2.7E-03	3.3E-05	5.7E-08	9.7E-11	1.6E-13	2.8E-16
150						5.4E-03	5.9E-05	1.0E-07	1.7E-10	2.9E-13
180							9.3E-03	9.3E-05	1.6E-07	2.7E-10
210								1.5E-02	1.3E-04	2.3E-07
240									2.0E-02	1.7E-04
270										2.3E-02

Table C5c. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 67Ga injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestation periods (days) 0	30	60	90	120	150	180	210	240	270
0	4.1E-06	2.6E-09	9.0E-13	6.8E-16	5.1E-19	3.2E-22	2.4E-25	1.8E-28	1.1E-31	8.2E-35
30		4.1E-06	1.2E-09	9.1E-13	6.9E-16	4.3E-19	3.3E-22	2.6E-25	1.6E-28	1.4E-31
60			1.9E-06	1.4E-09	1.2E-12	7.2E-16	6.8E-19	7.5E-22	6.4E-25	9.0E-28
90				1.9E-06	5.1E-09	3.0E-12	4.3E-15	6.8E-18	6.8E-21	1.1E-23
120					1.9E-06	3.9E-09	5.7E-12	9.0E-15	9.0E-18	1.5E-20
150						1.6E-06	6.1E-09	9.5E-12	9.4E-15	1.6E-17
180							1.6E-06	9.1E-09	9.0E-12	1.5E-14
210								1.6E-06	7.8E-09	1.3E-11
240									1.3E-06	9.6E-09
270										2.0E-06

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestation periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	3.8E-04	2.6E-07	9.0E-11	6.8E-14	5.0E-17					3.8E-04
30		4.2E-04	1.2E-07	9.1E-11	6.9E-14	4.2E-17				4.2E-04
60			1.8E-04	1.4E-07	1.2E-10	7.4E-14	7.1E-17			1.8E-04
90				2.7E-04	5.5E-07	3.3E-10	4.8E-13	7.5E-16		2.7E-04
120					4.0E-04	4.3E-07	6.4E-10	1.0E-12	1.0E-15	4.0E-04
150						2.9E-04	6.8E-07	1.1E-09	1.1E-12	2.9E-04
180							3.8E-04	1.0E-06	1.0E-09	3.8E-04
210								4.9E-04	8.8E-07	4.9E-04
240									3.9E-04	3.9E-04

Table C6a. Fraction of activity deposited in the maternal body and fractions retained at start of subsequent 30-day periods after injection of 72Ga into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	2.7E-01	1.6E-16	3.0E-32							
30		2.7E-01	1.6E-16	3.0E-32						
60			2.7E-01	1.6E-16	3.0E-32					
90				2.7E-01	1.6E-16	3.0E-32				
120					2.7E-01	1.6E-16	3.0E-32			
150						2.6E-01	1.5E-16	2.9E-32		
180							2.6E-01	1.5E-16	2.8E-32	
210								2.5E-01	1.5E-16	2.8E-32
240									2.5E-01	1.4E-16
270										2.4E-01

Table C6b. Fraction of activity deposited in the embryo/fetus and fractions retained at start of subsequent 30-day periods after injection of 72Ga into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Stage of Gestation (Initial Day of Period) 0	30	60	90	120	150	180	210	240	270
0	2.2E-11	5.6E-26								
30		1.1E-06	3.0E-21	1.3E-36						
60			3.6E-05	1.5E-19	6.4E-35					
90				3.5E-04	3.7E-18	1.6E-33				
120					1.0E-03	8.4E-18	3.6E-33			
150						2.0E-03	1.5E-17	6.4E-33		
180							3.5E-03	2.3E-17	1.0E-32	
210								5.6E-03	3.4E-17	1.5E-32
240									7.7E-03	4.3E-17
270										8.8E-03

Table C6c. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 72Ga injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestation periods (days) 0	30	60	90	120	150	180	210	240	270
0	5.8E-05	9.2E-21	8.4E-37							
30		5.8E-05	4.4E-21	8.4E-37						
60			2.8E-05	5.0E-21	1.1E-36					
90				2.8E-05	1.8E-20	2.6E-36				
120					2.8E-05	1.3E-20	4.9E-36			
150						2.3E-05	2.1E-20	8.1E-36		
180							2.3E-05	3.1E-20	7.6E-36	
210								2.3E-05	2.6E-20	1.1E-35
240									1.8E-05	3.2E-20
270										1.1E-05

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestation periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	1.2E-03									1.2E-03
30		1.3E-03								1.3E-03
60			6.0E-04							6.0E-04
90				6.5E-04						6.5E-04
120					7.5E-04					7.5E-04
150						5.9E-04				5.9E-04
180							6.6E-04			6.6E-04
210								7.5E-04		7.5E-04
240									6.0E-04	6.0E-04

Table C7a. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 99mTc-pertechnetate injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	2.9E-06									
30		2.9E-06								
60			2.9E-06							
90				1.6E-06						
120					1.6E-06					
150						1.4E-06				
180							1.4E-06			
210								1.4E-06		
240									1.1E-06	
270										1.4E-07

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	3.8E-05									3.8E-05
30		3.8E-05								3.8E-05
60			3.8E-05							3.8E-05
90				2.2E-05						2.2E-05
120					2.3E-05					2.3E-05
150						1.9E-05				1.9E-05
180							2.0E-05			2.0E-05
210								2.1E-05		2.1E-05
240									1.7E-05	1.7E-05

Table C7b. Radiation dose rates and doses to the fetal thyroid from 1 μCi of 99mTc-pertechnetate injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the fetal thyroid at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0										
30										
60										
90				1.6E-06						
120					1.6E-06					
150						1.4E-06				
180							1.4E-06			
210								1.4E-06		
240									1.1E-06	
270										2.1E-06

Days of Gestation at Introduction	Dose (rad) to the fetal thyroid during indicated gestation periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0										
30										
60										
90				5.9E-05						5.9E-05
120					1.0E-04					1.0E-04
150						1.5E-04				1.5E-04
180							1.3E-04			1.3E-04
210								1.1E-04		1.1E-04
240									8.5E-05	8.5E-05

Table C8. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 111In injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestation periods (days) 0	30	60	90	120	150	180	210	240	270
0	8.7E-06	2.9E-09	8.0E-13	3.9E-16	1.9E-19	7.3E-23	3.5E-26	1.7E-29	6.4E-33	3.1E-36
30		8.7E-06	1.7E-09	8.0E-13	3.9E-16	1.5E-19	7.3E-23	3.5E-26	1.3E-29	6.4E-33
60			5.0E-06	1.7E-09	8.5E-13	3.3E-16	1.6E-19	7.7E-23	3.0E-26	1.5E-29
90				5.0E-06	3.7E-09	1.1E-12	6.2E-16	3.5E-19	1.4E-22	8.0E-26
120					5.0E-06	2.9E-09	1.7E-12	9.9E-16	3.9E-19	2.3E-22
150						4.1E-06	4.1E-09	2.5E-12	9.8E-16	5.9E-19
180							4.1E-06	5.7E-09	2.3E-12	1.4E-15
210								4.1E-06	4.9E-09	3.0E-12
240									3.3E-06	5.8E-09
270										3.2E-06

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestation periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	6.9E-04	2.8E-07	7.6E-11	3.7E-14	1.6E-17					6.9E-04
30		7.3E-04	1.6E-07	7.6E-11	3.6E-14	1.3E-17				7.3E-04
60			4.0E-04	1.7E-07	8.0E-11	3.1E-14	1.4E-17			4.0E-04
90				5.0E-04	3.5E-07	1.1E-10	6.0E-14	3.3E-17		5.0E-04
120					6.2E-04	2.9E-07	1.6E-10	9.5E-14	3.7E-17	6.2E-04
150						4.8E-04	4.0E-07	2.4E-10	9.5E-14	4.8E-04
180							5.7E-04	5.5E-07	2.2E-10	5.7E-04
210								6.7E-04	4.8E-07	6.7E-04
240									5.4E-04	5.4E-04
270										

Table C9a. Maximum radiation dose rates and doses to the embryo/fetus from 1 μCi of 123I as sodium iodide injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	7.3E-07									
30		7.3E-07								
60			7.8E-07							
90				4.9E-07						
120					9.9E-07					
150						1.2E-06				
180							1.8E-06			
210								2.5E-06		
240									1.6E-06	
270										1.7E-06

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	1.1E-06									1.1E-06
30		1.1E-06								1.1E-06
60			1.1E-06							1.1E-06
90				7.0E-07						7.0E-07
120					1.4E-06					1.4E-06
150						1.6E-06				1.6E-06
180							2.4E-06			2.4E-06
210								3.4E-06		3.4E-06
240									2.1E-06	2.1E-06

Table C9b. Maximum radiation dose rates and doses to the fetal thyroid from 1 μCi of 123I as sodium iodide injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the fetal thyroid at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0										
30										
60										
90				5.3E-04						
120					1.2E-03					
150						1.8E-03				
180							1.5E-03			
210								1.2E-03		
240									9.6E-04	
270										6.8E-04

Days of Gestation at Introduction	Dose (rad) to the fetal thyroid during indicated gestation periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0										
30										
60										
90				6.9E-04						6.9E-04
120					1.5E-03					1.5E-03
150						2.3E-03				2.3E-03
180							1.9E-03			1.9E-03
210								1.6E-03		1.6E-03
240									1.2E-03	1.2E-03

Table C10a. Radiation dose rates and doses to the embryo/fetus from 1 μCi of 131I as sodium iodide injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the embryo/fetus at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0	1.4E-05	1.6E-08	1.0E-09	2.8E-11	3.6E-12	3.4E-13	4.2E-14	4.1E-15	1.5E-16	1.1E-17
30		1.4E-05	1.6E-08	4.4E-10	5.6E-11	5.4E-12	6.7E-13	6.5E-14	2.3E-15	1.7E-16
60			1.4E-05	6.9E-09	8.9E-10	8.5E-11	1.1E-11	1.0E-12	3.6E-14	2.7E-15
90				4.5E-06	2.5E-08	1.5E-09	1.7E-10	1.6E-11	5.7E-13	4.3E-14
120					4.5E-06	5.7E-08	3.3E-09	2.7E-10	9.2E-12	6.9E-13
150						3.7E-06	1.7E-07	6.6E-09	1.6E-10	1.1E-11
180							3.7E-06	2.8E-07	3.8E-09	2.0E-10
210								3.7E-06	1.5E-07	5.1E-09
240									3.0E-06	1.9E-07
270										7.8E-06

Days of Gestation at Introduction	Dose (rad) to the embryo/fetus during indicated gestational periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0	2.2E-04	4.0E-06	2.2E-07	8.2E-09	1.0E-09	1.1E-10	1.2E-11	9.5E-13	3.8E-14	2.2E-04
30		2.2E-04	3.5E-06	1.3E-07	1.7E-08	1.7E-09	1.9E-10	1.5E-11	6.0E-13	2.2E-04
60			2.1E-04	2.0E-06	2.6E-07	2.7E-08	3.0E-09	2.4E-10	9.4E-12	2.1E-04
90				1.9E-04	6.0E-06	4.4E-07	4.7E-08	3.8E-09	1.5E-10	1.9E-04
120					7.2E-04	1.3E-05	8.7E-07	6.2E-08	2.4E-09	7.3E-04
150						1.3E-03	3.5E-05	1.4E-06	4.1E-08	1.3E-03
180							2.1E-03	5.0E-05	8.8E-07	2.1E-03
210								2.7E-03	3.1E-05	2.8E-03
240									1.5E-03	1.5E-03

Table C10b. Radiation dose rates and doses to the fetal thyroid from 1 μCi of 131I as sodium iodide injected into the maternal transfer compartment (blood)

Days of Gestation at Introduction	Dose rate (rad/hr) to the fetal thyroid at indicated gestational periods (days) 0	30	60	90	120	150	180	210	240	270
0				3.6E-08	8.0E-09	9.3E-10	6.9E-11	4.0E-12	2.2E-13	1.1E-14
30				5.6E-07	1.3E-07	1.5E-08	1.1E-09	6.3E-11	3.4E-12	1.7E-13
60				8.7E-06	2.0E-06	2.3E-07	1.7E-08	1.0E-09	5.4E-11	2.7E-12
90				4.5E-06	7.8E-05	4.1E-06	2.8E-07	1.6E-08	8.5E-10	4.3E-11
120					4.5E-06	1.9E-04	5.6E-06	2.6E-07	1.4E-08	6.8E-10
150						3.7E-06	3.1E-04	6.7E-06	2.5E-07	1.1E-08
180							3.7E-06	2.9E-04	6.1E-06	2.0E-07
210								3.7E-06	2.6E-04	5.3E-06
240									3.0E-06	2.1E-04
270										8.5E-03

Days of Gestation at Introduction	Dose (rad) to the fetal thyroid during indicated gestation periods (days) 0-30	30-60	60-90	90-120	120-150	150-180	180-210	210-240	240-270	Cumulated dose 0-270
0				1.5E-05	2.4E-06	2.5E-07	1.7E-08	9.4E-10	5.0E-11	1.8E-05
30				2.4E-04	3.8E-05	4.0E-06	2.6E-07	1.5E-08	7.8E-10	2.8E-04
60				3.7E-03	6.0E-04	6.3E-05	4.1E-06	2.3E-07	1.2E-08	4.4E-03
90				1.0E+00	1.6E-02	1.1E-03	6.6E-05	3.7E-06	2.0E-07	1.0E+00
120					2.3E+00	3.6E-02	1.2E-03	6.1E-05	3.1E-06	2.4E+00
150						3.8E+00	5.5E-02	1.4E-03	5.4E-05	3.9E+00
180							3.3E+00	5.2E-02	1.2E-03	3.4E+00
210								2.8E+00	4.6E-02	2.8E+00
240									2.2E+00	2.2E+00

Appendix D

Radiation Doses to the Embryo/Fetus from Chronic Maternal Ingestion and Inhalation of Typical Chemical or Physical Forms of Radiologically Important Radionuclides and from Burdens at the Beginning of Pregnancy

Cumulated Doses, Simplified Dose Factors, and Comparisons

Radiation Doses to the Embryo/Fetus from Chronic Maternal Ingestion and Inhalation of Typical Chemical or Physical Forms of Radiologically Important Radionuclides and from Burdens at the Beginning of Pregnancy

Cumulated Doses, Simplified Dose Factors, and Comparisons

Calculations based on gestational-stage-dependent deposition and retention fractions and absorbed dose factors were tabulated in Appendices A and B of this report. These are applicable when radioactivity was introduced as a bolus directly into the maternal transfer compartment. Approaches are required, however, for evaluating multiple radionuclide intakes during gestation or activity that was present at the beginning of pregnancy.

The prior evaluations have been extended to encompass the intake phases or pre-existing burdens in order to prepare the tabulations of this appendix, which relates to descriptions in Section VIII of this report. Other tables are presented to compare results, methodology, and dose factors. The approach involved estimating activity that enters the transfer compartment from repeated or chronic exposures through all or significant fractions of gestation or from burdens incurred by the woman before pregnancy.

The ALI provides a convenient value of total maternal intake and was used for those tables that relate intakes to burdens and to radiation dose to the embryo/fetus. Values corresponding to ALI were derived from Eckerman et al. (1998). Chronic exposures were approximated by a series of intakes corresponding to 1/9 ALI at the beginning of successive 30-day periods of pregnancy. Similar approaches were used as a basis to develop approaches to evaluate doses from pre-existing body burdens derived from intake of an ALI. The underlying procedure involved multiplying intake or burden by appropriate conversion factors to obtain activity in the transfer compartment.

To avoid unduly cumbersome entries, some abbreviated notations have been used to indicate inclusion or exclusion of broad categories of radionuclidic compound. The two categories of compounds that are shown for ^{238}Pu in Tables 1 and 2 will illustrate the general approach. These categories are shown as 1) "Not PuO_2," which is used to signify inclusion of all compounds other than PuO_2, and 2) "PuO_2," which identifies the form or forms specifically excluded. These and other abbreviations or shorthand notations will be identified and elaborated as footnotes.

Table D1. Cumulated radiation doses to the embryo/fetus from chronic maternal ingestion of common chemical or physical forms of radiologically important radionuclides.

Nuclide	Compound	f_1	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
H-3	Water	1E+00	8E+04	5E+00	1E-02	8E+02
H-3	Organic	1E+00	8E+04	8E+00	6E-03	5E+02
C-14	Organic	1E+00	2E+03	7E-01	7E-02	1E+02
P-32	Phosphates	8E-01	6E+02	4E+00	1E-02	8E+00
Cr-51	All	1E-01	4E+04	1E+00	5E-02	2E+03
Fe-55	All	1E-01	9E+03	2E-01	2E-01	2E+03
Fe-59	All	1E-01	8E+02	2E+00	3E-02	2E+01
Co-57	Inorganic	5E-02	8E+03	3E-01	2E-01	1E+03
Co-58	Inorganic	5E-02	2E+03	3E-01	2E-01	3E+02
Co-60	Inorganic	5E-02	5E+02	3E-01	2E-01	8E+01
Zn-65	All	5E-01	4E+02	3E+00	2E-02	7E+00
Rb-86	All	1E+01	5E+02	5E+01	1E-03	5E-01
Sr-89	Soluble	3E-01	6E+02	6E-01	8E-02	5E+01
Sr-89	Insoluble	1E-02	5E+02	2E-02	3E+00	1E+03
Sr/Y-90	Soluble	3E-01	3E+01	8E-02	6E-01	2E+01
Sr/Y-90	Insoluble	1E-02	5E+02	5E-02	1E+00	5E+02
Tc-99m	All	8E-01	8E+04	2E+00	3E-02	2E+03
Ru/Rh106	All	5E-02	2E+02	6E-02	9E-01	2E+02
I-123	All	1E+00	3E+03	5E-03	1E+01	3E+04
I-125	All	1E+00	4E+01	2E-02	3E+00	1E+02
I-131	All	1E+00	3E+01	3E-02	2E+00	5E+01
I-132	All	1E+00	4E+03	2E-02	3E+00	1E+04
I-133	All	1E+00	1E+02	2E-03	3E+01	3E+03
Cs-134	All	1E+00	7E+01	3E+00	2E-02	1E+00
Cs-137	All	1E+00	1E+02	3E+00	2E-02	2E+00
Ce-141	All	3E-04	2E+03	1E-03	4E+01	9E+04
Ce-144	All	3E-04	2E+02	5E-05	1E+03	2E+05
Os-191	All	1E-02	2E+03	9E-03	5E+00	1E+04
Ir-192	All	1E-02	9E+02	9E-02	6E-01	5E+02
Tl-201	All	1E+00	2E+04	4E+00	1E-02	3E+02

Table D1. (cont.). Cumulated radiation doses to the embryo/fetus from chronic maternal ingestion of common chemical or physical forms of radiologically important radionuclides.

Nuclide	Compound	f_1	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Pb-210	All	2E-01	6E-01	5E-05	1E+03	6E+02
Bi-210	All	5E-02	8E+02	2E-02	2E+00	2E+03
Po-210	All	1E-01	3E+00	1E-01	4E-01	1E+00
Ra-224	All	2E-01	8E+00	3E-01	2E-01	1E+00
Ra-226	All	2E-01	2E+00	6E-01	8E-02	2E-01
Th-227	All	2E-04	1E+02	9E-04	6E+01	6E+03
Th-230	All	2E-04	4E+00	5E-05	1E+03	4E+03
Th-232	All	2E-04	7E-01	7E-06	7E+03	5E+03
Th-234	All	2E-04	3E+02	6E-06	8E+03	2E+06
U-234	Hexavalent	5E-02	1E+01	2E-01	2E-01	2E+00
U-234	Insoluble	2E-03	2E+02	2E-01	3E-01	6E+01
U-235	Hexavalent	5E-02	1E+01	2E-01	2E-01	2E+00
U-235	Insoluble	2E-03	2E+02	2E-01	3E-01	6E+01
U-238	Hexavalent	5E-02	1E+01	2E-01	3E-01	3E+00
U-238	Insoluble	2E-03	2E+02	2E-01	3E-01	6E+01
Np-237	All	1E-03	5E-01	2E-04	2E+02	1E+02
Pu-238	Not PuO2[a]	1E-03	9E-01	9E-04	6E+01	5E+01
Pu-238	PuO2	1E-05	9E+01	9E-04	6E+01	5E+03
Pu-239	Not PuO2	1E-03	8E-01	7E-04	7E+01	6E+01
Pu-239	PuO2	1E-05	8E+01	7E-04	7E+01	6E+03
Am-241	All	1E-03	8E-01	2E-04	3E+02	2E+02

(a) "Not PuO_2" is used to signify inclusion of all compounds other than PuO_2; PuO_2 identifies the dioxide form.

Table D2. Cumulated radiation doses to the embryo/fetus from chronic maternal inhalation of common chemical or physical forms of radiologically important radionuclides.[a]

Nuclide	Compound	Class	f_1	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
H-3	Water	- -	1E+00	8E+04	5E+00	1E-02	8E+02
H-3	Organic	- -	1E+00	8E+04	8E+00	6E-03	5E+02
C-14	Organic	- -	1E+00	2E+03	7E-01	7E-02	1E+02
P-32	Not W[b]	D	8E-01	9E+02	4E+00	1E-02	1E+01
P-32	Some PO4	W	8E-01	4E+02	2E+00	3E-02	1E+01
Cr-51	Not W or Y[b]	D	1E-01	5E+04	6E+00	8E-03	4E+02
Cr-51	Halides,...	W	1E-01	2E+04	8E-01	6E-02	1E+03
Cr-51	Oxides,...	Y	1E-01	2E+04	5E-01	1E-01	2E+03
Fe-55	Not W	D	1E-01	2E+03	3E-01	2E-01	4E+02
Fe-55	Oxides,...	W	1E-01	4E+03	2E-01	3E-01	1E+03
Fe-59	Not W	D	1E-01	3E+02	3E+00	2E-02	5E+00
Fe-59	Oxides,...	W	1E-01	5E+02	2E+00	3E-02	1E+01
Co-57	Inorganic	Y	5E-02	7E+02	4E-02	1E+00	8E+02
Co-58	Inorganic	Y	5E-02	7E+02	2E-01	3E-01	2E+02
Co-60	Inorganic	Y	5E-02	3E+01	3E-02	2E+00	5E+01
Zn-65	All	Y	5E-01	3E+02	2E+00	3E-02	1E+01
Rb-86	All	D	1E+01	8E+02	1E+01	3E-03	3E+00
Sr-89	Soluble	D	3E-01	8E+02	1E+00	3E-02	3E+01
Sr-89	Insoluble	Y	1E-02	1E+02	2E-02	3E+00	3E+02
Sr/Y-90	Soluble	D	3E-01	2E+01	1E-01	5E-01	1E+01
Sr/Y-90	Insoluble	Y	1E-02	4E+00	2E-03	2E+01	1E+02
Tc-99m	Not W	D	8E-01	2E+05	3E+00	2E-02	3E+03
Tc-99m	Oxides,...	W	8E-01	2E+05	3E+00	2E-02	4E+03
Ru/Rh106	Not W or Y[b]	D	5E-02	9E+01	3E-01	2E-01	2E+01
Ru/Rh106	Halides,...	W	5E-02	5E+01	4E-02	1E+00	6E+01
Ru/Rh106	Oxides,...	Y	5E-02	1E+01	5E-03	1E+01	1E+02
I-123	All	D	1E+00	6E+03	6E-03	8E+00	5E+04
I-125	All	D	1E+00	6E+01	1E-02	3E+00	2E+02
I-131	All	D	1E+00	5E+01	3E-02	2E+00	8E+01

Table D2 (cont.). Cumulated radiation doses to the embryo/fetus from chronic maternal inhalation of common chemical or physical forms of radiologically important radionuclides.[a]

Nuclide	Compound	Class	f_1	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
I-132	All	D	1E+00	8E+03	2E-02	2E+00	2E+04
I-133	All	D	1E+00	3E+02	3E-03	2E+01	5E+03
Cs-134	All	D	1E+00	1E+02	3E+00	2E-02	2E+00
Cs-137	All	D	1E+00	2E+02	3E+00	1E-02	3E+00
Ce-141	Not Y	W	3E-04	7E+02	2E-01	3E-01	2E+02
Ce-141	Oxides,...	Y	3E-04	6E+02	6E-02	9E-01	5E+02
Ce-144	Not Y	W	3E-04	3E+01	3E-03	2E+01	6E+02
Ce-144	Oxides,...	Y	3E-04	1E+01	4E-04	1E+02	1E+03
Os-191	Not W or Y	D	1E-02	2E+03	5E-01	1E-01	2E+02
Os-191	Halides,...	W	1E-02	2E+03	1E-01	4E-01	9E+02
Os-191	Oxides,...	Y	1E-02	1E+03	3E-02	2E+00	2E+03
Ir-192	Not W or Y	D	1E-02	3E+02	1E+00	4E-02	1E+01
Ir-192	Halides,...	W	1E-02	4E+02	5E-01	1E-01	4E+01
Ir-192	Oxides,...	Y	1E-02	2E+02	1E-01	5E-01	9E+01
Tl-201	All	D	1E+00	2E+04	2E+00	2E-02	4E+02
Pb-210	All	D	2E-01	2E-01	4E-05	1E+03	2E+02
Bi-210	Nitrates	D	5E-02	2E+02	5E-02	1E+00	2E+02
Bi-210	Not D	W	5E-02	3E+01	2E-03	2E+01	7E+02
Po-210	Not W	D	1E-01	6E-01	1E-01	4E-01	2E-01
Po-210	Oxides,...	W	1E-01	6E-01	4E-02	1E+00	7E-01
Ra-224	All	W	2E-01	2E+00	9E-02	6E-01	1E+00
Ra-226	All	W	2E-01	6E-01	2E-01	3E-01	2E-01
Th-227	Not Y	W	2E-04	3E-01	2E-03	3E+01	1E+01
Th-227	Oxides,...	Y	2E-04	3E-01	6E-04	8E+01	2E+01
Th-230	Not Y	W	2E-04	6E-03	5E-05	1E+03	7E+00
Th-230	Oxides,...	Y	2E-04	2E-02	6E-05	8E+02	2E+01
Th-232	Not Y	W	2E-04	1E-03	6E-06	8E+03	8E+00
Th-232	Oxides,...	Y	2E-04	3E-03	8E-06	6E+03	2E+01
Th-234	Not Y	W	2E-04	2E+02	3E-03	2E+01	4E+03
Th-234	Oxides,...	Y	2E-04	2E+02	1E-03	5E+01	1E+04
U-234	UF6,...[c]	D	5E-02	1E+00	2E-01	2E-01	2E-01

Table D2 (cont.). Cumulated radiation doses to the embryo/fetus from chronic maternal inhalation of common chemical or physical forms of radiologically important radionuclides.[a]

Nuclide	Compound	Class	f_1	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
U-234	U03,...	W	5E-02	7E-01	5E-02	1E+00	8E-01
U-234	U02,...	Y	2E-03	4E-02	9E-04	5E+01	2E+00
U-235	UF6,...	D	5E-02	1E+00	2E-01	2E-01	2E-01
U-235	U03,...	W	5E-02	8E-01	5E-02	1E+00	8E-01
U-235	U02,...	Y	2E-03	4E-02	9E-04	6E+01	2E+00
U-238	UF6,...	D	5E-02	1E+00	2E-01	3E-01	3E-01
U-238	U03,...	W	5E-02	8E-01	5E-02	1E+00	9E-01
U-238	U02,...	Y	2E-03	4E-02	8E-04	6E+01	2E+00
Np-237	All	W	1E-03	4E-03	2E-04	2E+02	9E-01
Pu-238	Not PuO2[a]	W	1E-03	7E-03	8E-04	6E+01	4E-01
Pu-238	PuO2	Y	1E-05	2E-02	1E-03	5E+01	1E+00
Pu-239	Not PuO2	W	1E-03	6E-03	6E-04	8E+01	5E-01
Pu-239	PuO2	Y	1E-05	2E-02	9E-04	6E+01	1E+00
Am-241	All	W	1E-03	6E-03	2E-04	3E+02	2E+00

(a) The entries for the common inhalation classes of D, W, and Y are identified.
(b) "Not W", "Not Y", and "Not W or Y" refers to all compounds that are not in class W, class Y, or classes W and Y, respectively.
(c) The primary compounds of uranium follow the common basis for subdivision and are shown as: UF_6... includes UF_6, UO_2F_2, $UO_2(NO_3)_2$; UO_3...includes UO_3, UF_4, UCl_4; and UO_2... includes UO_2 and U_3O_8.
(d) "Not PuO_2" is used to signify inclusion of all compounds other than PuO_2; PuO_2 identifies the dioxide form.

Table D3. Cumulated radiation doses to the embryo/fetus from pre-existing maternal burdens derived from ingestion of representative chemical or physical forms of the radiologically important radionuclides.

Nuclide	Compound	f_1	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
H-3	Water	1E+00	8E+04	5E+00	9E-03	7E+02
H-3	Organic	1E+00	8E+04	6E+00	9E-03	7E+02
C-14	Organic	1E+00	2E+03	4E-02	1E+00	3E+03
P-32	Phosphates	8E-01	6E+02	4E+00	1E-02	8E+00
Cr-51	All	1E-01	4E+04	1E+00	3E-02	1E+03
Fe-55	All	1E-01	9E+03	3E-01	2E-01	2E+03
Fe-59	All	1E-01	8E+02	2E+00	2E-02	2E+01
Co-57	Inorganic	5E-02	8E+03	6E-01	8E-02	7E+02
Co-58	Inorganic	5E-02	2E+03	6E-01	9E-02	2E+02
Co-60	Inorganic	5E-02	5E+02	6E-01	9E-02	4E+01
Zn-65	All	5E-01	4E+02	5E+00	1E-02	4E+00
Rb-86	All	1E+01	5E+02	8E+01	6E-04	3E-01
Sr-89	Soluble	3E-01	6E+02	1E+00	4E-02	2E+01
Sr-89	Insoluble	1E-02	5E+02	3E-02	1E+00	7E+02
Sr/Y-90	Soluble	3E-01	3E+01	2E-01	3E-01	9E+00
Sr/Y-90	Insoluble	1E-02	5E+02	9E-02	6E-01	3E+02
Tc-99m	All	8E-01	8E+04	2E+00	2E-02	2E+03
Ru/Rh106	All	5E-02	2E+02	7E-03	7E+00	1E+03
I-123	All	1E+00	3E+03	3E-03	2E+01	5E+04
I-125	All	1E+00	4E+01	3E-03	2E+01	7E+02
I-131	All	1E+00	3E+01	7E-03	8E+00	2E+02
I-132	All	1E+00	4E+03	2E-02	3E+00	1E+04
I-133	All	1E+00	1E+02	7E-04	7E+01	7E+03
Cs-134	All	1E+00	7E+01	5E+00	1E-02	7E-01
Cs-137	All	1E+00	1E+02	5E+00	1E-02	1E+00
Ce-141	All	3E-04	2E+03	4E-03	1E+01	3E+04
Ce-144	All	3E-04	2E+02	8E-05	6E+02	1E+05
Os-191	All	1E-02	2E+03	3E-02	2E+00	4E+03
Ir-192	All	1E-02	9E+02	2E-01	3E-01	3E+02
Tl-201	All	1E+00	2E+04	7E+00	7E-03	1E+02
Pb-210	All	2E-01	6E-01	4E-05	1E+03	8E+02
Bi-210	All	5E-02	8E+02	2E-03	3E+01	2E+04
Po-210	All	1E-01	3E+00	2E-03	2E+01	7E+01

Table D3. (cont.). Cumulated radiation doses to the embryo/fetus from pre-existing maternal burdens derived from ingestion of representative chemical or physical forms of the radiologically important radionuclides.

Nuclide	Compound	f_1	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Ra-224	All	2E-01	8E+00	3E-01	2E-01	1E+00
Ra-226	All	2E-01	2E+00	5E-01	1E-01	2E-01
Th-227	All	2E-04	1E+02	4E-04	1E+02	1E+04
Th-230	All	2E-04	4E+00	1E-05	4E+03	1E+04
Th-232	All	2E-04	7E-01	2E-06	2E+04	2E+04
Th-234	All	2E-04	3E+02	9E-06	6E+03	2E+06
U-234	Hexavalent	5E-02	1E+01	1E-05	5E+03	5E+04
U-234	Insoluble	2E-03	2E+02	8E-06	6E+03	1E+06
U-235	Hexavalent	5E-02	1E+01	9E-06	5E+03	5E+04
U-235	Insoluble	2E-03	2E+02	8E-06	7E+03	1E+06
U-238	Hexavalent	5E-02	1E+01	9E-06	6E+03	6E+04
U-238	Insoluble	2E-03	2E+02	7E-06	7E+03	1E+06
Np-237	All	1E-03	5E-01	9E-09	6E+06	3E+06
Pu-238	Not PuO2[a]	1E-03	9E-01	3E-08	2E+06	2E+06
Pu-238	PuO2	1E-05	9E+01	3E-08	2E+06	2E+08
Pu-239	Not PuO2	1E-03	8E-01	2E-08	2E+06	2E+06
Pu-239	PuO2	1E-05	8E+01	2E-08	2E+06	2E+08
Am-241	All	1E-03	8E-01	1E-08	4E+06	3E+06

(a) "Not PuO_2" is used to signify inclusion of all compounds other than PuO_2; PuO_2 identifies the dioxide form.

Table D4. Cumulated radiation doses to the embryo/fetus from pre-existing maternal burdens derived from inhalation of typical chemical or physical forms of the radiologically important radionuclides.[a]

Nuclide	Compound	Class	f_1	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
H-3	Water	- -	1E+00	8E+04	5E+00	9E-03	7E+02
H-3	Organic	- -	1E+00	8E+04	6E+00	9E-03	7E+02
C-14	Organic	- -	1E+00	2E+03	4E-02	1E+00	3E+03
P-32	Not W[b]	D	8E-01	9E+02	4E+00	1E-02	1E+01
P-32	Some PO4	W	8E-01	4E+02	2E+00	3E-02	1E+01
Cr-51	Not W or Y[b]	D	1E-01	5E+04	9E+00	6E-03	3E+02
Cr-51	Halides,...	W	1E-01	2E+04	1E+00	4E-02	8E+02
Cr-51	Oxides,...	Y	1E-01	2E+04	8E-01	6E-02	1E+03
Fe-55	Not W	D	1E-01	2E+03	3E-01	2E-01	3E+02
Fe-55	Oxides,...	W	1E-01	4E+03	2E-01	2E-01	9E+02
Fe-59	Not W	D	1E-01	3E+02	4E+00	1E-02	4E+00
Fe-59	Oxides,...	W	1E-01	5E+02	2E+00	2E-02	1E+01
Co-57	Inorganic	Y	5E-02	7E+02	8E-02	6E-01	4E+02
Co-58	Inorganic	Y	5E-02	7E+02	3E-01	2E-01	1E+02
Co-60	Inorganic	Y	5E-02	3E+01	5E-02	9E-01	3E+01
Zn-65	All	Y	5E-01	3E+02	2E+00	2E-02	6E+00
Rb-86	All	D	1E+01	8E+02	3E+01	2E-03	2E+00
Sr-89	Soluble	D	3E-01	8E+02	3E+00	2E-02	1E+01
Sr-89	Insoluble	Y	1E-02	1E+02	4E-02	1E+00	1E+02
Sr/Y-90	Soluble	D	3E-01	2E+01	2E-01	3E-01	5E+00
Sr/Y-90	Insoluble	Y	1E-02	4E+00	4E-03	1E+01	5E+01
Tc-99m	Not W	D	8E-01	2E+05	5E+00	1E-02	2E+03
Tc-99m	Oxides,...	W	8E-01	2E+05	4E+00	1E-02	2E+03
Ru/Rh106	Not W or Y	D	5E-02	9E+01	3E-02	2E+00	1E+02
Ru/Rh106	Halides,...	W	5E-02	5E+01	5E-03	1E+01	5E+02
Ru/Rh106	Oxides,...	Y	5E-02	1E+01	6E-04	9E+01	9E+02

Table D4 (cont.). Cumulated radiation doses to the embryo/fetus from pre-existing maternal burdens derived from inhalation of typical chemical or physical forms of the radiologically important radionuclides.

Nuclide	Compound	Class	f_1	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
I-123	All	D	1E+00	6E+03	4E-03	1E+01	7E+04
I-125	All	D	1E+00	6E+01	3E-03	2E+01	1E+03
I-131	All	D	1E+00	5E+01	7E-03	7E+00	4E+02
I-132	All	D	1E+00	8E+03	2E-02	2E+00	2E+04
I-133	All	D	1E+00	3E+02	1E-03	4E+01	1E+04
Cs-134	All	D	1E+00	1E+02	4E+00	1E-02	1E+00
Cs-137	All	D	1E+00	2E+02	6E+00	9E-03	2E+00
Ce-141	Not Y	W	3E-04	7E+02	6E-01	9E-02	6E+01
Ce-141	Oxides,...	Y	3E-04	6E+02	2E-01	3E-01	2E+02
Ce-144	Not Y	W	3E-04	3E+01	5E-03	1E+01	3E+02
Ce-144	Oxides,...	Y	3E-04	1E+01	7E-04	7E+01	7E+02
Os-191	Not W or Y	D	1E-02	2E+03	1E+00	4E-02	8E+01
Os-191	Halides,...	W	1E-02	2E+03	3E-01	2E-01	3E+02
Os-191	Oxides,...	Y	1E-02	1E+03	7E-02	7E-01	7E+02
Ir-192	Not W or Y	D	1E-02	3E+02	3E+00	2E-02	5E+00
Ir-192	Halides,...	W	1E-02	4E+02	1E+00	5E-02	2E+01
Ir-192	Oxides,...	Y	1E-02	2E+02	2E-01	2E-01	4E+01
Tl-201	All	D	1E+00	2E+04	5E+00	1E-02	2E+02
Pb-210	All	D	2E-01	2E-01	3E-05	2E+03	3E+02
Bi-210	Nitrates	D	5E-02	2E+02	5E-03	1E+01	2E+03
Bi-210	Not D	W	5E-02	3E+01	2E-04	2E+02	7E+03
Po-210	Not W	D	1E-01	6E-01	2E-03	2E+01	1E+01
Po-210	Oxides,...	W	1E-01	6E-01	7E-04	7E+01	4E+01
Ra-224	All	W	2E-01	2E+00	8E-02	6E-01	1E+00

Table D4 (cont.). Cumulated radiation doses to the embryo/fetus from pre-existing maternal burdens derived from inhalation of typical chemical or physical forms of the radiologically important radionuclides.

Nuclide	Compound	Class	f_1	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Ra-226	All	W	2E-01	6E-01	2E-01	3E-01	2E-01
Th-227	Not Y	W	2E-04	3E-01	7E-04	7E+01	2E+01
Th-227	Oxides,...	Y	2E-04	3E-01	3E-04	2E+02	5E+01
Th-230	Not Y	W	2E-04	6E-03	1E-05	4E+03	2E+01
Th-230	Oxides,...	Y	2E-04	2E-02	2E-05	3E+03	6E+01
Th-232	Not Y	W	2E-04	1E-03	2E-06	3E+04	3E+01
Th-232	Oxides,...	Y	2E-04	3E-03	2E-06	2E+04	7E+01
Th-234	Not Y	W	2E-04	2E+02	4E-03	1E+01	3E+03
Th-234	Oxides,...	Y	2E-04	2E+02	2E-03	3E+01	7E+03
U-234	UF6,...[c]	D	5E-02	1E+00	1E-05	5E+03	5E+03
U-234	U03,...	W	5E-02	7E-01	2E-06	2E+04	2E+04
U-234	U02,...	Y	2E-03	4E-02	4E-08	1E+06	5E+04
U-235	UF6,...	D	5E-02	1E+00	9E-06	5E+03	5E+03
U-235	U03,...	W	5E-02	8E-01	2E-06	2E+04	2E+04
U-235	U02,...	Y	2E-03	4E-02	4E-08	1E+06	5E+04
U-238	UF6,...	D	5E-02	1E+00	9E-06	6E+03	6E+03
U-238	U03,...	W	5E-02	8E-01	2E-06	2E+04	2E+04
U-238	U02,...	Y	2E-03	4E-02	4E-08	1E+06	5E+04
Np-237	All	W	1E-03	4E-03	9E-09	6E+06	2E+04
Pu-238	Not Pu02[a]	W	1E-03	7E-03	2E-08	2E+06	1E+04
Pu-238	Pu02	Y	1E-05	2E-02	3E-08	2E+06	4E+04
Pu-239	Not Pu02	W	1E-03	6E-03	2E-08	2E+06	1E+04
Pu-239	Pu02	Y	1E-05	2E-02	3E-08	2E+06	4E+04
Am-241	All	W	1E-03	6E-03	1E-08	4E+06	2E+04

(a) The entries for the common inhalation classes of D, W, and Y are identified.
(b) "Not W", "Not Y", and "Not W or Y" refers to all compounds that are not in class W, class Y, or classes W and Y, respectively.
(c) The primary compounds of uranium follow the common basis for subdivision and are shown as: UF_6... includes UF_6, UO_2F_2, $UO_2(NO_3)_2$; UO_3...includes UO_3, UF_4, UCl_4; and UO_2... includes UO_2 and U_3O_8.
(d) "Not PuO_2" is used to signify inclusion of all compounds other than PuO_2; PuO_2 identifies the dioxide form.

Table D5. Simplified dose factors for calculation of embryo/fetus dose from chronic ingestion of the radiologically important radionuclides throughout gestation or from a maternal burden at the start of pregnancy.

Nuclide	Compound	Dose Factor for Chronic Exposure (rem/μCi)[a]	Dose Factor for Pre-existing Burdens (rem/μCi)[b]
H-3	Water	7E-05	7E-05
H-3	Organic	3E-04	7E-05
C-14	Organic	9E-04	2E-05
P-32	Phosphates	6E-03	7E-03
Cr-51	All	5E-05	4E-05
Fe-55	All	5E-05	3E-05
Fe-59	All	2E-03	3E-03
Co-57	Inorganic	2E-03	8E-05
Co-58	Inorganic	6E-04	3E-04
Co-60	Inorganic	3E-03	1E-03
Zn-65	All	2E-02	1E-02
Rb-86	All	9E-02	2E-01
Sr-89	Soluble	1E-03	2E-03
Sr-89	Insoluble	4E-05	7E-05
Sr/Y-90	Soluble	3E-03	5E-03
Sr/Y-90	Insoluble	9E-05	2E-04
Tc-99m	All	2E-05	3E-05
Ru/Rh106	All	3E-04	3E-05
I-123	All	2E-04	1E-06
I-125	All	4E-04	7E-05
I-131	All	1E-03	2E-04
I-132	All	6E-06	5E-06
I-133	All	2E-05	7E-06
Cs-134	All	4E-02	7E-02
Cs-137	All	3E-02	5E-02
Ce-141	All	6E-07	2E-06

Table D5. (Cont.). Simplified dose factors for calculation of embryo/fetus dose from chronic ingestion of the radiologically important radionuclides throughout gestation or from a maternal burden at the start of pregnancy.

Nuclide	Compound	Dose Factor for Chronic Exposure (rem/μCi)	Dose Factor for Pre-existing Burdens (rem/μCi)
Ce-144	All	2E-07	4E-07
Os-191	All	5E-06	1E-05
Ir-192	All	1E-04	2E-04
Tl-201	All	2E-04	4E-04
Pb-210	All	8E-05	6E-05
Bi-210	All	3E-05	2E-06
Po-210	All	4E-02	7E-04
Ra-224	All	4E-02	4E-02
Ra-226	All	3E-01	2E-01
Th-227	All	9E-06	4E-06
Th-230	All	1E-05	3E-06
Th-232	All	1E-05	3E-06
Th-234	All	2E-08	3E-08
U-234	Hexavalent	2E-02	1E-06
U-234	Insoluble	9E-04	4E-08
U-235	Hexavalent	2E-02	9E-07
U-235	Insoluble	8E-04	4E-08
U-238	Hexavalent	2E-02	9E-07
U-238	Insoluble	8E-04	4E-08
Np-237	All	5E-04	2E-08
Pu-238	Not PuO2[c]	1E-03	3E-08
Pu-238	PuO2	1E-05	3E-10
Pu-239	Not PuO2	9E-04	3E-08
Pu-239	PuO2	9E-06	3E-10
Am-241	All	2E-04	2E-08

(a) The dose factor for chronic exposure is given as the average stage-related cumulated radiation doses to the embryo/fetus from introduction into the transfer compartment at the start of each 30-day interval of pregnancy.
(b) The dose factor simulates complete mobilization of a pre-existing burden and is given as the cumulative dose from radioactivity that would enter the transfer compartment after ingestion immediately prior to pregnancy.
(c) "Not PuO_2" is used to signify inclusion of all compounds other than PuO_2; PuO_2 identifies the dioxide form.

Table D6. Simplified dose factors for calculation of embryo/fetus dose from chronic inhalation of the radiologically important radionuclides throughout gestation or from a maternal burden at the start of pregnancy.

Nuclide	Compound	Class	Dose Factor for Chronic Exposure (rem/uCi)[a]	Dose Factor for Pre-existing Burdens (rem/uCi)[b]
H-3	Water	- -	7E-05	7E-05
H-3	Organic	- -	3E-04	7E-05
C-14	Organic	- -	9E-04	2E-05
P-32	Not W[c]	D	5E-03	5E-03
P-32	Some PO4	W	4E-03	4E-03
Cr-51	Not W or Y[c]	D	2E-04	2E-04
Cr-51	Halides,...	W	8E-05	6E-05
Cr-51	Oxides,...	Y	5E-05	4E-05
Fe-55	Not W	D	2E-04	2E-04
Fe-55	Oxides,...	W	8E-05	5E-05
Fe-59	Not W	D	1E-02	1E-02
Fe-59	Oxides,...	W	4E-03	5E-03
Co-57	Inorganic	Y	3E-03	1E-04
Co-58	Inorganic	Y	1E-03	4E-04
Co-60	Inorganic	Y	5E-03	2E-03
Zn-65	All	Y	1E-02	8E-03
Rb-86	All	D	2E-02	3E-02
Sr-89	Soluble	D	2E-03	4E-03
Sr-89	Insoluble	Y	2E-04	4E-04
Sr/Y-90	Soluble	D	5E-03	9E-03
Sr/Y-90	Insoluble	Y	5E-04	1E-03
Tc-99m	Not W	D	2E-05	2E-05
Tc-99m	Oxides,...	W	1E-05	2E-05
Ru/Rh106	Not W or Y	D	3E-03	3E-04
Ru/Rh106	Halides,...	W	9E-04	1E-04
Ru/Rh106	Oxides,...	Y	5E-04	6E-05

Table D6 (cont.). Simplified dose factors for calculation of embryo/fetus dose from chronic inhalation of the radiologically important radionuclides throughout gestation or from a maternal burden at the start of pregnancy.

Nuclide	Compound	Class	Dose Factor for Chronic Exposure (rem/uCi)	Dose Factor for Pre-existing Burdens (rem/uCi)
I-123	All	D	1E-04	7E-07
I-125	All	D	2E-04	5E-05
I-131	All	D	6E-04	1E-04
I-132	All	D	4E-06	3E-06
I-133	All	D	1E-05	4E-06
Cs-134	All	D	3E-02	4E-02
Cs-137	All	D	2E-02	3E-02
Ce-141	Not Y	W	2E-04	8E-04
Ce-141	Oxides,...	Y	1E-04	3E-04
Ce-144	Not Y	W	9E-05	2E-04
Ce-144	Oxides,...	Y	4E-05	7E-05
Os-191	Not W or Y	D	2E-04	6E-04
Os-191	Halides,...	W	6E-05	2E-04
Os-191	Oxides,...	Y	3E-05	7E-05
Ir-192	Not W or Y	D	5E-03	1E-02
Ir-192	Halides,...	W	1E-03	3E-03
Ir-192	Oxides,...	Y	6E-04	1E-03
Tl-201	All	D	1E-04	2E-04
Pb-210	All	D	2E-04	2E-04
Bi-210	Nitrates	D	3E-04	2E-05
Bi-210	Not D	W	7E-05	7E-06
Po-210	Not W	D	2E-01	3E-03
Po-210	Oxides,...	W	7E-02	1E-03
Ra-224	All	W	4E-02	4E-02
Ra-226	All	W	3E-01	3E-01
Th-227	Not Y	W	5E-03	2E-03
Th-227	Oxides,...	Y	2E-03	1E-03
Th-230	Not Y	W	8E-03	2E-03
Th-230	Oxides,...	Y	3E-03	9E-04
Th-232	Not Y	W	6E-03	2E-03
Th-232	Oxides,...	Y	3E-03	7E-04
Th-234	Not Y	W	1E-05	2E-05
Th-234	Oxides,...	Y	5E-06	8E-06

Table D6 (cont.). Simplified dose factors for calculation of embryo/fetus dose from chronic inhalation of the radiologically important radionuclides throughout gestation or from a maternal burden at the start

of pregnancy.

Nuclide	Compound	Class	Dose Factor for Chronic Exposure (rem/uCi)	Dose Factor for Pre-existing Burdens (rem/uCi)
U-234	UF6,...	D	2E-01	1E-05
U-234	U03,...	W	7E-02	3E-06
U-234	U02,...	Y	2E-02	1E-06
U-235	UF6,...	D	2E-01	9E-06
U-235	U03,...	W	6E-02	3E-06
U-235	U02,...	Y	2E-02	1E-06
U-238	UF6,...[a]	D	2E-01	9E-06
U-238	U03,...	W	6E-02	3E-06
U-238	U02,...	Y	2E-02	9E-07
Np-237	All	W	5E-02	2E-06
Pu-238	Not Pu02[e]	W	1E-01	3E-06
Pu-238	Pu02	Y	5E-02	1E-06
Pu-239	Not Pu02	W	1E-01	3E-06
Pu-239	Pu02	Y	4E-02	1E-06
Am-241	All	W	3E-02	2E-06

(a) The dose factor for chronic exposure is given as the average stage-related cumulated radiation doses to the embryo/fetus from introduction into the transfer compartment at the start of each 30-day interval of pregnancy.
(b) The dose factor simulates complete mobilization of a pre-existing burden and is given as the cumulative dose from radioactivity that would enter the transfer compartment from inhalation immediately prior to pregnancy.
(c) "Not W", "Not Y", and "Not W or Y" refers to all compounds that are not in class W, class Y, or classes W and Y, respectively.
(d) The primary compounds of uranium follow the common basis for subdivision and are shown as: UF_6... includes UF_6, UO_2F_2, $UO_2(NO_3)_2$; UO_3...includes UO_3, UF_4, UCl_4; and UO_2... includes UO_2 and U_3O_8.
(e) "Not PuO_2" is used to signify inclusion of all compounds other than PuO_2; PuO_2 identifies the dioxide form.

Table D7. Comparisons of the committed uterine dose equivalent surrogate and the maximized dose equivalent to the embryo/fetus with calculated dose equivalents from chronic ingestion of representative radionuclides throughout pregnancy.

Nuclide	ALI (μCi)	Embryo/ Fetus Dose per ALI (rem)	Uterine Dose per ALI (rem)	Ratio of Doses[a]	Maximized Embryo/ Fetus Dose per ALI (rem)[b]	Ratio of Doses[c]
H-3[a]	8E+04	5E+00	5E+00	1.0	5E+00	1.0
H-3[e]	8E+04	8E+00	5E+00	1.6	1E+01	0.8
C-14	2E+03	7E-01	4E+00	0.2	1E+00	0.7
P-32	6E+02	4E+00	1E+00	4.0	4E+00	1.0
Cr-51	4E+04	1E+00	3E+00	0.3	1E+00	1.0
Fe-55	9E+03	2E-01	3E+00	0.1	5E-01	0.4
Fe-59	8E+02	2E+00	4E+00	0.5	2E+00	1.0
Co-57	8E+03	3E-01	4E+00	0.1	6E-01	0.5
Co-58	2E+03	3E-01	3E+00	0.1	6E-01	0.5
Co-60	5E+02	3E-01	5E+00	0.1	6E-01	0.5
Zn-65	4E+02	3E+00	7E+00	0.4	5E+00	0.6
Rb-86	5E+02	5E+01	4E+00	12.5	9E+01	0.6
Sr-89	6E+02	6E-01	5E-01	1.2	1E+00	0.6
Sr/Y-90	3E+01	8E-02	2E-01	0.4	2E-01	0.4
Tc-99m	8E+04	2E+00	2E+00	1.0	2E+00	1.0
Ru/Rh106	2E+02	6E-02	1E+00	0.1	2E-01	0.3
I-123	3E+03	5E-03	7E-02	0.1	1E-02	0.5
I-125	4E+01	2E-02	4E-03	5.0	4E-02	0.5
I-131	3E+01	3E-02	5E-03	6.0	8E-02	0.4
I-132	4E+03	2E-02	4E-01	0.1	3E-02	0.7
I-133	1E+02	2E-03	1E-02	0.2	4E-03	0.5

Table D7. (cont.). Comparisons of the committed uterine dose equivalent surrogate and the maximized dose equivalent to the embryo/fetus with calculated dose equivalents from chronic ingestion of representative radionuclides throughout pregnancy.

Nuclide	ALI (μCi)	Embryo/ Fetus Dose per ALI (rem)	Uterine Dose per ALI (rem)	Ratio of Doses	Maximized Embryo/ Fetus Dose per ALI (rem)	Ratio of Doses
Cs-134	7E+01	3E+00	6E+00	0.5	5E+00	0.6
Cs-137	1E+02	3E+00	5E+00	0.6	5E+00	0.6
Ce-141	2E+03	1E-03	3E-01	0.0	4E-03	0.3
Ce-144	2E+02	5E-05	2E-02	0.0	8E-05	0.6
Os-191	2E+03	9E-03	4E-01	0.0	3E-02	0.3
Ir-192	9E+02	9E-02	1E+00	0.1	2E-01	0.5
Tl-201	2E+04	4E+00	5E+00	0.8	7E+00	0.6
Pb-210	6E-01	5E-05	9E-01	0.0	8E-05	0.6
Bi-210	8E+02	2E-02	6E-02	0.3	3E-02	0.7
Po-210	3E+00	1E-01	9E-01	0.1	4E-01	0.3
Ra-224	8E+00	3E-01	6E-01	0.5	4E-01	0.8
Ra-226	2E+00	6E-01	7E-01	0.9	8E-01	0.8
Th-227	1E+02	9E-04	7E-02	0.0	4E-03	0.2
Th-230	4E+00	5E-05	1E-02	0.0	2E-04	0.3
Th-232	7E-01	7E-06	3E-03	0.0	3E-05	0.2
Th-234	3E+02	6E-06	1E-02	0.0	1E-05	0.6
U-234	1E+01	2E-01	1E-01	2.0	5E-01	0.4
U-235	1E+01	2E-01	9E-02	2.2	5E-01	0.4
U-238	1E+01	2E-01	9E-02	2.2	4E-01	0.5
Np-237	5E-01	2E-04	2E-04	1.0	5E-04	0.4
Pu-238	9E-01	9E-04	3E-05	30.0	2E-03	0.5
Pu-239	8E-01	7E-04	2E-05	35.0	1E-03	0.7
Am-241	8E-01	2E-04	9E-05	2.2	3E-04	0.7

(a) Ratio is defined as embryo/fetus dose divided by uterine dose
(b) Embryo/fetus dose per ALI calculated using maximum dose factor during gestation, as was done in Regulatory Guide 8.36 (NRC 1992).
(c) Ratio is define as embryo/fetus dose calculated in this study divided by the maximum embryo/fetus dose.
(d) Tritiated water
(e) Organic forms typified by as sugar or amino acid.

Table D8. Comparisons of the committed uterine dose equivalent surrogate and the maximized dose equivalent to the embryo/fetus with calculated dose equivalents from chronic inhalation of representative radionuclides throughout pregnancy.

Nuclide	Class	ALI (uCi)	Embryo/ Fetus Dose per ALI (rem)	Uterine Dose per ALI (rem)	Ratio of Doses[a]	Maximized Embryo/ Fetus Dose per ALI (rem)[b]	Ratio of Doses[c]
H-3[a]	- -	8E+04	5E+00	5E+00	1.0	5E+00	1.0
C-14	- -	2E+03	7E-01	4E+00	0.2	1E+00	0.7
P-32	D	9E+02	4E+00	5E-01	8.0	4E+00	1.0
P-32	W	4E+02	2E+00	5E-01	4.0	2E+00	1.0
Cr-51	D	5E+04	6E+00	5E+00	1.2	9E+00	0.7
Cr-51	W	2E+04	8E-01	9E-01	0.9	1E+00	0.8
Cr-51	Y	2E+04	5E-01	7E-01	0.7	8E-01	0.6
Fe-55	D	2E+03	3E-01	4E+00	0.1	5E-01	0.6
Fe-55	W	4E+03	2E-01	3E+00	0.1	4E-01	0.5
Fe-59	D	3E+02	3E+00	4E+00	0.8	4E+00	0.8
Fe-59	W	5E+02	2E+00	2E+00	1.0	2E+00	1.0
Co-57	Y	7E+02	4E-02	2E-01	0.2	8E-02	0.5
Co-58	Y	7E+02	2E-01	8E-01	0.3	3E-01	0.7
Co-60	Y	3E+01	3E-02	5E-01	0.1	5E-02	0.6
Zn-65	Y	3E+02	2E+00	3E+00	0.7	2E+00	1.0
Rb-86	D	8E+02	1E+01	4E+00	2.5	3E+01	0.3
Sr-89	D	8E+02	1E+00	1E+00	1.0	3E+00	0.3
Sr-89	Y	1E+02	2E-02	3E-03	6.7	4E-02	0.5
Sr/Y-90	D	2E+01	1E-01	2E-01	0.5	2E-01	0.5
Sr/Y-90	Y	4E+00	2E-03	4E-03	0.5	4E-03	0.5
Tc-99m	D	2E+05	3E+00	2E+00	1.5	5E+00	0.6
Tc-99m	W	2E+05	3E+00	1E+00	3.0	4E+00	0.8
Ru/Rh-106	D	9E+01	3E-01	5E+00	0.1	8E-01	0.4
Ru/Rh-106	W	5E+01	4E-02	7E-01	0.1	1E-01	0.4
Ru/Rh-106	Y	1E+01	5E-03	4E-02	0.1	2E-02	0.3
I-123	D	6E+03	6E-03	7E-02	0.1	1E-02	0.6
I-125	D	6E+01	1E-02	4E-03	2.5	4E-02	0.3
I-131	D	5E+01	3E-02	5E-03	6.0	9E-02	0.3
I-132	D	8E+03	2E-02	3E-01	0.1	3E-02	0.7
I-133	D	3E+02	3E-03	2E-02	0.2	7E-03	0.4
Cs-134	D	1E+02	3E+00	5E+00	0.6	4E+00	0.8

Table D8 (cont.). Comparisons of the committed uterine dose equivalent surrogate and the maximized dose equivalent to the embryo/fetus with calculated dose equivalents from chronic inhalation of representative radionuclides throughout pregnancy.

Nuclide	Class	ALI (uCi)	Embryo/ Fetus Dose per ALI (rem)	Uterine Dose per ALI (rem)	Ratio of Doses	Maximized Embryo/ Fetus Dose per ALI (rem)	Ratio of Doses
Cs-137	D	2E+02	3E+00	7E+00	0.4	6E+00	0.5
Ce-141	W	7E+02	2E-01	1E-01	2.0	6E-01	0.3
Ce-141	Y	6E+02	6E-02	6E-02	1.0	2E-01	0.3
Ce-144	W	3E+01	3E-03	2E-01	0.0	5E-03	0.6
Ce-144	Y	1E+01	4E-04	8E-03	0.1	7E-04	0.6
Os-191	D	2E+03	5E-01	1E+00	0.5	1E+00	0.5
Os-191	W	2E+03	1E-01	4E-01	0.3	4E-01	0.3
Os-191	Y	1E+03	3E-02	1E-01	0.3	8E-02	0.4
Ir-192	D	3E+02	1E+00	2E+00	0.5	3E+00	0.3
Ir-192	W	4E+02	5E-01	1E+00	0.5	1E+00	0.5
Ir-192	Y	2E+02	1E-01	2E-01	0.5	2E-01	0.5
Tl-201	D	2E+04	2E+00	3E+00	0.7	5E+00	0.4
Pb-210	D	2E-01	4E-05	2E-01	0.0	6E-05	0.7
Bi-210	D	2E+02	5E-02	1E-01	0.5	6E-02	0.8
Bi-210	W	3E+01	2E-03	7E-03	0.3	3E-03	0.7
Po-210	D	6E-01	1E-01	9E-01	0.1	4E-01	0.3
Po-210	W	6E-01	4E-02	3E-01	0.1	1E-01	0.4
Ra-224	W	2E+00	9E-02	1E-01	0.9	1E-01	0.9
Ra-226	W	6E-01	2E-01	2E-01	1.0	3E-01	0.7
Th-227	W	3E-01	2E-03	6E-02	0.0	6E-03	0.3
Th-227	Y	3E-01	6E-04	3E-03	0.2	3E-03	0.2
Th-230	W	6E-03	5E-05	9E-03	0.0	2E-04	0.3
Th-230	Y	2E-02	6E-05	1E-02	0.0	3E-04	0.2
Th-232	W	1E-03	6E-06	3E-03	0.0	3E-05	0.2
Th-232	Y	3E-03	8E-06	7E-03	0.0	3E-05	0.3
Th-234	W	2E+02	3E-03	8E-02	0.0	5E-03	0.6
Th-234	Y	2E+02	1E-03	9E-03	0.1	2E-03	0.5
U-234	D	1E+00	2E-01	9E-02	2.2	5E-01	0.4

Table D8 (cont.). Comparisons of the committed uterine dose equivalent surrogate and the maximized dose equivalent to the embryo/fetus with calculated dose equivalents from chronic inhalation of representative radionuclides throughout pregnancy.

Nuclide	Class	ALI (uCi)	Embryo/ Fetus Dose per ALI (rem)	Uterine Dose per ALI (rem)	Ratio of Doses	Maximized Embryo/ Fetus Dose per ALI (rem)	Ratio of Doses
U-234	W	7E-01	5E-02	2E-02	2.5	1E-01	0.5
U-234	Y	4E-02	9E-04	4E-03	0.2	2E-03	0.5
U-235	D	1E+00	2E-01	9E-02	2.2	4E-01	0.5
U-235	W	8E-01	5E-02	2E-02	2.5	1E-01	0.5
U-235	Y	4E-02	9E-04	4E-03	0.2	2E-03	0.5
U-238	D	1E+00	2E-01	8E-02	2.5	4E-01	0.5
U-238	W	8E-01	5E-02	2E-02	2.5	1E-01	0.5
U-238	Y	4E-02	8E-04	4E-03	0.2	2E-03	0.4
Np-237	W	4E-03	2E-04	1E-04	2.0	5E-04	0.4
Pu-238	W	7E-03	8E-04	2E-05	40.0	2E-03	0.4
Pu-238	Y	2E-02	1E-03	3E-05	33.3	2E-03	0.5
Pu-239	W	6E-03	6E-04	2E-05	30.0	1E-03	0.6
Pu-239	Y	2E-02	9E-04	3E-05	30.0	2E-03	0.5
Am-241	W	6E-03	2E-04	3E-05	6.7	3E-04	0.7

(a) Ratio is defined as embryo/fetus dose divided by uterine dose
(b) Embryo/fetus dose per ALI calculated using maximum dose factor during gestation, as was done in Regulatory Guide 8.36 (NRC 1992).
(c) Ratio is define as embryo/fetus dose calculated in this study divided by the maximum embryo/fetus dose.
(d) Tritiated water

Appendix E

Radiation Doses to the Uterus: Ingestion and Inhalation

Radiation Doses to the Uterus: Ingestion and Inhalation

Section VIII with which this appendix is paired, discussed the use of uterine surrogate dose factors for situations in which values from evaluations of the radionuclides were not available. The indicated calculations provided dose factors using the uterine committed dose equivalent factors as a surrogate for situations in which values from specific evaluations of the radionuclides were not available. To convert these into surrogates for the embryo/fetus based on unit activity in blood, the uterine dose factors were divided by the corresponding fractional absorption value.

Table E1 gives the cumulated radiation doses to the uterus from chronic ingestion of representative radionuclides throughout pregnancy, together with their relationship to intakes of ALI. Table E2 is similar but gives cumulated radiation doses to the uterus from chronic inhalation of representative radionuclides throughout pregnancy.

Doses were calculated for inhalation classes using values of ALI derived from Eckerman et al. (1988). The entries for inhalation in Table E1 were segregated for the common inhalation classes of D, W and Y and are shown as V (vapor) for tritium and for carbon are subdivided into c (compound), m (carbon monoxide), and d (carbon dioxide).

The underlying values for these surrogates, from a similar tabulation, were used as the input for the calculations relating activity or ALI intake to dose in this table. Because the dose factors are based on previously calculated uterine doses per activity ingested, it was not necessary to make any adjustment for the transfer fraction.

Table E1. Radiation doses to the uterus from ingestion.

Nuclide	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
H-3	8E+04	5E+00	1E-02	8E+02
Be-7	4E+04	3E+00	2E-02	6E+02
Be-10	1E+03	9E-02	6E-01	6E+02
C-11	4E+05	5E+00	1E-02	4E+03
C-14	2E+03	4E+00	1E-02	2E+01
F-18	5E+04	7E-01	8E-02	4E+03
Na-22	4E+02	4E+00	1E-02	5E+00
Na-24	4E+03	5E+00	1E-02	4E+01
Mg-28	7E+02	1E+00	4E-02	3E+01
Al-26	4E+02	2E+00	2E-02	9E+00
Si-31	9E+03	3E-03	1E+01	1E+05
Si-32	2E+03	9E-01	6E-02	1E+02
P-32	6E+02	1E+00	3E-02	2E+01
P-33	6E+03	2E+00	2E-02	1E+02
S-35	1E+04	3E+00	2E-02	2E+02
Cl-36	2E+03	6E+00	8E-03	2E+01
Cl-38	2E+04	6E-01	8E-02	2E+03
Cl-39	2E+04	8E-01	6E-02	1E+03
K-40	3E+02	6E+00	9E-03	3E+00
K-42	5E+03	4E+00	1E-02	6E+01
K-43	6E+03	4E+00	1E-02	7E+01
K-44	2E+04	4E-01	1E-01	3E+03
K-45	3E+04	4E-01	1E-01	4E+03
Ca-41	3E+03	3E-02	2E+00	5E+03
Ca-45	2E+03	4E-01	1E-01	3E+02
Ca-47	8E+02	1E+00	4E-02	3E+01
Sc-43	7E+03	2E+00	3E-02	2E+02
Sc-44	4E+03	2E+00	3E-02	1E+02
Sc-44M	5E+02	1E+00	4E-02	2E+01
Sc-46	9E+02	3E+00	2E-02	2E+01
Sc-47	2E+03	4E-01	1E-01	3E+02
Sc-48	8E+02	3E+00	2E-02	1E+01
Sc-49	2E+04	8E-04	6E+01	1E+06
Ti-44	3E+02	4E+00	1E-02	4E+00
Ti-45	9E+03	1E+00	4E-02	3E+02
V-47	3E+04	7E-01	7E-02	2E+03
V-48	6E+02	3E+00	2E-02	1E+01
V-49	7E+04	6E-02	9E-01	6E+04
Cr-48	6E+03	3E+00	1E-02	9E+01
Cr-49	3E+04	1E+00	5E-02	1E+03
Cr-51	4E+04	3E+00	2E-02	7E+02
Mn-51	2E+04	7E-01	7E-02	1E+03
Mn-52	7E+02	3E+00	2E-02	1E+01

Table E1.(cont.). Radiation doses to the uterus from ingestion.

Nuclide	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Mn-52M	3E+04	8E-01	6E-02	2E+03
Mn-53	5E+04	3E-01	2E-01	9E+03
Mn-54	2E+03	4E+00	1E-02	3E+01
Mn-56	5E+03	1E+00	5E-02	2E+02
Fe-52	9E+02	1E+00	4E-02	4E+01
Fe-55	9E+03	3E+00	1E-02	1E+02
Fe-59	8E+02	4E+00	1E-02	1E+01
Fe-60	3E+01	4E+00	1E-02	3E-01
Co-55	1E+03	1E+00	4E-02	4E+01
Co-56	5E+02	5E+00	1E-02	5E+00
Co-57	8E+03	7E+00	7E-03	5E+01
Co-58	2E+03	6E+00	9E-03	2E+01
Co-58M	6E+04	9E-01	5E-02	3E+03
Co-60	5E+02	1E+01	4E-03	2E+00
Co-60M	1E+06	1E-01	4E-01	4E+05
Co-61	2E+04	3E-01	2E-01	4E+03
Co-62M	4E+04	6E-01	8E-02	3E+03
Ni-56	1E+03	3E+00	2E-02	2E+01
Ni-57	2E+03	4E+00	1E-02	3E+01
Ni-59	2E+04	3E+00	2E-02	4E+02
Ni-63	9E+03	3E+00	2E-02	2E+02
Ni-65	8E+03	6E-01	9E-02	7E+02
Ni-66	4E+02	6E-02	9E-01	4E+02
Cu-60	3E+04	1E+00	4E-02	1E+03
Cu-61	1E+04	1E+00	4E-02	4E+02
Cu-64	1E+04	1E+00	5E-02	5E+02
Cu-67	5E+03	2E+00	3E-02	2E+02
Zn-62	1E+03	7E-01	7E-02	7E+01
Zn-63	2E+04	6E-01	8E-02	2E+03
Zn-65	4E+02	7E+00	7E-03	3E+00
Zn-69	6E+04	9E-02	5E-01	3E+04
Zn-69M	4E+03	1E+00	5E-02	2E+02
Zn-71M	6E+03	2E+00	3E-02	2E+02
Zn-72	1E+03	3E+00	2E-02	2E+01
Ga-65	5E+04	5E-01	1E-01	5E+03
Ga-66	1E+03	1E+00	5E-02	5E+01
Ga-67	7E+03	2E+00	3E-02	2E+02
Ga-68	2E+04	1E+00	4E-02	9E+02
Ga-70	5E+04	4E-03	1E+01	6E+05
Ga-72	1E+03	2E+00	3E-02	3E+01
Ga-73	5E+03	5E-01	1E-01	5E+02
Ge-66	2E+04	3E+00	2E-02	4E+02
Ge-67	3E+04	3E-01	2E-01	5E+03

Table E1.(cont.). Radiation doses to the uterus from ingestion.

Nuclide	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Ge-68	5E+03	4E+00	1E-02	6E+01
Ge-69	1E+04	3E+00	2E-02	2E+02
Ge-71	5E+05	3E+00	1E-02	7E+03
Ge-75	4E+04	6E-01	8E-02	3E+03
Ge-77	9E+03	3E+00	2E-02	1E+02
Ge-78	2E+04	2E+00	2E-02	5E+02
As-69	3E+04	4E-01	1E-01	4E+03
As-70	1E+04	1E+00	3E-02	3E+02
As-71	4E+03	2E+00	2E-02	8E+01
As-72	9E+02	1E+00	4E-02	4E+01
As-73	8E+03	1E+00	4E-02	3E+02
As-74	1E+03	1E+00	3E-02	3E+01
As-76	1E+03	6E-01	9E-02	9E+01
As-77	4E+03	4E-01	1E-01	5E+02
As-78	8E+03	7E-01	7E-02	5E+02
Se-70	2E+04	3E+00	2E-02	4E+02
Se-73	3E+03	9E-01	6E-02	2E+02
Se-73M	6E+04	2E+00	3E-02	2E+03
Se-75	5E+02	4E+00	1E-02	7E+00
Se-79	6E+02	2E+00	2E-02	1E+01
Se-81	6E+04	5E-02	1E+00	6E+04
Se-81M	4E+04	5E-01	1E-01	4E+03
Se-83	4E+04	1E+00	4E-02	2E+03
Br-74	2E+04	7E-01	8E-02	2E+03
Br-74M	1E+04	6E-01	8E-02	8E+02
Br-75	3E+04	2E+00	3E-02	8E+02
Br-76	4E+03	5E+00	1E-02	4E+01
Br-77	2E+04	7E+00	8E-03	2E+02
Br-80	5E+04	2E-01	3E-01	2E+04
Br-80M	2E+04	3E+00	2E-02	3E+02
Br-82	3E+03	6E+00	9E-03	3E+01
Br-83	5E+04	1E+00	4E-02	2E+03
Br-84	2E+04	5E-01	1E-01	2E+03
Rb-79	4E+04	5E-01	1E-01	4E+03
Rb-81	4E+04	3E+00	2E-02	6E+02
Rb-81M	2E+05	2E+00	2E-02	5E+03
Rb-82M	1E+04	3E+00	1E-02	1E+02
Rb-83	6E+02	4E+00	1E-02	7E+00
Rb-84	5E+02	5E+00	1E-02	5E+00
Rb-86	5E+02	4E+00	1E-02	6E+00
Rb-87	1E+03	4E+00	1E-02	1E+01
Rb-88	2E+04	2E-01	2E-01	5E+03
Rb-89	4E+04	5E-01	1E-01	4E+03

Table E1.(cont.). Radiation doses to the uterus from ingestion.

Nuclide	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Sr-80	4E+03	5E-01	1E-01	4E+02
Sr-81	3E+04	1E+00	5E-02	1E+03
Sr-82	3E+02	1E+00	4E-02	1E+01
Sr-83	3E+03	2E+00	2E-02	7E+01
Sr-85	3E+03	4E+00	1E-02	4E+01
Sr-85M	2E+05	3E+00	2E-02	3E+03
Sr-87M	5E+04	2E+00	2E-02	1E+03
Sr-89	6E+02	5E-01	9E-02	6E+01
Sr-90	3E+01	2E-01	3E-01	9E+00
Sr-91	2E+03	9E-01	6E-02	1E+02
Sr-92	3E+03	7E-01	7E-02	2E+02
Y-86	1E+03	2E+00	2E-02	2E+01
Y-86M	2E+04	3E+00	2E-02	4E+02
Y-87	2E+03	2E+00	2E-02	5E+01
Y-88	1E+03	4E+00	1E-02	1E+01
Y-90	4E+02	2E-05	3E+03	1E+06
Y-90M	8E+03	1E+00	5E-02	4E+02
Y-91	5E+02	3E-03	2E+01	8E+03
Y-91M	1E+05	2E+00	2E-02	2E+03
Y-92	3E+03	1E-01	3E-01	1E+03
Y-93	1E+03	4E-02	1E+00	1E+03
Y-94	2E+04	2E-01	2E-01	5E+03
Y-95	4E+04	1E-01	4E-01	1E+04
Zr-86	1E+03	2E+00	3E-02	3E+01
Zr-88	4E+03	3E+00	2E-02	6E+01
Zr-89	2E+03	3E+00	2E-02	3E+01
Zr-93	1E+03	2E-04	3E+02	3E+05
Zr-95	1E+03	1E+00	4E-02	4E+01
Zr-97	6E+02	6E-01	8E-02	5E+01
Nb-88	5E+04	6E-01	9E-02	4E+03
Nb-89	5E+03	9E-01	5E-02	3E+02
Nb-89M	1E+04	1E+00	4E-02	4E+02
Nb-90	1E+03	2E+00	2E-02	2E+01
Nb-93M	9E+03	8E-02	6E-01	5E+03
Nb-94	9E+02	3E+00	2E-02	2E+01
Nb-95	2E+03	2E+00	2E-02	4E+01
Nb-95M	2E+03	3E-01	2E-01	4E+02
Nb-96	1E+03	2E+00	2E-02	2E+01
Nb-97	2E+04	8E-01	6E-02	1E+03
Nb-98	1E+04	1E+00	5E-02	5E+02
Mo-90	4E+03	2E+00	2E-02	8E+01
Mo-93	4E+03	1E+00	4E-02	1E+02
Mo-93M	9E+03	3E+00	1E-02	1E+02

Table E1.(cont.). Radiation doses to the uterus from ingestion.

Nuclide	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Mo-99	2E+03	2E+00	3E-02	7E+01
Mo-101	4E+04	5E-01	1E-01	4E+03
Tc-93	3E+04	3E+00	2E-02	5E+02
Tc-93M	7E+04	3E+00	2E-02	1E+03
Tc-94	9E+03	3E+00	2E-02	1E+02
Tc-94M	2E+04	1E+00	4E-02	9E+02
Tc-95	1E+04	3E+00	2E-02	2E+02
Tc-95M	4E+03	4E+00	1E-02	5E+01
Tc-96	2E+03	4E+00	1E-02	2E+01
Tc-96M	2E+05	4E+00	1E-02	3E+03
Tc-97	4E+04	1E+00	3E-02	1E+03
Tc-97M	5E+03	1E+00	5E-02	3E+02
Tc-98	1E+03	2E+00	2E-02	2E+01
Tc-99	4E+03	9E-01	6E-02	2E+02
Tc-99M	8E+04	2E+00	2E-02	2E+03
Tc-101	9E+04	2E-01	2E-01	2E+04
Tc-104	2E+04	3E-01	2E-01	3E+03
Ru-94	2E+04	2E+00	2E-02	4E+02
Ru-97	8E+03	3E+00	2E-02	1E+02
Ru-103	2E+03	2E+00	3E-02	5E+01
Ru-105	5E+03	1E+00	5E-02	2E+02
Ru-106	2E+02	1E+00	4E-02	9E+00
Rh-99	2E+03	2E+00	2E-02	5E+01
Rh-99M	2E+04	4E+00	1E-02	3E+02
Rh-100	2E+03	4E+00	1E-02	3E+01
Rh-101	2E+03	3E+00	2E-02	3E+01
Rh-101M	6E+03	3E+00	2E-02	1E+02
Rh-102	6E+02	6E+00	9E-03	5E+00
Rh-102M	1E+03	2E+00	3E-02	3E+01
Rh-103M	4E+05	2E-02	2E+00	8E+05
Rh-105	4E+03	4E-01	1E-01	5E+02
Rh-106M	8E+03	3E+00	2E-02	1E+02
Rh-107	7E+04	3E-01	2E-01	1E+04
Pd-100	1E+03	2E+00	3E-02	3E+01
Pd-101	1E+04	2E+00	3E-02	3E+02
Pd-103	6E+03	4E-02	1E+00	7E+03
Pd-107	3E+04	1E-03	5E+01	1E+06
Pd-109	2E+03	1E-02	4E+00	8E+03
Ag-102	5E+04	9E-01	5E-02	3E+03
Ag-103	4E+04	2E+00	3E-02	1E+03
Ag-104	2E+04	3E+00	2E-02	3E+02
Ag-104M	3E+04	2E+00	3E-02	9E+02

Table E1.(cont.). Radiation doses to the uterus from ingestion.

Nuclide	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Ag-105	3E+03	3E+00	2E-02	5E+01
Ag-106	6E+04	6E-01	8E-02	5E+03
Ag-106M	8E+02	3E+00	2E-02	1E+01
Ag-108M	6E+02	2E+00	3E-02	2E+01
Ag-110M	5E+02	3E+00	2E-02	1E+01
Ag-111	9E+02	6E-02	8E-01	7E+02
Ag-112	3E+03	3E-01	2E-01	5E+02
Ag-115	3E+04	3E-01	2E-01	5E+03
Cd-104	2E+04	3E+00	2E-02	3E+02
Cd-107	2E+04	2E-01	3E-01	5E+03
Cd-109	3E+02	3E-01	2E-01	5E+01
Cd-113	2E+01	3E-01	2E-01	4E+00
Cd-113M	2E+01	3E-01	2E-01	4E+00
Cd-115	9E+02	4E-01	1E-01	1E+02
Cd-115M	3E+02	2E-01	3E-01	8E+01
Cd-117	5E+03	1E+00	5E-02	2E+02
Cd-117M	5E+03	2E+00	2E-02	1E+02
In-109	2E+04	3E+00	2E-02	3E+02
In-110	5E+03	4E+00	1E-02	6E+01
In-110	2E+04	2E+00	3E-02	6E+02
In-111	4E+03	2E+00	2E-02	8E+01
In-112	2E+05	4E-01	1E-01	3E+04
In-113M	5E+04	1E+00	4E-02	2E+03
In-114M	3E+02	2E-01	3E-01	8E+01
In-115	4E+01	7E-01	7E-02	3E+00
In-115M	1E+04	4E-01	1E-01	1E+03
In-116M	2E+04	2E+00	3E-02	5E+02
In-117	6E+04	1E+00	3E-02	2E+03
In-117M	1E+04	5E-01	1E-01	1E+03
In-119M	4E+04	1E-02	4E+00	2E+05
Sn-110	4E+03	2E+00	3E-02	1E+02
Sn-111	7E+04	1E+00	4E-02	3E+03
Sn-113	2E+03	1E+00	5E-02	1E+02
Sn-117M	2E+03	6E-01	8E-02	2E+02
Sn-119M	3E+03	1E-01	4E-01	1E+03
Sn-121	6E+03	4E-03	1E+01	7E+04
Sn-121M	3E+03	3E-01	1E-01	4E+02
Sn-123	5E+02	6E-02	8E-01	4E+02
Sn-123M	5E+04	2E-01	2E-01	1E+04
Sn-125	4E+02	2E-01	3E-01	1E+02
Sn-126	3E+02	1E+00	4E-02	1E+01
Sn-127	7E+03	2E+00	3E-02	2E+02

Table E1.(cont.). Radiation doses to the uterus from ingestion.

Nuclide	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Sn-128	9E+03	1E+00	4E-02	4E+02
Sb-115	8E+04	2E+00	3E-02	2E+03
Sb-116	7E+04	1E+00	4E-02	3E+03
Sb-116M	2E+04	3E+00	2E-02	3E+02
Sb-117	7E+04	2E+00	2E-02	1E+03
Sb-118M	5E+03	3E+00	2E-02	8E+01
Sb-119	2E+04	4E-01	1E-01	2E+03
Sb-120	1E+05	4E-01	1E-01	1E+04
Sb-120	9E+02	3E+00	2E-02	1E+01
Sb-122	7E+02	4E-01	1E-01	9E+01
Sb-124	5E+02	1E+00	3E-02	2E+01
Sb-124M	2E+05	1E+00	5E-02	1E+04
Sb-125	2E+03	2E+00	3E-02	6E+01
Sb-126	5E+02	2E+00	2E-02	1E+01
Sb-126M	5E+04	8E-01	6E-02	3E+03
Sb-127	8E+02	8E-01	6E-02	5E+01
Sb-128	8E+04	1E+00	5E-02	4E+03
Sb-128	1E+03	9E-01	6E-02	6E+01
Sb-129	3E+03	1E+00	5E-02	1E+02
Sb-130	2E+04	2E+00	3E-02	5E+02
Sb-131	1E+04	3E-01	1E-01	1E+03
Te-116	8E+03	2E+00	2E-02	2E+02
Te-121	3E+03	3E+00	2E-02	5E+01
Te-121M	5E+02	8E-01	6E-02	3E+01
Te-123	5E+02	3E-03	2E+01	8E+03
Te-123M	6E+02	4E-01	1E-01	8E+01
Te-125M	1E+03	2E-01	3E-01	3E+02
Te-127	7E+03	9E-02	6E-01	4E+03
Te-127M	6E+02	2E-01	2E-01	1E+02
Te-129	3E+04	1E-01	4E-01	1E+04
Te-129M	5E+02	3E-01	1E-01	7E+01
Te-131	3E+03	1E-01	4E-01	1E+03
Te-131M	3E+02	4E-01	1E-01	4E+01
Te-132	2E+02	3E-01	1E-01	3E+01
Te-133	1E+04	7E-02	8E-01	8E+03
Te-133M	3E+03	3E-01	2E-01	5E+02
Te-134	2E+04	2E+00	3E-02	6E+02
I-120	4E+03	4E-01	1E-01	5E+02
I-120M	1E+04	9E-01	6E-02	6E+02
I-121	1E+04	2E-01	3E-01	3E+03
I-123	3E+03	7E-02	7E-01	2E+03
I-124	5E+01	1E-02	5E+00	2E+02

Table E1.(cont.). Radiation doses to the uterus from ingestion.

Nuclide	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
I-125	4E+01	4E-03	1E+01	5E+02
I-126	2E+01	4E-03	1E+01	2E+02
I-128	4E+04	2E-01	2E-01	1E+04
I-129	5E+00	3E-03	2E+01	1E+02
I-130	4E+02	9E-02	5E-01	2E+02
I-131	3E+01	5E-03	1E+01	3E+02
I-132	4E+03	4E-01	1E-01	5E+02
I-132M	4E+03	2E-01	2E-01	8E+02
I-133	1E+02	1E-02	4E+00	4E+02
I-134	2E+04	9E-01	5E-02	1E+03
I-135	8E+02	1E-01	4E-01	4E+02
Cs-125	5E+04	7E-01	8E-02	4E+03
Cs-127	6E+04	4E+00	1E-02	8E+02
Cs-129	2E+04	4E+00	1E-02	2E+02
Cs-130	6E+04	4E-01	1E-01	7E+03
Cs-131	2E+04	5E+00	1E-02	2E+02
Cs-132	3E+03	6E+00	8E-03	2E+01
Cs-134	7E+01	6E+00	9E-03	6E-01
Cs-134M	1E+05	3E+00	2E-02	2E+03
Cs-135	7E+02	5E+00	1E-02	7E+00
Cs-135M	1E+05	2E+00	2E-02	2E+03
Cs-136	4E+02	6E+00	9E-03	4E+00
Cs-137	1E+02	5E+00	9E-03	9E-01
Cs-138	2E+04	6E-01	8E-02	2E+03
Ba-126	6E+03	7E-01	7E-02	4E+02
Ba-128	5E+02	6E-01	9E-02	4E+01
Ba-131	3E+03	2E+00	2E-02	7E+01
Ba-131M	4E+05	5E-01	9E-02	4E+04
Ba-133	2E+03	3E+00	2E-02	4E+01
Ba-133M	2E+03	2E-01	3E-01	6E+02
Ba-135M	3E+03	2E-01	2E-01	7E+02
Ba-139	1E+04	5E-02	1E+00	1E+04
Ba-140	5E+02	8E-01	7E-02	3E+01
Ba-141	2E+04	2E-01	3E-01	5E+03
Ba-142	5E+04	1E+00	4E-02	2E+03
La-131	5E+04	2E+00	3E-02	1E+03
La-132	3E+03	2E+00	3E-02	1E+02
La-135	4E+04	1E+00	4E-02	1E+03
La-137	1E+04	8E-01	7E-02	7E+02
La-138	9E+02	3E+00	2E-02	2E+01
La-140	6E+02	1E+00	4E-02	2E+01
La-141	4E+03	4E-02	1E+00	5E+03

Table E1.(cont.). Radiation doses to the uterus from ingestion.

Nuclide	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
La-142	8E+03	2E+00	3E-02	3E+02
La-143	4E+04	1E-01	4E-01	2E+04
Ce-134	5E+02	5E-01	1E-01	5E+01
Ce-135	2E+03	3E+00	2E-02	4E+01
Ce-137	5E+04	1E+00	5E-02	2E+03
Ce-137M	2E+03	2E-01	3E-01	5E+02
Ce-139	5E+03	2E+00	3E-02	1E+02
Ce-141	2E+03	3E-01	1E-01	3E+02
Ce-143	1E+03	3E-01	2E-01	2E+02
Ce-144	2E+02	2E-02	2E+00	4E+02
Pr-136	5E+04	6E-01	8E-02	4E+03
Pr-137	4E+04	2E+00	3E-02	1E+03
Pr-138M	1E+04	3E+00	2E-02	2E+02
Pr-139	4E+04	1E+00	4E-02	1E+03
Pr-142	1E+03	4E-02	1E+00	1E+03
Pr-142M	8E+04	4E-02	1E+00	1E+05
Pr-143	9E+02	1E-08	4E+06	4E+09
Pr-144	3E+04	8E-03	7E+00	2E+05
Pr-145	3E+03	1E-02	4E+00	1E+04
Pr-147	5E+04	3E-01	2E-01	9E+03
Nd-136	1E+04	1E+00	5E-02	5E+02
Nd-138	2E+03	5E-01	1E-01	2E+02
Nd-139	9E+04	1E+00	5E-02	4E+03
Nd-139M	5E+03	3E+00	2E-02	1E+02
Nd-141	2E+05	3E+00	2E-02	4E+03
Nd-147	1E+03	3E-01	2E-01	2E+02
Nd-149	1E+04	4E-01	1E-01	1E+03
Nd-151	7E+04	5E-01	9E-02	7E+03
Pm-141	5E+04	5E-01	9E-02	5E+03
Pm-143	5E+03	3E+00	2E-02	9E+01
Pm-144	1E+03	3E+00	2E-02	2E+01
Pm-145	1E+04	8E-01	6E-02	6E+02
Pm-146	2E+03	3E+00	2E-02	4E+01
Pm-147	4E+03	4E-05	1E+03	5E+06
Pm-148	4E+02	3E-01	2E-01	6E+01
Pm-148M	7E+02	2E+00	2E-02	2E+01
Pm-149	1E+03	1E-02	4E+00	4E+03
Pm-150	5E+03	1E+00	5E-02	2E+02
Pm-151	2E+03	7E-01	7E-02	1E+02
Sm-141	5E+04	6E-01	8E-02	4E+03
Sm-141M	3E+04	1E+00	4E-02	1E+03
Sm-142	8E+03	5E-01	1E-01	8E+02

Table E1.(cont.). Radiation doses to the uterus from ingestion.

Nuclide	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Sm-145	6E+03	1E+00	5E-02	3E+02
Sm-151	1E+04	4E-05	1E+03	1E+07
Sm-153	2E+03	2E-01	2E-01	5E+02
Sm-155	6E+04	1E-01	5E-01	3E+04
Sm-156	5E+03	5E-01	9E-02	5E+02
Eu-145	2E+03	4E+00	1E-02	3E+01
Eu-146	1E+03	3E+00	1E-02	1E+01
Eu-147	3E+03	3E+00	2E-02	6E+01
Eu-148	1E+03	4E+00	1E-02	1E+01
Eu-149	1E+04	1E+00	4E-02	4E+02
Eu-150	3E+03	9E-02	6E-01	2E+03
Eu-150	8E+02	2E+00	2E-02	2E+01
Eu-152	8E+02	2E+00	3E-02	2E+01
Eu-152M	3E+03	4E-01	1E-01	4E+02
Eu-154	5E+02	1E+00	4E-02	2E+01
Eu-155	4E+03	6E-01	8E-02	3E+02
Eu-156	6E+02	1E+00	4E-02	3E+01
Eu-157	2E+03	4E-01	1E-01	2E+02
Eu-158	2E+04	7E-01	7E-02	1E+03
Gd-145	5E+04	2E+00	3E-02	2E+03
Gd-146	1E+03	1E+00	4E-02	4E+01
Gd-147	2E+03	3E+00	2E-02	3E+01
Gd-149	3E+03	2E+00	2E-02	7E+01
Gd-151	6E+03	9E-01	6E-02	3E+02
Gd-153	5E+03	1E+00	4E-02	2E+02
Gd-159	3E+03	1E-01	4E-01	1E+03
Tb-147	9E+03	2E+00	3E-02	2E+02
Tb-149	5E+03	2E+00	3E-02	1E+02
Tb-150	5E+03	2E+00	3E-02	2E+02
Tb-151	4E+03	3E+00	2E-02	7E+01
Tb-153	5E+03	2E+00	3E-02	1E+02
Tb-154	2E+03	3E+00	1E-02	3E+01
Tb-155	6E+03	2E+00	3E-02	2E+02
Tb-156	1E+03	3E+00	2E-02	2E+01
Tb-156M	7E+03	2E+00	3E-02	2E+02
Tb-156M	2E+04	2E+00	3E-02	6E+02
Tb-157	5E+04	4E-01	1E-01	7E+03
Tb-158	1E+03	1E+00	3E-02	3E+01
Tb-160	8E+02	1E+00	3E-02	3E+01
Tb-161	2E+03	2E-01	3E-01	6E+02
Dy-155	9E+03	3E+00	2E-02	2E+02
Dy-157	2E+04	3E+00	1E-02	3E+02
Dy-159	1E+04	1E+00	4E-02	4E+02

Table E1.(cont.). Radiation doses to the uterus from ingestion.

Nuclide	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Dy-165	1E+04	4E-02	1E+00	1E+04
Dy-166	6E+02	6E-02	8E-01	5E+02
Ho-155	4E+04	2E+00	3E-02	1E+03
Ho-157	3E+05	2E+00	2E-02	6E+03
Ho-159	2E+05	2E+00	2E-02	5E+03
Ho-161	1E+05	1E+00	4E-02	4E+03
Ho-162	5E+05	7E-01	7E-02	4E+04
Ho-162M	5E+04	2E+00	2E-02	1E+03
Ho-164	2E+05	2E-01	3E-01	5E+04
Ho-164M	1E+05	4E-01	1E-01	1E+04
Ho-166	9E+02	3E-02	2E+00	2E+03
Ho-166M	6E+02	2E+00	3E-02	2E+01
Ho-167	2E+04	1E+00	4E-02	7E+02
Er-161	2E+04	4E+00	1E-02	3E+02
Er-165	6E+04	2E+00	2E-02	1E+03
Er-169	3E+03	1E-04	4E+02	1E+06
Er-171	4E+03	7E-01	7E-02	3E+02
Er-172	1E+03	8E-01	6E-02	6E+01
Tm-162	7E+04	1E+00	3E-02	2E+03
Tm-166	4E+03	3E+00	2E-02	7E+01
Tm-167	2E+03	6E-01	8E-02	2E+02
Tm-170	8E+02	1E-02	4E+00	3E+03
Tm-171	1E+04	2E-02	2E+00	2E+04
Tm-172	7E+02	4E-01	1E-01	9E+01
Tm-173	4E+03	7E-01	7E-02	3E+02
Tm-175	7E+04	6E-01	9E-02	6E+03
Yb-162	7E+04	2E+00	3E-02	2E+03
Yb-166	1E+03	2E+00	3E-02	3E+01
Yb-167	3E+05	1E+00	5E-02	1E+04
Yb-169	2E+03	1E+00	3E-02	7E+01
Yb-175	3E+03	2E-01	3E-01	8E+02
Yb-177	2E+04	4E-01	1E-01	2E+03
Yb-178	1E+04	1E-01	4E-01	4E+03
Lu-169	3E+03	3E+00	2E-02	5E+01
Lu-170	1E+03	3E+00	2E-02	2E+01
Lu-171	2E+03	2E+00	2E-02	4E+01
Lu-172	1E+03	3E+00	2E-02	2E+01
Lu-173	5E+03	2E+00	3E-02	2E+02
Lu-174	5E+03	1E+00	4E-02	2E+02
Lu-174M	2E+03	3E-01	2E-01	3E+02
Lu-176	7E+02	7E-01	7E-02	5E+01
Lu-176M	8E+03	4E-02	1E+00	1E+04
Lu-177	2E+03	1E-01	4E-01	7E+02

Table E1.(cont.). Radiation doses to the uterus from ingestion.

Nuclide	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Lu-177M	7E+02	1E+00	4E-02	2E+01
Lu-178	4E+04	1E-01	5E-01	2E+04
Lu-178M	5E+04	8E-01	6E-02	3E+03
Lu-179	6E+03	5E-02	9E-01	5E+03
Hf-170	3E+03	3E+00	2E-02	5E+01
Hf-172	1E+03	9E-01	5E-02	5E+01
Hf-173	5E+03	2E+00	2E-02	1E+02
Hf-175	3E+03	2E+00	2E-02	7E+01
Hf-177M	2E+04	2E+00	2E-02	5E+02
Hf-178M	3E+02	2E+00	3E-02	8E+00
Hf-179M	1E+03	2E+00	3E-02	3E+01
Hf-180M	7E+03	2E+00	2E-02	1E+02
Hf-181	1E+03	1E+00	5E-02	5E+01
Hf-182	2E+02	5E-01	1E-01	2E+01
Hf-182M	4E+04	2E+00	2E-02	1E+03
Hf-183	2E+04	9E-01	5E-02	1E+03
Hf-184	2E+03	8E-01	6E-02	1E+02
Ta-172	4E+04	2E+00	3E-02	1E+03
Ta-173	7E+03	1E+00	4E-02	3E+02
Ta-174	3E+04	1E+00	4E-02	1E+03
Ta-175	6E+03	3E+00	2E-02	1E+02
Ta-176	4E+03	3E+00	2E-02	6E+01
Ta-177	1E+04	1E+00	4E-02	4E+02
Ta-178	2E+04	3E+00	2E-02	3E+02
Ta-179	2E+04	2E+00	3E-02	5E+02
Ta-180	1E+03	1E+00	4E-02	4E+01
Ta-180M	2E+04	7E-01	7E-02	1E+03
Ta-182	8E+02	2E+00	3E-02	2E+01
Ta-182M	2E+05	5E-01	9E-02	2E+04
Ta-183	9E+02	5E-01	1E-01	9E+01
Ta-184	2E+03	1E+00	3E-02	7E+01
Ta-185	3E+04	3E-01	2E-01	5E+03
Ta-186	5E+04	4E-01	1E-01	7E+03
W-176	1E+04	2E+00	3E-02	3E+02
W-177	2E+04	2E+00	2E-02	5E+02
W-178	5E+03	1E+00	5E-02	3E+02
W-179	5E+05	1E+00	4E-02	2E+04
W-181	2E+04	2E+00	3E-02	6E+02
W-185	2E+03	2E-04	2E+02	5E+05
W-187	2E+03	6E-01	8E-02	2E+02
W-188	4E+02	2E-02	2E+00	1E+03
Re-177	9E+04	1E+00	5E-02	4E+03

Table E1.(cont.). Radiation doses to the uterus from ingestion.

Nuclide	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Re-178	7E+04	5E-01	1E-01	7E+03
Re-181	5E+03	2E+00	3E-02	1E+02
Re-182	7E+03	3E+00	2E-02	1E+02
Re-182	1E+03	2E+00	3E-02	3E+01
Re-184	2E+03	3E+00	2E-02	4E+01
Re-184M	2E+03	2E+00	2E-02	5E+01
Re-186	2E+03	7E-01	7E-02	1E+02
Re-186M	1E+03	8E-01	7E-02	7E+01
Re-187	6E+05	9E-01	6E-02	3E+04
Re-188	2E+03	6E-01	8E-02	2E+02
Re-188M	8E+04	5E-01	1E-01	8E+03
Re-189	3E+03	6E-01	8E-02	3E+02
Os-180	1E+05	2E+00	3E-02	3E+03
Os-181	1E+04	2E+00	3E-02	3E+02
Os-182	2E+03	2E+00	2E-02	5E+01
Os-185	2E+03	3E+00	2E-02	4E+01
Os-189M	8E+04	4E-03	1E+01	1E+06
Os-191	2E+03	4E-01	1E-01	3E+02
Os-191M	1E+04	1E-01	4E-01	4E+03
Os-193	2E+03	2E-01	3E-01	6E+02
Os-194	4E+02	3E-01	1E-01	6E+01
Ir-182	4E+04	9E-01	6E-02	2E+03
Ir-184	8E+03	3E+00	2E-02	2E+02
Ir-185	5E+03	2E+00	3E-02	1E+02
Ir-186	2E+03	2E+00	2E-02	4E+01
Ir-187	1E+04	2E+00	2E-02	2E+02
Ir-188	2E+03	3E+00	2E-02	3E+01
Ir-189	5E+03	1E+00	5E-02	3E+02
Ir-190	1E+03	3E+00	2E-02	2E+01
Ir-190M	2E+05	2E+00	2E-02	5E+03
Ir-192	9E+02	1E+00	3E-02	3E+01
Ir-192M	3E+03	3E+00	2E-02	6E+01
Ir-194	1E+03	8E-02	7E-01	7E+02
Ir-194M	6E+02	3E+00	2E-02	1E+01
Ir-195	1E+04	1E-01	4E-01	4E+03
Ir-195M	8E+03	8E-01	6E-02	5E+02
Pt-186	1E+04	2E+00	2E-02	2E+02
Pt-188	2E+03	2E+00	2E-02	4E+01
Pt-189	1E+04	2E+00	2E-02	2E+02
Pt-191	4E+03	2E+00	3E-02	1E+02
Pt-193	4E+04	4E-02	1E+00	5E+04
Pt-193M	3E+03	8E-02	6E-01	2E+03
Pt-195M	2E+03	3E-01	2E-01	3E+02

Table E1.(cont.). Radiation doses to the uterus from ingestion.

Nuclide	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Pt-197	3E+03	8E-02	6E-01	2E+03
Pt-197M	2E+04	2E-01	2E-01	4E+03
Pt-199	5E+04	3E-01	2E-01	9E+03
Pt-200	1E+03	2E-01	2E-01	2E+02
Au-193	9E+03	1E+00	3E-02	3E+02
Au-194	3E+03	3E+00	2E-02	5E+01
Au-195	5E+03	1E+00	4E-02	2E+02
Au-198	1E+03	6E-01	9E-02	9E+01
Au-198M	1E+03	1E+00	5E-02	5E+01
Au-199	3E+03	5E-01	1E-01	3E+02
Au-200	3E+04	3E-01	2E-01	5E+03
Au-200M	1E+03	2E+00	3E-02	3E+01
Au-201	7E+04	8E-02	6E-01	4E+04
Hg-193	2E+04	1E+00	5E-02	1E+03
Hg-193M	4E+03	1E+00	4E-02	2E+02
Hg-194	2E+01	4E+00	1E-02	3E-01
Hg-195	2E+04	1E+00	3E-02	7E+02
Hg-195M	3E+03	2E+00	3E-02	9E+01
Hg-197	7E+03	2E+00	3E-02	2E+02
Hg-197M	4E+03	1E+00	4E-02	2E+02
Hg-199M	6E+04	5E-01	1E-01	7E+03
Hg-203	5E+02	3E+00	2E-02	9E+00
Tl-194	3E+05	2E+00	3E-02	8E+03
Tl-194M	5E+04	1E+00	5E-02	2E+03
Tl-195	6E+04	2E+00	2E-02	1E+03
Tl-197	7E+04	3E+00	2E-02	1E+03
Tl-198	2E+04	4E+00	1E-02	3E+02
Tl-198M	3E+04	3E+00	2E-02	6E+02
Tl-199	6E+04	3E+00	2E-02	9E+02
Tl-200	8E+03	5E+00	1E-02	8E+01
Tl-201	2E+04	5E+00	1E-02	2E+02
Tl-202	4E+03	6E+00	9E-03	4E+01
Tl-204	2E+03	5E+00	1E-02	2E+01
Pb-195M	6E+04	2E+00	3E-02	2E+03
Pb-198	3E+04	2E+00	2E-02	6E+02
Pb-199	2E+04	3E+00	2E-02	4E+02
Pb-200	3E+03	2E+00	2E-02	7E+01
Pb-201	7E+03	2E+00	2E-02	1E+02
Pb-202	1E+02	1E+00	4E-02	4E+00
Pb-202M	9E+03	3E+00	1E-02	1E+02
Pb-203	5E+03	2E+00	2E-02	1E+02
Pb-205	4E+03	3E-01	2E-01	7E+02
Pb-209	2E+04	4E-02	1E+00	3E+04

Table E1.(cont.). Radiation doses to the uterus from ingestion.

Nuclide	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Pb-210	6E-01	3E-01	2E-01	1E-01
Pb-211	1E+04	7E-01	7E-02	7E+02
Pb-212	8E+01	5E-01	9E-02	8E+00
Pb-214	9E+03	1E+00	5E-02	4E+02
Bi-200	3E+04	2E+00	2E-02	6E+02
Bi-201	1E+04	2E+00	2E-02	2E+02
Bi-202	1E+04	2E+00	2E-02	2E+02
Bi-203	2E+03	3E+00	2E-02	4E+01
Bi-205	1E+03	2E+00	2E-02	2E+01
Bi-206	6E+02	3E+00	2E-02	1E+01
Bi-207	1E+03	2E+00	2E-02	2E+01
Bi-210	8E+02	6E-02	9E-01	7E+02
Bi-210M	4E+01	2E-01	3E-01	1E+01
Bi-212	5E+03	4E-01	1E-01	6E+02
Bi-213	7E+03	2E-01	3E-01	2E+03
Bi-214	2E+04	4E-01	1E-01	3E+03
Po-203	3E+04	3E+00	2E-02	5E+02
Po-205	2E+04	3E+00	2E-02	3E+02
Po-207	8E+03	3E+00	2E-02	1E+02
Po-210	3E+00	9E-01	5E-02	2E-01
At-207	6E+03	5E+00	1E-02	6E+01
At-211	1E+02	4E+00	1E-02	1E+00
Fr-222	2E+03	4E+00	1E-02	2E+01
Fr-223	6E+02	5E+00	1E-02	6E+00
Ra-223	5E+00	8E-01	6E-02	3E-01
Ra-224	8E+00	6E-01	8E-02	6E-01
Ra-225	8E+00	1E+00	5E-02	4E-01
Ra-226	2E+00	7E-01	7E-02	1E-01
Ra-227	2E+04	2E-01	2E-01	4E+03
Ra-228	2E+00	1E+00	4E-02	9E-02
Ac-224	2E+03	2E-01	3E-01	5E+02
Ac-225	5E+01	2E-02	3E+00	1E+02
Ac-226	1E+02	2E-02	3E+00	3E+02
Ac-227	2E-01	5E-05	1E+03	2E+02
Ac-228	2E+03	6E-01	8E-02	2E+02
Th-226	5E+03	3E-03	2E+01	8E+04
Th-227	1E+02	7E-02	7E-01	7E+01
Th-228	6E+00	5E-02	9E-01	6E+00
Th-229	6E-01	1E-02	5E+00	3E+00
Th-230	4E+00	1E-02	5E+00	2E+01
Th-231	4E+03	7E-02	7E-01	3E+03
Th-232	7E-01	3E-03	2E+01	1E+01
Th-234	3E+02	1E-02	4E+00	1E+03

Table E1.(cont.). Radiation doses to the uterus from ingestion.

Nuclide	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Pa-227	4E+03	1E-02	5E+00	2E+04
Pa-228	1E+03	1E+00	5E-02	5E+01
Pa-230	6E+02	6E-01	8E-02	5E+01
Pa-231	2E-01	4E-05	1E+03	2E+02
Pa-232	1E+03	9E-01	6E-02	6E+01
Pa-233	1E+03	4E-01	1E-01	1E+02
Pa-234	2E+03	1E+00	4E-02	7E+01
U-230	4E+00	1E-01	4E-01	2E+00
U-231	5E+03	7E-01	8E-02	4E+02
U-232	2E+00	6E-02	8E-01	2E+00
U-233	1E+01	1E-01	5E-01	5E+00
U-234	1E+01	1E-01	5E-01	5E+00
U-235	1E+01	9E-02	5E-01	5E+00
U-236	1E+01	9E-02	6E-01	6E+00
U-237	2E+03	5E-01	9E-02	2E+02
U-238	1E+01	9E-02	6E-01	6E+00
U-239	7E+04	2E-01	3E-01	2E+04
U-240	1E+03	2E-01	2E-01	2E+02
Np-232	1E+05	9E-01	6E-02	6E+03
Np-233	8E+05	2E+00	2E-02	2E+04
Np-234	2E+03	3E+00	2E-02	3E+01
Np-235	2E+04	6E-02	8E-01	2E+04
Np-236	3E+00	1E-03	4E+01	1E+02
Np-236	3E+03	2E-01	3E-01	1E+03
Np-237	5E-01	2E-04	3E+02	1E+02
Np-238	1E+03	6E-01	8E-02	8E+01
Np-239	2E+03	5E-01	1E-01	2E+02
Np-240	2E+04	1E+00	4E-02	7E+02
Pu-234	8E+03	1E+00	5E-02	4E+02
Pu-235	9E+05	2E+00	3E-02	3E+04
Pu-236	2E+00	1E-04	4E+02	7E+02
Pu-237	1E+04	1E+00	5E-02	5E+02
Pu-238	9E-01	3E-05	2E+03	2E+03
Pu-239	8E-01	2E-05	2E+03	2E+03
Pu-240	8E-01	2E-05	2E+03	2E+03
Pu-241	4E+01	1E-05	4E+03	2E+05
Pu-242	8E-01	2E-05	2E+03	2E+03
Pu-243	2E+04	2E-01	3E-01	5E+03
Pu-244	8E-01	9E-04	6E+01	5E+01
Pu-245	2E+03	4E-01	1E-01	2E+02
Pu-246	4E+02	5E-01	9E-02	4E+01
Am-237	8E+04	2E+00	2E-02	2E+03
Am-238	4E+04	3E+00	2E-02	6E+02

Table E1.(cont.). Radiation doses to the uterus from ingestion.

Nuclide	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Am-239	5E+03	8E-01	6E-02	3E+02
Am-240	2E+03	2E+00	2E-02	4E+01
Am-241	8E-01	9E-05	6E+02	5E+02
Am-242M	8E-01	3E-05	2E+03	1E+03
Am-242	4E+03	5E-02	9E-01	4E+03
Am-243	8E-01	4E-04	1E+02	1E+02
Am-244M	6E+04	6E-04	8E+01	5E+06
Am-244	3E+03	1E+00	4E-02	1E+02
Am-245	3E+04	8E-03	6E+00	2E+05
Am-246M	5E+04	8E-01	7E-02	3E+03
Am-246	3E+04	6E-01	8E-02	2E+03
Cm-238	2E+04	3E+00	2E-02	4E+02
Cm-240	6E+01	2E-03	2E+01	1E+03
Cm-241	1E+03	9E-01	6E-02	6E+01
Cm-242	3E+01	1E-03	5E+01	2E+03
Cm-243	1E+00	4E-04	1E+02	1E+02
Cm-244	1E+00	3E-05	2E+03	2E+03
Cm-245	7E-01	2E-04	2E+02	2E+02
Cm-246	7E-01	9E-05	6E+02	4E+02
Cm-247	8E-01	8E-04	7E+01	5E+01
Cm-248	2E-01	7E-03	7E+00	1E+00
Cm-249	5E+04	5E-02	9E-01	5E+04
Cm-250	4E-02	1E-02	5E+00	2E-01
Bk-245	2E+03	8E-01	6E-02	1E+02
Bk-246	3E+03	3E+00	2E-02	5E+01
Bk-247	5E-01	1E-04	4E+02	2E+02
Bk-249	2E+02	2E-04	3E+02	6E+04
Bk-250	9E+03	1E+00	4E-02	3E+02
Cf-244	3E+04	3E-03	2E+01	5E+05
Cf-246	4E+02	1E-02	4E+00	2E+03
Cf-248	8E+00	3E-04	1E+02	1E+03
Cf-249	5E-01	5E-04	1E+02	5E+01
Cf-250	1E+00	3E-04	2E+02	2E+02
Cf-251	5E-01	2E-04	2E+02	1E+02
Cf-252	2E+00	2E-02	2E+00	4E+00
Cf-253	2E+02	2E-04	3E+02	6E+04
Cf-254	2E+00	7E-01	7E-02	1E-01
Es-250	4E+04	2E+00	3E-02	1E+03
Es-251	7E+03	9E-01	6E-02	4E+02
Es-253	2E+02	7E-03	7E+00	1E+03
Es-254	8E+00	1E-02	5E+00	4E+01
Fm-252	5E+02	1E-02	4E+00	2E+03
Fm-253	1E+03	1E-01	4E-01	4E+02

Table E1.(cont.). Radiation doses to the uterus from ingestion.

Nuclide	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Fm-254	3E+03	2E-02	3E+00	8E+03
Fm-255	5E+02	1E-02	4E+00	2E+03
Fm-257	2E+01	5E-03	1E+01	2E+02
Md-257	7E+03	3E-01	2E-01	1E+03
Md-258	3E+01	2E-03	3E+01	8E+02

Table E2. Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
H-3	V	8E+04	5E+00	1E-02	8E+02
Be-7	W	2E+04	1E+00	4E-02	8E+02
	Y	2E+04	1E+00	5E-02	1E+03
Be-10	W	2E+02	4E-01	1E-01	2E+01
	Y	1E+01	9E-03	5E+00	5E+01
C-11	c	4E+05	5E+00	1E-02	4E+03
	m	1E+06	4E+00	1E-02	1E+04
	d	6E+05	5E+00	1E-02	6E+03
C-14	c	2E+03	4E+00	1E-02	2E+01
	m	2E+06	6E+00	9E-03	2E+04
	d	2E+05	5E+00	1E-02	2E+03
F-18	D	7E+04	3E-01	1E-01	1E+04
	W	9E+04	2E-01	3E-01	3E+04
	Y	8E+04	1E-01	4E-01	3E+04
Na-22	D	6E+02	4E+00	1E-02	7E+00
Na-24	D	5E+03	3E+00	2E-02	8E+01
Mg-28	D	2E+03	2E+00	3E-02	6E+01
	W	1E+03	6E-01	8E-02	8E+01
Al-26	D	6E+01	4E+00	1E-02	8E-01
	W	9E+01	2E+00	3E-02	3E+00
Si-31	D	3E+04	5E-01	1E-01	3E+03
	W	3E+04	1E-01	4E-01	1E+04
	Y	3E+04	8E-03	6E+00	2E+05
Si-32	D	2E+02	4E+00	1E-02	2E+00
	W	1E+02	6E-01	9E-02	9E+00
	Y	5E+00	1E-02	4E+00	2E+01
P-32	D	9E+02	2E+00	3E-02	3E+01
	W	4E+02	5E-01	1E-01	4E+01
P-33	D	8E+03	2E+00	2E-02	2E+02
	W	3E+03	6E-01	9E-02	3E+02
S-35	D	2E+04	4E+00	1E-02	2E+02
	W	2E+03	3E-01	1E-01	3E+02
	V	1E+04	4E+00	1E-02	1E+02
Cl-36	D	2E+03	4E+00	1E-02	3E+01
	W	2E+02	4E-01	1E-01	3E+01
Cl-38	D	4E+04	6E-01	9E-02	4E+03
	W	5E+04	2E-01	2E-01	1E+04
Cl-39	D	5E+04	8E-01	6E-02	3E+03
	W	6E+04	3E-01	2E-01	9E+03
K-40	D	4E+02	5E+00	1E-02	4E+00
K-42	D	5E+03	2E+00	3E-02	1E+02
K-43	D	9E+03	3E+00	1E-02	1E+02
K-44	D	7E+04	6E-01	9E-02	6E+03

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
K-45	D	1E+05	5E-01	1E-01	1E+04
Ca-41	W	4E+03	3E-02	1E+00	6E+03
Ca-45	W	8E+02	1E-01	4E-01	3E+02
Ca-47	W	9E+02	7E-01	7E-02	7E+01
Sc-43	Y	2E+04	7E-01	8E-02	2E+03
Sc-44	Y	1E+04	6E-01	8E-02	8E+02
Sc-44M	Y	7E+02	8E-01	6E-02	4E+01
Sc-46	Y	2E+02	5E-01	1E-01	2E+01
Sc-47	Y	3E+03	2E-01	2E-01	6E+02
Sc-48	Y	1E+03	1E+00	4E-02	4E+01
Sc-49	Y	5E+04	5E-03	1E+01	5E+05
Ti-44	D	1E+01	5E+00	1E-02	1E-01
	W	3E+01	4E+00	1E-02	4E-01
	Y	6E+00	4E-01	1E-01	8E-01
Ti-45	D	3E+04	1E+00	3E-02	1E+03
	W	4E+04	8E-01	6E-02	2E+03
	Y	3E+04	5E-01	9E-02	3E+03
V-47	D	8E+04	6E-01	9E-02	7E+03
	W	1E+05	2E-01	3E-01	3E+04
V-48	D	1E+03	3E+00	2E-02	2E+01
	W	6E+02	1E+00	3E-02	2E+01
V-49	D	3E+04	1E+00	4E-02	1E+03
	W	2E+04	2E-01	3E-01	5E+03
Cr-48	D	1E+04	4E+00	1E-02	1E+02
	W	7E+03	2E+00	3E-02	2E+02
	Y	7E+03	2E+00	3E-02	2E+02
Cr-49	D	8E+04	8E-01	6E-02	5E+03
	W	1E+05	3E-01	2E-01	2E+04
	Y	9E+04	1E-01	4E-01	4E+04
Cr-51	D	5E+04	5E+00	1E-02	5E+02
	W	2E+04	9E-01	5E-02	1E+03
	Y	2E+04	7E-01	7E-02	1E+03
Mn-51	D	5E+04	6E-01	8E-02	4E+03
	W	6E+04	2E-01	2E-01	1E+04
Mn-52	D	9E+04	2E+02	2E-04	2E+01
	W	1E+05	2E+02	2E-04	2E+01
Mn-52M	D	1E+03	7E-03	7E+00	7E+03
	W	9E+02	2E-03	2E+01	2E+04
Mn-53	D	1E+04	3E-01	2E-01	2E+03
	W	1E+04	1E-01	5E-01	5E+03
Mn-54	D	9E+02	3E+00	2E-02	1E+01
	W	8E+02	1E+00	3E-02	3E+01
Mn-56	D	2E+04	1E+00	4E-02	7E+02

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Mn-56	W	2E+04	6E-01	9E-02	2E+03
Fe-52	D	3E+03	1E+00	3E-02	1E+02
	W	2E+03	6E-01	8E-02	2E+02
Fe-55	D	2E+03	4E+00	1E-02	3E+01
	W	4E+03	3E+00	2E-02	8E+01
Fe-59	D	3E+02	4E+00	1E-02	3E+00
	W	5E+02	2E+00	2E-02	1E+01
Fe-60	D	6E+00	4E+00	1E-02	7E-02
	W	2E+01	5E+00	1E-02	2E-01
Co-55	W	3E+03	1E+00	4E-02	1E+02
	Y	3E+03	1E+00	4E-02	1E+02
Co-56	W	3E+02	2E+00	3E-02	9E+00
	Y	2E+02	9E-01	5E-02	1E+01
Co-57	W	3E+03	1E+00	4E-02	1E+02
	Y	7E+02	2E-01	2E-01	2E+02
Co-58	W	1E+03	2E+00	3E-02	3E+01
	Y	7E+02	8E-01	6E-02	4E+01
Co-58M	W	9E+04	8E-01	7E-02	6E+03
	Y	6E+04	4E-01	1E-01	9E+03
Co-60	W	2E+02	3E+00	2E-02	4E+00
	Y	3E+01	5E-01	1E-01	3E+00
Co-60M	W	4E+06	3E-01	2E-01	7E+05
	Y	3E+06	2E-01	3E-01	8E+05
Co-61	W	6E+04	2E-01	3E-01	2E+04
	Y	6E+04	6E-02	9E-01	5E+04
Co-62M	W	2E+05	3E-01	2E-01	4E+04
	Y	2E+05	1E-01	4E-01	9E+04
Ni-56	D	2E+03	5E+00	9E-03	2E+01
	W	1E+03	2E+00	3E-02	3E+01
	V	1E+03	5E+00	1E-02	1E+01
Ni-57	D	5E+03	3E+00	2E-02	9E+01
	W	3E+03	2E+00	3E-02	8E+01
	V	6E+03	4E+00	1E-02	8E+01
Ni-59	D	4E+03	5E+00	1E-02	4E+01
	W	7E+03	3E+00	2E-02	1E+02
	V	2E+03	5E+00	9E-03	2E+01
Ni-63	D	2E+03	6E+00	8E-03	2E+01
	W	3E+03	3E+00	2E-02	5E+01
	V	8E+02	5E+00	1E-02	8E+00
Ni-65	D	2E+04	6E-01	9E-02	2E+03
	W	3E+04	3E-01	2E-01	5E+03
	V	2E+04	8E-01	6E-02	1E+03

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
I-66	D	2E+03	9E-01	5E-02	1E+02
	W	6E+02	7E-02	7E-01	4E+02
	V	3E+03	3E+00	2E-02	5E+01
Cu-60	D	9E+04	1E+00	5E-02	4E+03
	W	1E+05	3E-01	2E-01	2E+04
	Y	1E+05	2E-01	3E-01	3E+04
Cu-61	D	3E+04	1E+00	4E-02	1E+03
	W	4E+04	8E-01	6E-02	3E+03
	Y	4E+04	7E-01	7E-02	3E+03
Cu-64	D	3E+04	1E+00	3E-02	1E+03
	W	2E+04	6E-01	8E-02	2E+03
	Y	2E+04	5E-01	9E-02	2E+03
Cu-67	D	8E+03	2E+00	2E-02	2E+02
	W	5E+03	7E-01	7E-02	3E+02
	Y	5E+03	7E-01	8E-02	4E+02
Zn-62	Y	3E+03	5E-01	1E-01	3E+02
Zn-63	Y	7E+04	8E-02	6E-01	4E+04
Zn-65	Y	3E+02	3E+00	2E-02	5E+00
Zn-69	Y	1E+05	1E-02	5E+00	5E+05
Zn-69M	Y	7E+03	5E-01	1E-01	7E+02
Zn-71M	Y	2E+04	8E-01	6E-02	1E+03
Zn-72	Y	1E+03	1E+00	4E-02	4E+01
Ga-65	D	2E+05	5E-01	9E-02	2E+04
	W	2E+05	2E-01	3E-01	6E+04
Ga-66	D	4E+03	1E+00	3E-02	1E+02
	W	3E+03	7E-01	7E-02	2E+02
Ga-67	D	1E+04	1E+00	4E-02	4E+02
	W	1E+04	1E+00	5E-02	5E+02
Ga-68	D	4E+04	7E-01	7E-02	3E+03
	W	5E+04	3E-01	2E-01	9E+03
Ga-70	D	2E+05	3E-01	2E-01	4E+04
	W	2E+05	8E-02	6E-01	1E+05
Ga-72	D	4E+03	2E+00	2E-02	1E+02
	W	3E+03	1E+00	4E-02	1E+02
Ga-73	D	2E+04	9E-01	5E-02	1E+03
	W	2E+04	4E-01	1E-01	3E+03
Ge-66	D	3E+44	2E+40	2E-42	7E+02
	W	2E+04	8E-01	6E-02	1E+03
Ge-67	D	9E+04	4E-01	1E-01	1E+04
	W	1E+05	1E-01	4E-01	4E+04
Ge-68	D	4E+03	2E+00	2E-02	9E+01
	W	1E+02	7E-02	7E-01	7E+01

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Ge-69	D	2E+04	3E+00	1E-02	3E+02
	W	8E+03	1E+00	5E-02	4E+02
Ge-71	D	4E+05	2E+00	3E-02	1E+04
	W	4E+04	1E-01	4E-01	1E+04
Ge-75	D	8E+04	6E-01	9E-02	7E+03
	W	8E+04	2E-01	3E-01	2E+04
Ge-77	D	1E+04	2E+00	3E-02	3E+02
	W	6E+03	6E-01	8E-02	5E+02
Ge-78	D	2E+04	1E+00	5E-02	1E+03
	W	2E+04	3E-01	1E-01	3E+03
As-69	W	1E+05	3E-01	2E-01	2E+04
As-70	W	5E+04	6E-01	9E-02	4E+03
As-71	W	5E+02	1E-01	4E-01	2E+02
As-72	W	1E+03	5E-01	1E-01	1E+02
As-73	W	2E+03	2E-01	3E-01	5E+02
As-74	W	8E+02	6E-01	8E-02	6E+01
As-76	W	1E+03	2E-01	2E-01	2E+02
As-77	W	5E+03	2E-01	2E-01	1E+03
As-78	W	2E+04	2E-01	2E-01	4E+03
Se-70	D	4E+04	2E+00	3E-02	1E+03
	W	4E+04	5E-01	9E-02	4E+03
Se-73	D	1E+04	1E+00	4E-02	4E+02
	W	2E+04	1E+00	4E-02	7E+02
Se-73M	D	2E+05	2E+00	2E-02	5E+03
	W	1E+05	5E-01	9E-02	9E+03
Se-75	D	7E+02	4E+00	1E-02	1E+01
	W	6E+02	3E+00	2E-02	1E+01
Se-79	D	8E+02	2E+00	2E-02	2E+01
	W	6E+02	1E+00	4E-02	2E+01
Se-81	D	2E+05	2E-01	2E-01	4E+04
	W	2E+05	7E-02	7E-01	1E+05
Se-81M	D	7E+04	6E-01	9E-02	6E+03
	W	7E+04	2E-01	3E-01	2E+04
Se-83	D	1E+05	9E-01	6E-02	6E+03
	W	1E+05	3E-01	2E-01	2E+04
Br-74	D	7E+04	9E-01	6E-02	4E+03
	W	8E+04	3E-01	2E-01	1E+04
Br-74M	D	4E+04	1E+00	5E-02	2E+03
	W	4E+04	3E-01	2E-01	6E+03
Br-75	D	5E+04	1E+00	4E-02	2E+03
	W	5E+04	5E-01	1E-01	6E+03
Br-76	D	5E+03	3E+00	2E-02	8E+01
	W	4E+03	2E+00	3E-02	1E+02

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Br-77	D	2E+04	4E+00	1E-02	3E+02
	W	2E+04	3E+00	2E-02	4E+02
Br-80	D	2E+05	3E-01	2E-01	3E+04
	W	2E+05	8E-02	6E-01	1E+05
Br-80M	D	2E+04	1E+00	4E-02	7E+02
	W	1E+04	3E-01	2E-01	2E+03
Br-82	D	4E+03	4E+00	1E-02	5E+01
	W	4E+03	3E+00	2E-02	7E+01
Br-83	D	6E+04	7E-01	7E-02	4E+03
	W	6E+04	3E-01	2E-01	1E+04
Br-84	D	6E+04	7E-01	8E-02	5E+03
	W	6E+04	2E-01	3E-01	2E+04
Rb-79	D	1E+05	5E-01	1E-01	1E+04
Rb-81	D	5E+04	2E+00	3E-02	1E+03
Rb-81M	D	3E+05	1E+00	3E-02	1E+04
Rb-82M	D	2E+04	3E+00	2E-02	3E+02
Rb-83	D	1E+03	4E+00	1E-02	1E+01
Rb-84	D	8E+02	5E+00	9E-03	8E+00
Rb-86	D	8E+02	4E+00	1E-02	1E+01
Rb-87	D	2E+03	5E+00	9E-03	2E+01
Rb-88	D	6E+04	3E-01	2E-01	1E+04
Rb-89	D	1E+05	5E-01	1E-01	1E+04
Sr-80	D	1E+04	6E-01	9E-02	9E+02
	Y	1E+04	9E-02	6E-01	6E+03
Sr-81	D	8E+04	9E-01	5E-02	4E+03
	Y	8E+04	3E-01	2E-01	2E+04
Sr-82	D	4E+02	2E+00	3E-02	1E+01
	Y	9E+01	9E-02	6E-01	5E+01
Sr-83	D	7E+03	2E+00	2E-02	2E+02
	Y	4E+03	1E+00	4E-02	2E+02
Sr-85	D	3E+03	4E+00	1E-02	4E+01
	Y	2E+03	1E+00	5E-02	9E+01
Sr-85M	D	6E+05	2E+00	2E-02	1E+04
	Y	8E+05	9E-01	5E-02	4E+04
Sr-87M	D	1E+05	1E+00	4E-02	4E+03
	Y	2E+05	1E+00	4E-02	9E+03
Sr-89	D	8E+02	1E+00	4E-02	3E+01
	Y	1E+02	3E-03	2E+01	2E+03
Sr-90	D	2E+01	2E-01	3E-01	5E+00
	Y	4E+00	4E-03	1E+01	5E+01
Sr-91	D	6E+03	1E+00	4E-02	2E+02
	Y	4E+03	4E-01	1E-01	5E+02

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Sr-92	D	9E+03	9E-01	5E-02	5E+02
	Y	7E+03	2E-01	2E-01	2E+03
Y-86	W	3E+03	2E+00	3E-02	9E+01
	Y	3E+03	2E+00	3E-02	8E+01
Y-86M	W	6E+04	2E+00	3E-02	2E+03
	Y	5E+04	2E+00	3E-02	1E+03
Y-87	W	3E+03	1E+00	4E-02	1E+02
	Y	3E+03	1E+00	4E-02	1E+02
Y-88	W	3E+02	2E+00	2E-02	7E+00
	Y	2E+02	8E-01	6E-02	1E+01
Y-90	W	7E+02	2E-02	2E+00	1E+03
	Y	6E+02	1E-03	4E+01	3E+04
Y-90M	W	1E+04	2E-01	3E-01	3E+03
	Y	1E+04	1E-01	4E-01	4E+03
Y-91	W	2E+02	8E-02	6E-01	1E+02
	Y	1E+02	3E-03	2E+01	2E+03
Y-91M	W	2E+05	3E-01	2E-01	3E+04
	Y	2E+05	2E-01	3E-01	5E+04
Y-92	W	9E+03	1E-01	4E-01	3E+03
	Y	8E+03	5E-02	9E-01	7E+03
Y-93	W	3E+03	7E-02	7E-01	2E+03
	Y	2E+03	2E-02	2E+00	5E+03
Y-94	W	8E+04	1E-01	4E-01	3E+04
	Y	8E+04	3E-02	2E+00	1E+05
Y-95	W	2E+05	2E-01	3E-01	6E+04
	Y	1E+05	3E-02	2E+00	2E+05
Zr-86	D	4E+03	3E+00	2E-02	7E+01
	W	3E+03	2E+00	2E-02	7E+01
	Y	2E+03	2E+00	3E-02	7E+01
Zr-88	D	2E+02	2E+00	3E-02	5E+00
	W	5E+02	1E+00	3E-02	2E+01
	Y	3E+02	6E-01	9E-02	3E+01
Zr-89	D	4E+03	3E+00	2E-02	6E+01
	W	2E+03	1E+00	4E-02	8E+01
	Y	2E+03	1E+00	4E-02	8E+01
Zr-93	D	6E+00	3E-04	2E+02	1E+03
	W	2E+01	2E-04	2E+02	5E+03
	Y	6E+01	3E-04	1E+02	9E+03
Zr-95	D	1E+02	5E-01	9E-02	9E+00
	W	4E+02	8E-01	7E-02	3E+01
	Y	3E+02	3E-01	2E-01	5E+01

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Zr-97	D	2E+03	1E+00	5E-02	1E+02
	W	1E+03	3E-01	2E-01	2E+02
	Y	1E+03	3E-01	2E-01	2E+02
Nb-88	W	2E+05	2E-01	3E-01	6E+04
	Y	2E+05	9E-02	6E-01	1E+05
Nb-89	W	2E+04	7E-01	7E-02	1E+03
	Y	2E+04	6E-01	8E-02	2E+03
Nb-89	W	4E+04	7E-01	7E-02	3E+03
	Y	4E+04	6E-01	8E-02	3E+03
Nb-90	W	3E+03	2E+00	3E-02	8E+01
	Y	2E+03	1E+00	4E-02	7E+01
Nb-93M	W	2E+03	2E-01	2E-01	4E+02
	Y	2E+02	8E-03	6E+00	1E+03
Nb-94	W	2E+02	2E+00	3E-02	6E+00
	Y	2E+01	2E-01	2E-01	5E+00
Nb-95	W	1E+03	1E+00	5E-02	5E+01
	Y	1E+03	7E-01	7E-02	7E+01
Nb-95M	W	3E+03	4E-01	1E-01	4E+02
	Y	2E+03	2E-01	3E-01	7E+02
Nb-96	W	3E+03	2E+00	3E-02	8E+01
	Y	2E+03	1E+00	4E-02	8E+01
Nb-97	W	8E+04	3E-01	2E-01	1E+04
	Y	7E+04	2E-01	3E-01	2E+04
Nb-98	W	5E+04	4E-01	1E-01	7E+03
	Y	5E+04	2E-01	2E-01	1E+04
Mo-90	D	7E+03	2E+00	2E-02	2E+02
	Y	5E+03	2E+00	3E-02	1E+02
Mo-93	D	5E+03	1E+00	4E-02	2E+02
	Y	2E+02	9E-03	6E+00	1E+03
Mo-93M	D	2E+04	3E+00	2E-02	4E+02
	Y	1E+04	1E+00	3E-02	3E+02
Mo-99	D	3E+03	1E+00	3E-02	1E+02
	Y	1E+03	2E-01	3E-01	3E+02
Mo-101	D	1E+05	4E-01	1E-01	1E+04
	Y	1E+05	4E-02	1E+00	1E+05
Tc-93	D	7E+04	2E+00	2E-02	2E+03
	W	1E+05	2E+00	3E-02	3E+03
Tc-93M	D	2E+05	2E+00	2E-02	4E+03
	W	3E+05	1E+00	3E-02	1E+04
Tc-94	D	2E+04	2E+00	2E-02	4E+02
	W	2E+04	1E+00	4E-02	8E+02
Tc-94M	D	4E+04	7E-01	7E-02	3E+03
	W	6E+04	3E-01	2E-01	9E+03

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Tc-95	D	2E+04	3E+00	2E-02	4E+02
	W	2E+04	2E+00	3E-02	5E+02
Tc-95M	D	5E+03	3E+00	2E-02	8E+01
	W	2E+03	1E+00	4E-02	8E+01
Tc-96	D	3E+03	3E+00	1E-02	4E+01
	W	2E+03	2E+00	3E-02	5E+01
Tc-96M	D	3E+05	3E+00	2E-02	5E+03
	W	2E+05	2E+00	3E-02	6E+03
Tc-97	D	5E+04	1E+00	4E-02	2E+03
	W	6E+03	1E-01	3E-01	2E+03
Tc-97M	D	7E+03	1E+00	5E-02	3E+02
	W	1E+03	1E-01	4E-01	4E+02
Tc-98	D	2E+03	3E+00	2E-02	3E+01
	W	3E+02	5E-01	9E-02	3E+01
Tc-99	D	5E+03	8E-01	6E-02	3E+02
	W	7E+02	1E-01	5E-01	3E+02
Tc-99M	D	2E+05	2E+00	3E-02	5E+03
	W	2E+05	1E+00	5E-02	1E+04
Tc-101	D	3E+05	3E-01	2E-01	5E+04
	W	4E+05	1E-01	5E-01	2E+05
Tc-104	D	7E+04	4E-01	1E-01	9E+03
	W	9E+04	2E-01	3E-01	3E+04
Ru-94	D	4E+04	1E+00	4E-02	2E+03
	W	6E+04	6E-01	8E-02	5E+03
	Y	6E+04	5E-01	1E-01	6E+03
Ru-97	D	2E+04	4E+00	1E-02	3E+02
	W	1E+04	1E+00	3E-02	3E+02
	Y	1E+04	1E+00	3E-02	3E+02
Ru-103	D	2E+03	5E+00	1E-02	2E+01
	W	1E+03	9E-01	5E-02	5E+01
	Y	6E+02	3E-01	1E-01	9E+01
Ru-105	D	1E+04	8E-01	6E-02	6E+02
	W	1E+04	4E-01	1E-01	1E+03
	Y	1E+04	3E-01	1E-01	1E+03
Ru-106	D	9E+01	5E+00	1E-02	1E+00
	W	5E+01	7E-01	7E-02	3E+00
	Y	1E+01	4E-02	1E+00	1E+01
Rh-99	D	3E+03	5E+00	1E-02	3E+01
	W	2E+03	1E+00	3E-02	7E+01
	Y	2E+03	1E+00	4E-02	9E+01
Rh-99M	D	6E+04	3E+00	2E-02	1E+03
	W	8E+04	2E+00	2E-02	2E+03
	Y	7E+04	2E+00	3E-02	2E+03

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Rh-100	D	5E+03	3E+00	1E-02	7E+01
	W	4E+03	2E+00	2E-02	9E+01
	Y	4E+03	2E+00	2E-02	8E+01
Rh-101	D	5E+02	6E+00	9E-03	4E+00
	W	8E+02	3E+00	2E-02	1E+01
	Y	2E+02	4E-01	1E-01	3E+01
Rh-101M	D	1E+04	3E+00	2E-02	2E+02
	W	8E+03	2E+00	3E-02	2E+02
	Y	8E+03	2E+00	3E-02	2E+02
Rh-102	D	9E+01	6E+00	9E-03	8E-01
	W	2E+02	4E+00	1E-02	2E+00
	Y	6E+01	7E-01	7E-02	4E+00
Rh-102M	D	5E+02	5E+00	1E-02	5E+00
	W	4E+02	1E+00	4E-02	2E+01
	Y	1E+02	1E-01	4E-01	4E+01
Rh-103M	D	1E+06	3E-01	2E-01	2E+05
	W	1E+06	9E-02	5E-01	5E+05
	Y	1E+06	7E-03	7E+00	7E+06
Rh-105	D	1E+04	1E+00	4E-02	4E+02
	W	6E+03	3E-01	2E-01	1E+03
	Y	6E+03	2E-01	2E-01	1E+03
Rh-106M	D	3E+04	3E+00	2E-02	6E+02
	W	4E+04	1E+00	4E-02	1E+03
	Y	4E+04	1E+00	4E-02	2E+03
Rh-107	D	2E+05	3E-01	1E-01	3E+04
	W	3E+05	1E-01	3E-01	1E+05
	Y	3E+05	4E-02	1E+00	4E+05
Pd-100	D	1E+03	8E-01	6E-02	6E+01
	W	1E+03	1E+00	4E-02	4E+01
	Y	1E+03	1E+00	4E-02	4E+01
Pd-101	D	3E+04	1E+00	4E-02	1E+03
	W	3E+04	1E+00	4E-02	1E+03
	Y	3E+04	1E+00	4E-02	1E+03
Pd-103	D	6E+03	1E-01	5E-01	3E+03
	W	4E+03	2E-02	2E+00	9E+03
	Y	4E+03	1E-02	4E+00	1E+04
Pd-107	D	2E+04	7E-02	7E-01	1E+04
	W	7E+03	6E-03	8E+00	6E+04
	Y	4E+02	2E-04	3E+02	1E+05
Pd-109	D	6E+03	2E-01	3E-01	2E+03
	W	5E+03	4E-02	1E+00	7E+03
	Y	5E+03	1E-02	5E+00	3E+04

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Ag-102	D	2E+05	8E-01	6E-02	1E+04
	W	2E+05	2E-01	2E-01	4E+04
	Y	2E+05	1E-01	4E-01	8E+04
Ag-103	D	1E+05	1E+00	5E-02	5E+03
	W	1E+05	3E-01	1E-01	1E+04
	Y	1E+05	2E-01	2E-01	2E+04
Ag-104	D	7E+04	2E+00	2E-02	2E+03
	W	1E+05	1E+00	5E-02	5E+03
	Y	1E+05	9E-01	6E-02	6E+03
Ag-104M	D	9E+04	1E+00	4E-02	4E+03
	W	1E+05	4E-01	1E-01	1E+04
	Y	1E+05	3E-01	2E-01	2E+04
Ag-105	D	1E+03	1E+00	4E-02	4E+01
	W	2E+03	1E+00	4E-02	7E+01
	Y	2E+03	1E+00	5E-02	9E+01
Ag-106	D	2E+05	6E-01	8E-02	2E+04
	W	2E+05	2E-01	3E-01	6E+04
	Y	2E+05	6E-02	8E-01	2E+05
Ag-106M	D	7E+02	2E+00	3E-02	2E+01
	W	9E+02	2E+00	3E-02	2E+01
	Y	9E+02	2E+00	3E-02	3E+01
Ag-108M	D	2E+02	1E+00	3E-02	7E+00
	W	3E+02	1E+00	4E-02	1E+01
	Y	2E+01	2E-01	3E-01	6E+00
Ag-110M	D	1E+02	1E+00	5E-02	5E+00
	W	2E+02	1E+00	5E-02	9E+00
	Y	9E+01	5E-01	1E-01	9E+00
Ag-111	D	2E+03	5E-01	9E-02	2E+02
	W	9E+02	6E-02	8E-01	7E+02
	Y	9E+02	3E-02	2E+00	1E+03
Ag-112	D	8E+03	5E-01	1E-01	8E+02
	W	1E+04	2E-01	2E-01	2E+03
	Y	9E+03	1E-01	4E-01	4E+03
Ag-115	D	9E+04	4E-01	1E-01	1E+04
	W	9E+04	2E-01	3E-01	2E+04
	Y	8E+04	1E-01	4E-01	4E+04
Cd-104	D	7E+04	3E+00	2E-02	1E+03
	W	1E+05	1E+00	3E-02	3E+03
	Y	1E+05	1E+00	4E-02	4E+03
Cd-107	D	5E+04	4E-01	1E-01	6E+03
	W	6E+04	2E-01	3E-01	2E+04
	Y	5E+04	9E-02	5E-01	3E+04

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Cd-109	D	4E+01	4E-01	1E-01	5E+00
	W	1E+02	3E-01	2E-01	2E+01
	Y	1E+02	9E-02	6E-01	6E+01
Cd-113	D	2E+00	3E-01	2E-01	4E-01
	W	8E+00	3E-01	2E-01	1E+00
	Y	1E+01	2E-01	2E-01	2E+00
Cd-113M	D	2E+00	2E-01	2E-01	4E-01
	W	8E+00	3E-01	2E-01	1E+00
	Y	1E+01	2E-01	3E-01	3E+00
Cd-115	D	1E+03	4E-01	1E-01	1E+02
	W	1E+03	2E-01	2E-01	2E+02
	Y	1E+03	2E-01	2E-01	2E+02
Cd-115M	D	5E+01	3E-01	2E-01	9E+00
	W	1E+02	1E-01	4E-01	4E+01
	Y	1E+02	4E-02	1E+00	1E+02
Cd-117	D	1E+04	7E-01	7E-02	7E+02
	W	2E+04	6E-01	8E-02	2E+03
	Y	1E+04	3E-01	2E-01	2E+03
Cd-117M	D	1E+04	1E+00	4E-02	4E+02
	W	2E+04	1E+00	4E-02	8E+02
	Y	1E+04	6E-01	8E-02	8E+02
In-109	D	4E+04	2E+00	3E-02	1E+03
	W	6E+04	1E+00	4E-02	2E+03
In-110	D	2E+04	4E+00	1E-02	2E+02
	W	2E+04	2E+00	2E-02	4E+02
In-110	D	4E+04	1E+00	5E-02	2E+03
	W	6E+04	5E-01	1E-01	7E+03
In-111	D	6E+03	2E+00	2E-02	1E+02
	W	6E+03	2E+00	3E-02	2E+02
In-112	D	6E+05	4E-01	1E-01	8E+04
	W	7E+05	1E-01	4E-01	3E+05
In-113M	D	1E+05	7E-01	7E-02	7E+03
	W	2E+05	5E-01	1E-01	2E+04
In-114M	D	6E+01	6E-01	8E-02	5E+00
	W	1E+02	2E-01	2E-01	2E+01
In-115	D	1E+00	4E-01	1E-01	1E-01
	W	5E+00	6E-01	9E-02	4E-01
In-115M	D	4E+04	7E-01	7E-02	3E+03
	W	5E+04	4E-01	1E-01	6E+03
In-116M	D	8E+04	2E+00	3E-02	2E+03
	W	1E+05	7E-01	7E-02	7E+03
In-117	D	2E+05	1E+00	4E-02	8E+03
	W	2E+05	3E-01	1E-01	3E+04

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
In-117M	D	3E+04	6E-01	8E-02	2E+03
	W	4E+04	3E-01	2E-01	7E+03
In-119M	D	1E+05	2E-01	3E-01	3E+04
	W	1E+05	5E-02	9E-01	9E+04
Sn-110	D	1E+04	1E+00	4E-02	4E+02
	W	1E+04	7E-01	8E-02	8E+02
Sn-111	D	2E+05	1E+00	5E-02	1E+04
	W	3E+05	9E-01	6E-02	2E+04
Sn-113	D	1E+03	2E+00	3E-02	3E+01
	W	5E+02	3E-01	1E-01	7E+01
Sn-117M	D	1E+03	3E-01	2E-01	2E+02
	W	1E+03	2E-01	3E-01	3E+02
Sn-119M	D	2E+03	2E+00	3E-02	6E+01
	W	1E+03	2E-01	2E-01	2E+02
Sn-121	D	2E+04	3E-01	2E-01	3E+03
	W	1E+04	3E-02	2E+00	2E+04
Sn-121M	D	9E+02	2E+00	2E-02	2E+01
	W	5E+02	3E-01	1E-01	7E+01
Sn-123	D	6E+02	2E+00	3E-02	2E+01
	W	2E+02	1E-01	4E-01	8E+01
Sn-123M	D	1E+05	3E-01	2E-01	2E+04
	W	1E+05	9E-02	6E-01	6E+04
Sn-125	D	9E+02	8E-01	6E-02	6E+01
	W	4E+02	1E-01	4E-01	1E+02
Sn-126	D	6E+01	3E+00	2E-02	1E+00
	W	7E+01	1E+00	5E-02	3E+00
Sn-127	D	2E+04	1E+00	4E-02	8E+02
	W	2E+04	6E-01	8E-02	2E+03
Sn-128	D	3E+04	1E+00	4E-02	1E+03
	W	4E+04	5E-01	1E-01	4E+03
Sb-115	D	2E+05	9E-01	6E-02	1E+04
	W	3E+05	4E-01	1E-01	4E+04
Sb-116	D	3E+05	1E+00	5E-02	1E+04
	W	3E+05	3E-01	2E-01	5E+04
Sb-116M	D	7E+04	2E+00	2E-02	2E+03
	W	1E+05	1E+00	5E-02	5E+03
Sb-117	D	2E+05	2E+00	3E-02	6E+03
	W	3E+05	1E+00	4E-02	1E+04
Sb-118M	D	2E+04	3E+00	1E-02	3E+02
	W	2E+04	2E+00	2E-02	5E+02
Sb-119	D	5E+04	1E+00	5E-02	3E+03
	W	3E+04	3E-01	2E-01	6E+03

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Sb-120	D	4E+05	4E-01	1E-01	5E+04
	W	5E+05	1E-01	4E-01	2E+05
Sb-120	D	2E+03	4E+00	1E-02	3E+01
	W	1E+03	2E+00	3E-02	3E+01
Sb-122	D	2E+03	1E+00	5E-02	1E+02
	W	1E+03	3E-01	2E-01	2E+02
Sb-124	D	9E+02	3E+00	2E-02	2E+01
	W	2E+02	4E-01	1E-01	2E+01
Sb-124M	D	8E+05	1E+00	4E-02	3E+04
	W	6E+05	4E-01	1E-01	8E+04
Sb-125	D	2E+03	2E+00	2E-02	5E+01
	W	5E+02	3E-01	1E-01	7E+01
Sb-126	D	1E+03	3E+00	2E-02	2E+01
	W	5E+02	1E+00	4E-02	2E+01
Sb-126M	D	2E+05	9E-01	6E-02	1E+04
	W	2E+05	3E-01	2E-01	4E+04
Sb-127	D	2E+03	1E+00	4E-02	7E+01
	W	9E+02	4E-01	1E-01	1E+02
Sb-128	D	4E+05	1E+00	5E-02	2E+04
	W	4E+05	3E-01	2E-01	7E+04
Sb-128	D	4E+03	1E+00	4E-02	2E+02
	W	3E+03	6E-01	8E-02	2E+02
Sb-129	D	9E+03	1E+00	5E-02	4E+02
	W	9E+03	5E-01	1E-01	9E+02
Sb-130	D	6E+04	1E+00	4E-02	2E+03
	W	8E+04	5E-01	1E-01	8E+03
Sb-131	D	2E+04	2E-01	2E-01	5E+03
	W	2E+04	7E-02	7E-01	1E+04
Te-116	D	2E+04	2E+00	3E-02	6E+02
	W	3E+04	1E+00	5E-02	1E+03
Te-121	D	4E+03	3E+00	2E-02	7E+01
	W	3E+03	2E+00	3E-02	9E+01
Te-121M	D	2E+02	6E-01	8E-02	2E+01
	W	4E+02	6E-01	8E-02	3E+01
Te-123	D	2E+02	3E-03	2E+01	3E+03
	W	4E+02	3E-03	2E+01	7E+03
Te-123M	D	2E+02	2E-01	3E-01	6E+01
	W	5E+02	2E-01	2E-01	1E+02
Te-125M	D	4E+02	2E-01	3E-01	1E+02
	W	7E+02	1E-01	5E-01	3E+02
Te-127	D	2E+04	5E-01	1E-01	2E+03
	W	2E+04	1E-01	4E-01	7E+03

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Te-127M	D	3E+02	3E-01	2E-01	6E+01
	W	3E+02	1E-01	5E-01	1E+02
Te-129	D	6E+04	4E-01	1E-01	8E+03
	W	7E+04	1E-01	4E-01	3E+04
Te-129M	D	6E+02	9E-01	6E-02	3E+01
	W	2E+02	1E-01	4E-01	9E+01
Te-131	D	5E+03	1E-01	5E-01	2E+03
	W	5E+03	4E-02	1E+00	7E+03
Te-131M	D	4E+02	2E-01	2E-01	9E+01
	W	4E+02	2E-01	3E-01	1E+02
Te-132	D	2E+02	3E-01	2E-01	3E+01
	W	2E+02	3E-01	2E-01	3E+01
Te-133	D	2E+04	5E-02	1E+00	2E+04
	W	2E+04	3E-02	2E+00	4E+04
Te-133M	D	5E+03	2E-01	3E-01	2E+03
	W	5E+03	6E-02	8E-01	4E+03
Te-134	D	2E+04	8E-01	6E-02	1E+03
	W	2E+04	7E-01	7E-02	1E+03
I-120	D	9E+03	4E-01	1E-01	1E+03
I-120M	D	2E+04	7E-01	7E-02	1E+03
I-121	D	2E+04	2E-01	3E-01	6E+03
I-123	D	6E+03	7E-02	7E-01	4E+03
I-124	D	8E+01	1E-02	5E+00	4E+02
I-125	D	6E+01	4E-03	1E+01	7E+02
I-126	D	4E+01	6E-03	9E+00	4E+02
I-128	D	1E+05	3E-01	2E-01	2E+04
I-129	D	9E+00	3E-03	2E+01	2E+02
I-130	D	7E+02	8E-02	6E-01	4E+02
I-131	D	5E+01	5E-03	1E+01	5E+02
I-132	D	8E+03	3E-01	1E-01	1E+03
I-132M	D	8E+03	2E-01	2E-01	2E+03
I-133	D	3E+02	2E-02	2E+00	7E+02
I-134	D	5E+04	9E-01	5E-02	3E+03
I-135	D	2E+03	1E-01	4E-01	7E+02
Cs-125	D	1E+05	6E-01	9E-02	9E+03
Cs-127	D	9E+04	3E+00	2E-02	2E+03
Cs-129	D	3E+04	4E+00	1E-02	4E+02
Cs-130	D	2E+05	6E-01	8E-02	2E+04
Cs-131	D	3E+04	4E+00	1E-02	4E+02
Cs-132	D	4E+03	5E+00	1E-02	4E+01
Cs-134	D	1E+02	5E+00	1E-02	1E+00
Cs-134M	D	1E+05	1E+00	3E-02	3E+03
Cs-135	D	1E+03	4E+00	1E-02	1E+01

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Cs-135M	D	2E+05	2E+00	3E-02	5E+03
Cs-136	D	7E+02	6E+00	8E-03	6E+00
Cs-137	D	2E+02	7E+00	7E-03	1E+00
Cs-138	D	6E+04	7E-01	7E-02	4E+03
Ba-126	D	2E+04	8E-01	6E-02	1E+03
Ba-128	D	2E+03	1E+00	5E-02	1E+02
Ba-131	D	8E+03	2E+00	2E-02	2E+02
Ba-131M	D	1E+06	5E-01	1E-01	1E+05
Ba-133	D	7E+02	2E+00	3E-02	2E+01
Ba-133M	D	9E+03	6E-01	9E-02	8E+02
Ba-135M	D	1E+04	5E-01	1E-01	1E+03
Ba-139	D	3E+04	3E-01	2E-01	5E+03
Ba-140	D	1E+03	1E+00	4E-02	4E+01
Ba-141	D	7E+04	4E-01	1E-01	1E+04
Ba-142	D	1E+05	7E-01	7E-02	7E+03
La-131	D	1E+05	1E+00	5E-02	5E+03
	W	2E+05	8E-01	6E-02	1E+04
La-132	D	1E+04	1E+00	4E-02	4E+02
	W	1E+04	8E-01	6E-02	6E+02
La-135	D	1E+05	1E+00	5E-02	5E+03
	W	9E+04	9E-01	6E-02	5E+03
La-137	D	6E+01	7E-01	7E-02	4E+00
	W	3E+02	9E-01	6E-02	2E+01
La-138	D	4E+00	2E+00	3E-02	1E-01
	W	1E+01	1E+00	5E-02	5E-01
La-140	D	1E+03	9E-01	6E-02	6E+01
	W	1E+03	9E-01	6E-02	6E+01
La-141	D	9E+03	3E-01	2E-01	1E+03
	W	1E+04	1E-01	5E-01	5E+03
La-142	D	2E+04	1E+00	5E-02	9E+02
	W	3E+04	6E-01	9E-02	3E+03
La-143	D	1E+05	3E-01	2E-01	2E+04
	W	9E+04	1E-01	4E-01	4E+04
Ce-134	W	7E+02	3E-01	2E-01	1E+02
	Y	7E+02	3E-01	2E-01	1E+02
Ce-135	W	4E+03	1E+00	3E-02	1E+02
	Y	4E+03	2E+00	3E-02	1E+02
Ce-137	W	1E+05	4E-01	1E-01	1E+04
	Y	1E+05	5E-01	1E-01	1E+04
Ce-137M	W	4E+03	2E-01	3E-01	1E+03
	Y	4E+03	2E-01	3E-01	1E+03
Ce-139	W	8E+02	6E-01	9E-02	7E+01
	Y	7E+02	2E-01	3E-01	2E+02

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Ce-141	W	7E+02	1E-01	3E-01	2E+02
	Y	6E+02	6E-02	9E-01	5E+02
Ce-143	W	2E+03	2E-01	2E-01	4E+02
	Y	2E+03	2E-01	2E-01	4E+02
Ce-144	W	3E+01	2E-01	2E-01	7E+00
	Y	1E+01	8E-03	6E+00	6E+01
Pr-136	W	2E+05	6E-02	8E-01	2E+05
	Y	2E+05	7E-02	8E-01	2E+05
Pr-137	W	2E+05	5E-01	1E-01	2E+04
	Y	1E+05	3E-01	2E-01	2E+04
Pr-138M	W	5E+04	1E+00	5E-02	2E+03
	Y	4E+04	1E+00	5E-02	2E+03
Pr-139	W	1E+05	5E-01	1E-01	1E+04
	Y	1E+05	5E-01	9E-02	9E+03
Pr-142	W	2E+03	2E-02	2E+00	5E+03
	Y	2E+03	3E-02	2E+00	4E+03
Pr-142M	W	2E+05	3E-02	2E+00	4E+05
	Y	1E+05	2E-02	3E+00	3E+05
Pr-143	W	8E+02	6E-09	9E+06	7E+09
	Y	7E+02	5E-09	1E+07	7E+09
Pr-144	W	1E+05	8E-04	6E+01	6E+06
	Y	1E+05	9E-04	6E+01	6E+06
Pr-145	W	9E+03	6E-03	9E+00	8E+04
	Y	8E+03	6E-03	8E+00	7E+04
Pr-147	W	2E+05	5E-02	1E+00	2E+05
	Y	2E+05	5E-02	1E+00	2E+05
Nd-136	W	6E+04	3E-01	2E-01	1E+04
	Y	5E+04	3E-01	2E-01	1E+04
Nd-138	W	6E+03	2E-01	3E-01	2E+03
	Y	5E+03	2E-01	3E-01	1E+03
Nd-139	W	3E+05	2E-01	2E-01	6E+04
	Y	3E+05	3E-01	2E-01	6E+04
Nd-139M	W	2E+04	2E+00	3E-02	7E+02
	Y	1E+04	9E-01	5E-02	5E+02
Nd-141	W	7E+05	7E-01	7E-02	5E+04
	Y	6E+05	7E-01	7E-02	4E+04
Nd-147	W	9E+02	1E-01	5E-01	4E+02
	Y	8E+02	1E-01	5E-01	4E+02
Nd-149	W	3E+04	8E-02	6E-01	2E+04
	Y	2E+04	6E-02	8E-01	2E+04
Nd-151	W	2E+05	2E-01	3E-01	6E+04
	Y	2E+05	2E-01	3E-01	5E+04

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Pm-141	W	2E+05	8E-02	7E-01	1E+05
	Y	2E+05	9E-02	6E-01	1E+05
Pm-143	W	6E+02	8E-01	6E-02	4E+01
	Y	7E+02	4E-01	1E-01	8E+01
Pm-144	W	1E+02	9E-01	6E-02	6E+00
	Y	1E+02	4E-01	1E-01	1E+01
Pm-145	W	2E+02	1E-01	4E-01	9E+01
	Y	2E+02	5E-02	1E+00	2E+02
Pm-146	W	5E+01	7E-01	7E-02	3E+00
	Y	4E+01	2E-01	2E-01	8E+00
Pm-147	W	1E+02	5E-06	1E+04	1E+06
	Y	1E+02	2E-06	3E+04	3E+06
Pm-148	W	5E+02	2E-01	3E-01	1E+02
	Y	5E+02	2E-01	3E-01	1E+02
Pm-148M	W	3E+02	8E-01	6E-02	2E+01
	Y	3E+02	6E-01	9E-02	3E+01
Pm-149	W	2E+03	1E-02	5E+00	1E+04
	Y	2E+03	1E-02	4E+00	9E+03
Pm-150	W	2E+04	4E-01	1E-01	3E+03
	Y	2E+04	4E-01	1E-01	2E+03
Pm-151	W	4E+03	4E-01	1E-01	5E+02
	Y	3E+03	3E-01	1E-01	4E+02
Sm-141	W	2E+05	7E-02	7E-01	1E+05
Sm-141M	W	1E+05	1E-01	4E-01	4E+04
Sm-142	W	3E+04	9E-02	6E-01	2E+04
Sm-145	W	5E+02	1E-01	4E-01	2E+02
Sm-151	W	1E+02	2E-06	2E+04	2E+06
Sm-153	W	3E+03	1E-01	5E-01	1E+03
Sm-155	W	2E+05	8E-03	6E+00	1E+06
Sm-156	W	9E+03	4E-01	1E-01	1E+03
Eu-145	W	2E+03	2E+00	3E-02	6E+01
Eu-146	W	1E+03	1E+00	4E-02	4E+01
Eu-147	W	2E+03	1E+00	5E-02	1E+02
Eu-148	W	4E+02	1E+00	4E-02	2E+01
Eu-149	W	3E+03	4E-01	1E-01	4E+02
Eu-150	W	8E+03	5E-02	1E+00	8E+03
Eu-150	W	2E+01	1E+00	5E-02	9E-01
Eu-152	W	2E+01	7E-01	7E-02	1E+00
Eu-152M	W	6E+03	2E-01	3E-01	2E+03
Eu-154	W	2E+01	6E-01	8E-02	2E+00
Eu-155	W	9E+01	8E-02	6E-01	6E+01
Eu-156	W	5E+02	5E-01	9E-02	5E+01
Eu-157	W	5E+03	2E-01	2E-01	1E+03

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Eu-158	W	6E+04	8E-02	6E-01	4E+04
Gd-145	D	2E+05	1E+00	5E-02	1E+04
	W	2E+05	7E-01	8E-02	2E+04
Gd-146	D	1E+02	7E-01	7E-02	7E+00
	W	3E+02	8E-01	7E-02	2E+01
Gd-147	D	4E+03	1E+00	3E-02	1E+02
	W	4E+03	2E+00	3E-02	1E+02
Gd-149	D	2E+03	7E-01	8E-02	2E+02
	W	2E+03	7E-01	7E-02	1E+02
Gd-151	D	4E+02	1E-01	4E-01	2E+02
	W	1E+03	1E-01	4E-01	4E+02
Gd-153	D	1E+02	1E-01	5E-01	5E+01
	W	6E+02	2E-01	2E-01	1E+02
Gd-159	D	8E+03	6E-02	8E-01	6E+03
	W	6E+03	7E-02	7E-01	4E+03
Tb-147	W	3E+04	9E-01	5E-02	2E+03
Tb-149	W	7E+02	4E-02	1E+00	9E+02
Tb-150	W	2E+04	6E-01	8E-02	2E+03
Tb-151	W	9E+03	2E+00	3E-02	3E+02
Tb-153	W	7E+03	9E-01	6E-02	4E+02
Tb-154	W	4E+03	2E+00	3E-02	1E+02
Tb-155	W	8E+03	9E-01	5E-02	4E+02
Tb-156	W	1E+03	1E+00	4E-02	4E+01
Tb-156M	W	8E+03	1E+00	4E-02	3E+02
Tb-156M	W	3E+04	1E+00	4E-02	1E+03
Tb-157	W	3E+02	2E-02	2E+00	7E+02
Tb-158	W	2E+01	8E-01	6E-02	1E+00
Tb-160	W	2E+02	4E-01	1E-01	2E+01
Tb-161	W	2E+03	7E-02	8E-01	2E+03
Dy-155	W	3E+04	2E+00	2E-02	7E+02
Dy-157	W	6E+04	2E+00	3E-02	2E+03
Dy-159	W	2E+03	2E-01	2E-01	5E+02
Dy-165	W	5E+04	2E-02	3E+00	2E+05
Dy-166	W	7E+02	3E-02	2E+00	1E+03
Ho-155	W	2E+05	1E+00	4E-02	8E+03
Ho-157	W	1E+06	9E-01	6E-02	6E+04
Ho-159	W	1E+06	3E-01	2E-01	2E+05
Ho-161	W	4E+05	4E-01	1E-01	5E+04
Ho-162	W	2E+06	6E-02	8E-01	2E+06
Ho-162M	W	3E+05	6E-01	8E-02	2E+04
Ho-164	W	6E+05	1E-02	5E+00	3E+06
Ho-164M	W	3E+05	3E-02	1E+00	4E+05
Ho-166	W	2E+03	2E-02	3E+00	5E+03

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Ho-166M	W	7E+00	6E-01	8E-02	6E-01
Ho-167	W	6E+04	4E-01	1E-01	8E+03
Er-161	W	6E+04	1E+00	4E-02	2E+03
Er-165	W	2E+05	1E+00	4E-02	7E+03
Er-169	W	3E+03	3E-02	2E+00	5E+03
Er-171	W	1E+04	4E-01	1E-01	1E+03
Er-172	W	1E+03	3E-01	1E-01	1E+02
Tm-162	W	3E+05	4E-01	1E-01	4E+04
Tm-166	W	1E+04	1E+00	4E-02	4E+02
Tm-167	W	2E+03	3E-01	2E-01	3E+02
Tm-170	W	2E+02	1E-01	5E-01	1E+02
Tm-171	W	3E+02	6E-02	8E-01	2E+02
Tm-172	W	1E+03	2E-01	2E-01	2E+02
Tm-173	W	1E+04	4E-01	1E-01	1E+03
Tm-175	W	3E+05	2E-01	3E-01	8E+04
Yb-162	W	3E+05	3E-01	2E-01	6E+04
	Y	3E+05	3E-01	2E-01	5E+04
Yb-166	W	2E+03	2E+00	3E-02	6E+01
	Y	2E+03	2E+00	3E-02	5E+01
Yb-167	W	8E+05	2E-01	3E-01	2E+05
	Y	7E+05	2E-01	3E-01	2E+05
Yb-169	W	8E+02	3E-01	2E-01	1E+02
	Y	7E+02	3E-01	2E-01	1E+02
Yb-175	W	4E+03	1E-01	5E-01	2E+03
	Y	3E+03	8E-02	6E-01	2E+03
Yb-177	W	5E+04	8E-02	6E-01	3E+04
	Y	5E+04	1E-01	5E-01	2E+04
Yb-178	W	4E+04	3E-02	2E+00	7E+04
	Y	4E+04	4E-02	1E+00	6E+04
Lu-169	W	4E+03	1E+00	4E-02	1E+02
	Y	4E+03	2E+00	3E-02	1E+02
Lu-170	W	2E+03	2E+00	3E-02	6E+01
	Y	2E+03	2E+00	2E-02	5E+01
Lu-171	W	2E+03	1E+00	5E-02	1E+02
	Y	2E+03	1E+00	5E-02	9E+01
Lu-172	W	1E+03	1E+00	4E-02	4E+01
	Y	1E+03	1E+00	4E-02	4E+01
Lu-173	W	3E+02	2E-01	2E-01	7E+01
	Y	3E+02	1E-01	5E-01	1E+02
Lu-174	W	1E+02	1E-01	3E-01	3E+01
	Y	2E+02	1E-01	3E-01	7E+01
Lu-174M	W	2E+02	6E-02	8E-01	2E+02
	Y	2E+02	3E-02	1E+00	3E+02

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Lu-176	W	5E+00	1E-01	5E-01	2E+00
	Y	8E+00	8E-02	6E-01	5E+00
Lu-176M	W	3E+04	1E-02	4E+00	1E+05
	Y	2E+04	1E-02	4E+00	9E+04
Lu-177	W	2E+03	6E-02	9E-01	2E+03
	Y	2E+03	6E-02	8E-01	2E+03
Lu-177M	W	1E+02	3E-01	2E-01	2E+01
	Y	8E+01	1E-01	4E-01	3E+01
Lu-178	W	1E+05	9E-03	6E+00	6E+05
	Y	1E+05	1E-02	5E+00	5E+05
Lu-178M	W	2E+05	7E-02	7E-01	1E+05
	Y	2E+05	8E-02	6E-01	1E+05
Lu-179	W	2E+04	2E-02	2E+00	5E+04
	Y	2E+04	3E-02	2E+00	4E+04
Hf-170	D	6E+03	3E+00	2E-02	1E+02
	W	5E+03	2E+00	3E-02	1E+02
Hf-172	D	9E+00	5E-01	9E-02	8E-01
	W	4E+01	6E-01	8E-02	3E+00
Hf-173	D	1E+04	1E+00	3E-02	3E+02
	W	1E+04	1E+00	4E-02	4E+02
Hf-175	D	9E+02	1E+00	4E-02	3E+01
	W	1E+03	7E-01	8E-02	8E+01
Hf-177M	D	6E+04	1E+00	3E-02	2E+03
	W	9E+04	6E-01	8E-02	7E+03
Hf-178M	D	1E+00	4E-01	1E-01	1E-01
	W	5E+00	5E-01	1E-01	5E-01
Hf-179M	D	3E+02	6E-01	8E-02	2E+01
	W	6E+02	7E-01	7E-02	4E+01
Hf-180M	D	2E+04	2E+00	3E-02	6E+02
	W	3E+04	2E+00	3E-02	9E+02
Hf-181	D	2E+02	3E-01	1E-01	3E+01
	W	4E+02	3E-01	2E-01	6E+01
Hf-182	D	8E-01	3E-01	1E-01	1E-01
	W	3E+00	3E-01	1E-01	4E-01
Hf-182M	D	9E+04	1E+00	4E-02	3E+03
	W	1E+05	4E-01	1E-01	1E+04
Hf-183	D	5E+04	9E-01	6E-02	3E+03
	W	6E+04	4E-01	1E-01	8E+03
Hf-184	D	8E+03	1E+00	4E-02	3E+02
	W	6E+03	6E-01	8E-02	5E+02
Ta-172	W	1E+05	3E-01	2E-01	2E+04
	Y	1E+05	2E-01	3E-01	3E+04

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Ta-173	W	2E+04	8E-01	6E-02	1E+03
	Y	2E+04	8E-01	6E-02	1E+03
Ta-174	W	1E+05	4E-01	1E-01	1E+04
	Y	9E+04	2E-01	2E-01	2E+04
Ta-175	W	2E+04	2E+00	2E-02	4E+02
	Y	1E+04	1E+00	4E-02	4E+02
Ta-176	W	1E+04	2E+00	3E-02	3E+02
	Y	1E+04	2E+00	3E-02	3E+02
Ta-177	W	2E+04	1E+00	5E-02	1E+03
	Y	2E+04	1E+00	5E-02	1E+03
Ta-178	W	9E+04	1E+00	4E-02	4E+03
	Y	7E+04	9E-01	5E-02	4E+03
Ta-179	W	5E+03	9E-01	5E-02	3E+02
	Y	9E+02	9E-02	6E-01	5E+02
Ta-180	W	4E+02	1E+00	4E-02	2E+01
	Y	2E+01	7E-02	7E-01	1E+01
Ta-180M	W	7E+04	5E-01	9E-02	7E+03
	Y	6E+04	4E-01	1E-01	7E+03
Ta-182	W	3E+02	1E+00	5E-02	1E+01
	Y	1E+02	2E-01	2E-01	2E+01
Ta-182M	W	5E+05	3E-01	2E-01	9E+04
	Y	4E+05	1E-01	5E-01	2E+05
Ta-183	W	1E+03	3E-01	2E-01	2E+02
	Y	1E+03	2E-01	2E-01	2E+02
Ta-184	W	5E+03	8E-01	6E-02	3E+02
	Y	5E+03	8E-01	6E-02	3E+02
Ta-185	W	7E+04	1E-01	4E-01	3E+04
	Y	6E+04	3E-02	2E+00	1E+05
Ta-186	W	2E+05	1E-01	5E-01	9E+04
	Y	2E+05	4E-02	1E+00	3E+05
W-176	D	5E+04	2E+00	3E-02	2E+03
W-177	D	9E+04	1E+00	3E-02	3E+03
W-178	D	2E+04	7E-01	7E-02	1E+03
W-179	D	2E+06	5E-01	9E-02	2E+05
W-181	D	3E+04	6E-01	9E-02	3E+03
W-185	D	7E+03	2E-04	3E+02	2E+06
W-187	D	9E+03	4E-01	1E-01	1E+03
W-188	D	1E+03	2E-02	3E+00	3E+03
Re-177	D	3E+05	1E+00	5E-02	1E+04
	W	4E+05	6E-01	9E-02	4E+04
Re-178	D	3E+05	6E-01	9E-02	3E+04
	W	3E+05	2E-01	3E-01	8E+04
Re-181	D	9E+03	1E+00	3E-02	3E+02

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
	W	9E+03	1E+00	5E-02	4E+02
Re-182	D	1E+04	1E+00	3E-02	3E+02
	W	2E+04	2E+00	2E-02	5E+02
Re-182	D	2E+03	2E+00	3E-02	6E+01
	W	2E+03	1E+00	4E-02	8E+01
Re-184	D	4E+03	3E+00	2E-02	6E+01
	W	1E+03	8E-01	6E-02	6E+01
Re-184M	D	3E+03	2E+00	2E-02	7E+01
	W	4E+02	3E-01	2E-01	6E+01
Re-186	D	3E+03	8E-01	7E-02	2E+02
	W	2E+03	3E-01	2E-01	3E+02
Re-186M	D	2E+03	1E+00	4E-02	9E+01
	W	2E+02	1E-01	4E-01	9E+01
Re-187	D	8E+05	9E-01	6E-02	5E+04
	W	1E+05	1E-01	5E-01	5E+04
Re-188	D	3E+03	5E-01	9E-02	3E+02
	W	3E+03	3E-01	2E-01	5E+02
Re-188M	D	1E+05	4E-01	1E-01	1E+04
	W	1E+05	2E-01	3E-01	3E+04
Re-189	D	5E+03	6E-01	8E-02	4E+02
	W	4E+03	3E-01	2E-01	7E+02
Os-180	D	4E+05	2E+00	3E-02	1E+04
	W	5E+05	5E-01	1E-01	5E+04
	Y	5E+05	3E-01	2E-01	1E+05
Os-181	D	4E+04	2E+00	3E-02	1E+03
	W	5E+04	1E+00	4E-02	2E+03
	Y	4E+04	1E+00	4E-02	2E+03
Os-182	D	6E+03	2E+00	2E-02	1E+02
	W	4E+03	2E+00	3E-02	1E+02
	Y	4E+03	2E+00	3E-02	1E+02
Os-185	D	5E+02	3E+00	2E-02	8E+00
	W	8E+02	2E+00	3E-02	3E+01
	Y	8E+02	8E-01	6E-02	5E+01
Os-189M	D	2E+05	4E-01	1E-01	3E+04
	W	2E+05	9E-02	6E-01	1E+05
	Y	2E+05	6E-03	8E+00	2E+06
Os-191	D	2E+03	1E+00	4E-02	7E+01
	W	2E+03	4E-01	1E-01	3E+02
	Y	1E+03	1E-01	5E-01	5E+02
Os-191M	D	3E+04	1E+00	5E-02	1E+03
	W	2E+04	2E-01	3E-01	5E+03
	Y	2E+04	1E-01	5E-01	1E+04

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Os-193	D	5E+03	7E-01	7E-02	3E+02
	W	3E+03	1E-01	3E-01	1E+03
	Y	3E+03	9E-02	5E-01	2E+03
Os-194	D	4E+01	1E+00	3E-02	1E+00
	W	6E+01	6E-01	9E-02	5E+00
	Y	8E+00	3E-02	2E+00	2E+01
Ir-182	D	1E+05	8E-01	7E-02	7E+03
	W	2E+05	1E+00	4E-02	9E+03
	Y	1E+05	5E-01	9E-02	9E+03
Ir-184	D	2E+04	2E+00	3E-02	6E+02
	W	3E+04	1E+00	4E-02	1E+03
	Y	3E+04	1E+00	4E-02	1E+03
Ir-185	D	1E+04	2E+00	3E-02	3E+02
	W	1E+04	1E+00	5E-02	5E+02
	Y	1E+04	1E+00	5E-02	5E+02
Ir-186	D	8E+03	3E+00	2E-02	2E+02
	W	6E+03	2E+00	3E-02	2E+02
	Y	6E+03	2E+00	3E-02	2E+02
Ir-187	D	3E+04	2E+00	3E-02	8E+02
	W	3E+04	1E+00	4E-02	1E+03
	Y	3E+04	1E+00	3E-02	1E+03
Ir-188	D	5E+03	3E+00	2E-02	8E+01
	W	4E+03	2E+00	2E-02	8E+01
	Y	3E+03	2E+00	3E-02	8E+01
Ir-189	D	5E+03	2E+00	3E-02	1E+02
	W	4E+03	6E-01	9E-02	4E+02
	Y	4E+03	4E-01	1E-01	5E+02
Ir-190	D	9E+02	3E+00	2E-02	2E+01
	W	1E+03	2E+00	3E-02	3E+01
	Y	9E+02	1E+00	4E-02	4E+01
Ir-190M	D	2E+05	2E+00	2E-02	4E+03
	W	2E+05	1E+00	4E-02	8E+03
	Y	2E+05	1E+00	5E-02	1E+04
Ir-192	D	3E+02	2E+00	2E-02	6E+00
	W	4E+02	1E+00	5E-02	2E+01
	Y	2E+02	2E-01	2E-01	5E+01
Ir-192M	D	9E+01	2E+00	2E-02	2E+00
	W	2E+02	1E+00	3E-02	7E+00
	Y	2E+01	1E-01	3E-01	7E+00
Ir-194	D	3E+03	6E-01	9E-02	3E+02
	W	2E+03	1E-01	5E-01	1E+03
	Y	2E+03	5E-02	1E+00	2E+03

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Ir-194M	D	9E+01	3E+00	2E-02	2E+00
	W	2E+02	2E+00	3E-02	6E+00
	Y	1E+02	4E-01	1E-01	1E+01
Ir-195	D	4E+04	5E-01	1E-01	4E+03
	W	5E+04	2E-01	3E-01	1E+04
	Y	4E+04	5E-02	1E+00	4E+04
Ir-195M	D	2E+04	7E-01	7E-02	1E+03
	W	3E+04	5E-01	1E-01	3E+03
	Y	2E+04	3E-01	2E-01	4E+03
Pt-186	D	4E+04	2E+00	2E-02	1E+03
Pt-188	D	2E+03	3E+00	2E-02	3E+01
Pt-189	D	3E+04	2E+00	3E-02	8E+02
Pt-191	D	8E+03	2E+00	3E-02	2E+02
Pt-193	D	2E+04	1E+00	5E-02	1E+03
Pt-193M	D	6E+03	8E-01	6E-02	4E+02
Pt-195M	D	4E+03	9E-01	6E-02	2E+02
Pt-197	D	1E+04	6E-01	9E-02	9E+02
Pt-197M	D	4E+04	4E-01	1E-01	4E+03
Pt-199	D	1E+05	4E-01	1E-01	1E+04
Pt-200	D	3E+03	6E-01	9E-02	3E+02
Au-193	D	3E+04	2E+00	3E-02	8E+02
	W	2E+04	1E+00	5E-02	1E+03
	Y	2E+04	1E+00	5E-02	1E+03
Au-194	D	8E+03	4E+00	1E-02	1E+02
	W	5E+03	2E+00	2E-02	1E+02
	Y	5E+03	2E+00	2E-02	1E+02
Au-195	D	1E+04	2E+00	2E-02	2E+02
	W	1E+03	2E-01	3E-01	3E+02
	Y	4E+02	6E-02	8E-01	3E+02
Au-198	D	4E+03	2E+00	3E-02	1E+02
	W	2E+03	5E-01	1E-01	2E+02
	Y	2E+03	5E-01	1E-01	2E+02
Au-198M	D	3E+03	2E+00	2E-02	7E+01
	W	1E+03	5E-01	1E-01	1E+02
	Y	1E+03	5E-01	1E-01	1E+02
Au-199	D	9E+03	2E+00	3E-02	3E+02
	W	4E+03	3E-01	1E-01	6E+02
	Y	4E+03	3E-01	2E-01	7E+02
Au-200	D	6E+04	4E-01	1E-01	7E+03
	W	8E+04	2E-01	3E-01	2E+04
	Y	7E+04	4E-02	1E+00	9E+04

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Au-200M	D	4E+03	3E+00	2E-02	8E+01
	W	3E+03	1E+00	3E-02	1E+02
	Y	2E+04	1E+01	5E-03	1E+02
Au-201	D	2E+05	3E-01	2E-01	3E+04
	W	2E+05	9E-02	6E-01	1E+05
	Y	2E+05	1E-02	5E+00	9E+05
Hg-193	D	4E+04	1E+00	4E-02	2E+03
	W	4E+04	7E-01	7E-02	3E+03
	D	3E+04	7E-01	7E-02	2E+03
	V	6E+04	5E-01	1E-01	6E+03
Hg-193M	D	9E+03	2E+00	2E-02	2E+02
	W	8E+03	1E+00	4E-02	3E+02
	D	8E+03	1E+00	4E-02	3E+02
	V	1E+04	8E-01	6E-02	6E+02
Hg-194	D	4E+01	4E+00	1E-02	5E-01
	W	1E+02	3E+00	2E-02	2E+00
	D	3E+01	3E+00	1E-02	4E-01
	V	3E+01	4E+00	1E-02	4E-01
Hg-195	D	4E+04	2E+00	3E-02	1E+03
	W	3E+04	9E-01	6E-02	2E+03
	D	3E+04	1E+00	4E-02	1E+03
	V	5E+04	9E-01	6E-02	3E+03
Hg-195M	D	5E+03	2E+00	3E-02	2E+02
	W	4E+03	7E-01	7E-02	3E+02
	D	4E+03	1E+00	4E-02	2E+02
	V	6E+03	2E+00	3E-02	2E+02
Hg-197	D	1E+04	1E+00	3E-02	3E+02
	W	9E+03	6E-01	8E-02	7E+02
	D	8E+03	1E+00	4E-02	4E+02
	V	1E+04	1E+00	4E-02	4E+02
Hg-197M	D	7E+03	1E+00	4E-02	3E+02
	W	5E+03	3E-01	1E-01	7E+02
	D	5E+03	8E-01	6E-02	3E+02
	V	9E+03	1E+00	5E-02	4E+02
Hg-199M	D	1E+05	3E-01	1E-01	1E+04
	W	2E+05	2E-01	3E-01	5E+04
	D	8E+04	3E-01	2E-01	1E+04
	V	2E+05	5E-02	1E+00	2E+05
Hg-203	D	1E+03	2E+00	2E-02	2E+01
	W	1E+03	7E-01	7E-02	7E+01
	D	8E+02	3E+00	2E-02	1E+01
	V	8E+02	3E+00	2E-02	1E+01

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Tl-194	D	6E+05	1E+00	3E-02	2E+04
Tl-194M	D	2E+05	2E+00	3E-02	6E+03
Tl-195	D	1E+05	2E+00	3E-02	3E+03
Tl-197	D	1E+05	2E+00	3E-02	3E+03
Tl-198	D	3E+04	3E+00	2E-02	6E+02
Tl-198M	D	5E+04	2E+00	3E-02	1E+03
Tl-199	D	8E+04	2E+00	2E-02	2E+03
Tl-200	D	1E+04	4E+00	1E-02	1E+02
Tl-201	D	2E+04	3E+00	2E-02	3E+02
Tl-202	D	5E+03	4E+00	1E-02	6E+01
Tl-204	D	2E+03	3E+00	2E-02	3E+01
Pb-195M	D	2E+05	2E+00	3E-02	7E+03
Pb-198	D	6E+04	2E+00	3E-02	2E+03
Pb-199	D	7E+04	2E+00	2E-02	2E+03
Pb-200	D	6E+03	2E+00	3E-02	2E+02
Pb-201	D	2E+04	2E+00	3E-02	5E+02
Pb-202	D	5E+01	2E+00	3E-02	1E+00
Pb-202M	D	3E+04	3E+00	2E-02	5E+02
Pb-203	D	9E+03	1E+00	4E-02	3E+02
Pb-205	D	1E+03	2E-01	3E-01	3E+02
Pb-209	D	6E+04	3E-01	2E-01	9E+03
Pb-210	D	2E-01	2E-01	2E-01	4E-02
Pb-211	D	6E+02	4E-01	1E-01	8E+01
Pb-212	D	3E+01	4E-01	1E-01	4E+00
Pb-214	D	8E+02	5E-01	1E-01	8E+01
Bi-200	D	8E+04	1E+00	4E-02	3E+03
	W	1E+05	1E+00	4E-02	4E+03
Bi-201	D	3E+04	1E+00	4E-02	1E+03
	W	4E+04	1E+00	5E-02	2E+03
Bi-202	D	4E+04	2E+00	3E-02	1E+03
	W	8E+04	1E+00	4E-02	3E+03
Bi-203	D	7E+03	2E+00	3E-02	2E+02
	W	6E+03	2E+00	3E-02	2E+02
Bi-205	D	3E+03	2E+00	2E-02	7E+01
	W	1E+03	1E+00	4E-02	4E+01
Bi-206	D	1E+03	1E+00	4E-02	4E+01
	W	9E+02	2E+00	3E-02	3E+01
Bi-207	D	2E+03	2E+00	3E-02	6E+01
	W	4E+02	7E-01	7E-02	3E+01
Bi-210	D	2E+02	1E-01	3E-01	7E+01
	W	3E+01	7E-03	7E+00	2E+02
Bi-210M	D	5E+00	2E-01	3E-01	1E+00
	W	7E-01	8E-03	6E+00	4E+00

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Bi-212	D	2E+02	1E-01	4E-01	8E+01
	W	3E+02	5E-02	1E+00	3E+02
Bi-213	D	3E+02	1E-01	3E-01	1E+02
	W	4E+02	6E-02	9E-01	4E+02
Bi-214	D	8E+02	2E-01	3E-01	3E+02
	W	9E-02	5E-06	1E+04	9E+02
Po-203	D	6E+04	2E+00	3E-02	2E+03
	W	9E+04	2E+00	3E-02	2E+03
Po-205	D	4E+04	2E+00	2E-02	9E+02
	W	7E+04	2E+00	3E-02	2E+03
Po-207	D	3E+04	3E+00	2E-02	5E+02
	W	3E+04	2E+00	2E-02	7E+02
Po-210	D	6E-01	9E-01	6E-02	3E-02
	W	6E-01	3E-01	2E-01	1E-01
At-207	D	3E+03	1E+00	4E-02	1E+02
	W	2E+03	3E-01	2E-01	4E+02
At-211	D	8E+01	2E+00	3E-02	3E+00
	W	5E+01	4E-01	1E-01	6E+00
Fr-222	D	5E+02	6E-01	8E-02	4E+01
Fr-223	D	8E+02	4E+00	1E-02	9E+00
Ra-223	W	7E-01	9E-02	6E-01	4E-01
Ra-224	W	2E+00	1E-01	4E-01	9E-01
Ra-225	W	7E-01	8E-02	6E-01	4E-01
Ra-226	W	6E-01	2E-01	2E-01	1E-01
Ra-227	W	1E+04	8E-02	6E-01	6E+03
Ra-228	W	1E+00	7E-01	7E-02	7E-02
Ac-224	D	3E+01	7E-04	7E+01	2E+03
	W	5E+01	1E-03	4E+01	2E+03
	Y	5E+01	1E-03	4E+01	2E+03
Ac-225	D	3E-01	5E-05	9E+02	3E+02
	W	6E-01	1E-04	5E+02	3E+02
	Y	6E-01	1E-04	5E+02	3E+02
Ac-226	D	3E+00	1E-04	5E+02	2E+03
	W	5E+00	2E-04	2E+02	1E+03
	Y	5E+00	3E-04	2E+02	9E+02
Ac-227	D	4E-04	5E-05	1E+03	4E-01
	W	2E-03	6E-05	8E+02	2E+00
	Y	4E-03	5E-05	1E+03	4E+00
Ac-228	D	9E+00	7E-04	8E+01	7E+02
	W	4E+01	2E-03	2E+01	1E+03
	Y	4E+01	2E-03	2E+01	9E+02
Th-226	W	2E+02	1E-01	4E-01	8E+01
	Y	1E+02	3E-03	1E+01	1E+03

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Th-227	W	3E-01	6E-02	8E-01	3E-01
	Y	3E-01	3E-03	2E+01	5E+00
Th-228	W	1E-02	5E-02	1E+00	1E-02
	Y	2E-02	2E-02	3E+00	6E-02
Th-229	W	9E-04	9E-03	5E+00	5E-03
	Y	2E-03	9E-03	6E+00	1E-02
Th-230	W	6E-03	9E-03	6E+00	3E-02
	Y	2E-02	1E-02	4E+00	8E-02
Th-231	W	6E+03	7E-02	7E-01	4E+03
	Y	6E+03	4E-02	1E+00	8E+03
Th-232	W	1E-03	3E-03	2E+01	2E-02
	Y	3E-03	7E-03	8E+00	2E-02
Th-234	W	2E+02	8E-02	6E-01	1E+02
	Y	2E+02	9E-03	6E+00	1E+03
Pa-227	W	1E+02	1E-05	5E+03	5E+05
	Y	1E+02	1E-05	4E+03	4E+05
Pa-228	W	1E+01	3E-03	2E+01	2E+02
	Y	1E+01	3E-03	2E+01	2E+02
Pa-230	W	5E+00	3E-03	2E+01	9E+01
	Y	4E+00	2E-03	2E+01	9E+01
Pa-231	W	2E-03	4E-05	1E+03	3E+00
	Y	4E-03	3E-05	2E+03	6E+00
Pa-232	W	2E+01	6E-03	9E+00	2E+02
	Y	6E+01	2E-02	3E+00	2E+02
Pa-233	W	7E+02	1E-01	3E-01	2E+02
	Y	6E+02	1E-01	4E-01	2E+02
Pa-234	W	8E+03	8E-01	6E-02	5E+02
	Y	7E+03	9E-01	6E-02	4E+02
U-230	D	4E-01	1E-01	4E-01	2E-01
	W	4E-01	3E-02	2E+00	8E-01
	Y	3E-01	1E-03	5E+01	2E+01
U-231	D	8E+03	5E-01	1E-01	9E+02
	W	6E+03	3E-01	2E-01	9E+02
	Y	5E+03	3E-01	2E-01	9E+02
U-232	D	2E-01	6E-02	9E-01	2E-01
	W	4E-01	4E-02	1E+00	5E-01
	Y	8E-03	5E-04	1E+02	8E-01
U-233	D	1E+00	9E-02	5E-01	5E-01
	W	7E-01	2E-02	3E+00	2E+00
	Y	4E-02	4E-04	1E+02	5E+00
U-234	D	1E+00	9E-02	5E-01	5E-01
	W	7E-01	2E-02	3E+00	2E+00
	Y	4E-02	4E-04	1E+02	5E+00

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
U-235	D	1E+00	9E-02	6E-01	6E-01
	W	8E-01	2E-02	2E+00	2E+00
	Y	4E-02	4E-04	1E+02	5E+00
U-236	D	1E+00	9E-02	6E-01	6E-01
	W	8E-01	2E-02	2E+00	2E+00
	Y	4E-02	4E-04	1E+02	5E+00
U-237	D	3E+03	4E-01	1E-01	3E+02
	W	2E+03	3E-01	2E-01	4E+02
	Y	2E+03	3E-01	2E-01	4E+02
U-238	D	1E+00	8E-02	6E-01	6E-01
	W	8E-01	2E-02	3E+00	2E+00
	Y	4E-02	4E-04	1E+02	6E+00
U-239	D	2E+05	4E-01	1E-01	3E+04
	W	2E+05	2E-01	2E-01	5E+04
	Y	2E+05	2E-01	3E-01	7E+04
U-240	D	4E+03	5E-01	1E-01	4E+02
	W	3E+03	2E-01	3E-01	8E+02
	Y	2E+03	1E-01	4E-01	9E+02
Np-232	W	2E+03	1E-03	5E+01	1E+05
Np-233	W	3E+06	5E-01	1E-01	3E+05
Np-234	W	3E+03	2E+00	3E-02	8E+01
Np-235	W	8E+02	6E-03	8E+00	7E+03
Np-236	W	2E-02	4E-04	1E+02	3E+00
Np-236	W	3E+01	6E-04	9E+01	3E+03
Np-237	W	4E-03	1E-04	4E+02	1E+00
Np-238	W	6E+01	1E-02	4E+00	2E+02
Np-239	W	2E+03	2E-01	3E-01	5E+02
Np-240	W	8E+04	4E-01	1E-01	9E+03
Pu-234	W	2E+02	3E-02	2E+00	4E+02
	Y	2E+02	1E-02	4E+00	8E+02
Pu-235	W	3E+06	3E-01	2E-01	5E+05
	Y	3E+06	1E-01	4E-01	1E+06
Pu-236	W	2E-02	2E-04	3E+02	6E+00
	Y	4E-02	1E-04	4E+02	2E+01
Pu-237	W	3E+03	2E-01	2E-01	7E+02
	Y	3E+03	2E-01	3E-01	9E+02
Pu-238	W	7E-03	2E-05	2E+03	1E+01
	Y	2E-02	3E-05	2E+03	4E+01
Pu-239	W	6E-03	2E-05	2E+03	1E+01
	Y	2E-02	3E-05	2E+03	4E+01
Pu-240	W	6E-03	2E-05	2E+03	1E+01
	Y	2E-02	3E-05	2E+03	4E+01

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Pu-241	W	3E-01	1E-05	5E+03	1E+03
	Y	8E-01	2E-05	3E+03	2E+03
Pu-242	W	7E-03	2E-05	2E+03	2E+01
	Y	2E-02	3E-05	2E+03	4E+01
Pu-243	W	4E+04	1E-01	5E-01	2E+04
	Y	4E+04	6E-02	8E-01	3E+04
Pu-244	W	7E-03	4E-04	1E+02	9E-01
	Y	2E-02	5E-04	1E+02	2E+00
Pu-245	W	5E+03	3E-01	2E-01	9E+02
	Y	4E+03	2E-01	2E-01	9E+02
Pu-246	W	3E+02	2E-01	2E-01	7E+01
	Y	3E+02	2E-01	3E-01	8E+01
Am-237	W	3E+05	6E-01	8E-02	2E+04
Am-238	W	3E+03	2E-02	3E+00	8E+03
Am-239	W	1E+04	4E-01	1E-01	1E+03
Am-240	W	3E+03	1E+00	4E-02	1E+02
Am-241	W	6E-03	3E-05	2E+03	9E+00
Am-242M	W	6E-03	1E-05	4E+03	2E+01
Am-242	W	8E+01	1E-03	5E+01	4E+03
Am-243	W	6E-03	2E-04	3E+02	2E+00
Am-244M	W	4E+03	2E-03	3E+01	1E+05
Am-244	W	2E+02	2E-02	3E+00	6E+02
Am-245	W	8E+04	9E-02	6E-01	4E+04
Am-246M	W	2E+05	2E-01	2E-01	4E+04
Am-246	W	1E+05	2E-01	3E-01	3E+04
Cm-238	W	1E+03	8E-02	6E-01	6E+02
Cm-240	W	6E-01	2E-03	3E+01	2E+01
Cm-241	W	3E+01	2E-02	3E+00	8E+01
Cm-242	W	3E-01	1E-03	5E+01	1E+01
Cm-243	W	9E-03	1E-04	4E+02	4E+00
Cm-244	W	1E-02	4E-05	1E+03	1E+01
Cm-245	W	6E-03	8E-05	6E+02	4E+00
Cm-246	W	6E-03	4E-05	1E+03	7E+00
Cm-247	W	6E-03	2E-04	2E+02	1E+00
Cm-248	W	2E-03	3E-03	2E+01	4E-02
Cm-249	W	2E+04	1E-02	3E+00	7E+04
Cm-250	W	3E-04	3E-03	2E+01	5E-03
Bk-245	W	1E+03	2E-01	3E-01	3E+02
Bk-246	W	3E+03	1E+00	5E-02	1E+02
Bk-247	W	4E-03	6E-05	9E+02	4E+00
Bk-249	W	2E+00	2E-04	2E+02	5E+02
Bk-250	W	3E+02	6E-03	8E+00	2E+03

Table E2.(cont.). Radiation doses to the uterus from inhalation.

Nuclide	Class	ALI (μCi)	Dose per ALI (rem)	Fraction ALI for 50 mrem	Activity for 50 mrem (μCi)
Cf-244	W	6E+02	5E-02	1E+00	6E+02
	Y	6E+02	3E-03	2E+01	1E+04
Cf-246	W	9E+00	2E-02	3E+00	2E+01
	Y	9E+00	1E-03	4E+01	4E+02
Cf-248	W	6E-02	2E-04	2E+02	1E+01
	Y	1E-01	5E-05	1E+03	1E+02
Cf-249	W	4E-03	2E-04	3E+02	1E+00
	Y	1E-02	2E-04	3E+02	3E+00
Cf-250	W	9E-03	9E-05	6E+02	5E+00
	Y	3E-02	1E-04	4E+02	1E+01
Cf-251	W	4E-03	8E-05	6E+02	3E+00
	Y	1E-02	8E-05	6E+02	6E+00
Cf-252	W	2E-02	2E-03	3E+01	6E-01
	Y	3E-02	9E-04	6E+01	2E+00
Cf-253	W	2E+00	7E-04	7E+01	1E+02
	Y	2E+00	4E-05	1E+03	2E+03
Cf-254	W	2E-02	8E-03	6E+00	1E-01
	Y	2E-02	5E-03	1E+01	2E-01
Es-250	W	5E+02	2E-03	2E+01	1E+04
Es-251	W	9E+02	5E-02	1E+00	1E+03
Es-253	W	1E+00	3E-03	2E+01	2E+01
Es-254M	W	1E+01	2E-02	3E+00	3E+01
Es-254	W	7E-02	7E-04	7E+01	5E+00
Fm-252	W	1E+01	2E-02	2E+00	2E+01
Fm-253	W	1E+01	4E-03	1E+01	1E+02
Fm-254	W	9E+01	8E-02	6E-01	6E+01
Fm-255	W	2E+01	4E-02	1E+00	2E+01
Fm-257	W	2E-01	9E-04	6E+01	1E+01
Md-257	W	8E+01	1E-02	5E+00	4E+02
Md-258	W	2E-01	1E-03	5E+01	1E+01

NRC FORM 335 (2-89) NRCM 1102, 3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER (Assigned by NRC. Add Vol., Supp., Rev., and Addendum Numbers, if any.)

NUREG/CR-5631
PNL-7445
Rev. 2

2. TITLE AND SUBTITLE

Contribution of Maternal Radionuclide Burdens to Prenatal Radiation Doses

3. DATE REPORT PUBLISHED

MONTH	YEAR
May	1996

4. FIN OR GRANT NUMBER

5. AUTHOR(S)

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6. TYPE OF REPORT

Technical

7. PERIOD COVERED *(Inclusive Dates)*

8. PERFORMING ORGANIZATION – NAME AND ADDRESS *(If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)*

Pacific Northwest National Laboratory
Richland, Washington 99352

*Westinghouse Hanford Company
Richland, WA 99352

9. SPONSORING ORGANIZATION – NAME AND ADDRESS *(If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)*

Division of Regulatory Applications
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

10. SUPPLEMENTARY NOTES

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11. ABSTRACT *(200 words or less)*

This report describes approaches to calculating and expressing radiation doses to the embryo/fetus from internal radionuclides. Information for occupationally and medically significant radioelements was used to derive biokinetic transfer models and integrated with metabolic patterns. Placental transfer and radioactivty levels in the embryo/fetus were calculated as a function of stage of pregnancy and time after administration and are given as tables of deposition and retention in the embryo/fetus. Methodologies described by MIRD were extended to calculate radiation absorbed doses to the embryo/fetus using a scenario that assumed injection of a bolus into the woman's blood. Calculations were performed for administration at successive months of pregnancy to accommodate stage dependence of geometric relationships and biological behaviors of radionuclides. The gestational-stage-dependent dosimetric dose factors are based on radiation absorbed doses. Multiplication by appropriate quality factors convert these to dose equivalent, the most common quantity for stating prenatal dose limits in the United States. The dose factor tabulations are supplemented with tables of correlations and surrogate dose factors.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

radionuclide intakes by pregnant women
radiation doses to embryo/fetus
placental transfer radionuclides
prenatal dose calculations
radionuclide metabolism in pregnancy

13. AVAILABILITY STATEMENT

Unlimited

14. SECURITY CLASSIFICATION

(This Page) Unclassified

(This Report) Unclassified

15. NUMBER OF PAGES

16. PRICE

NRC FORM 335 (2-89)

F-53

Printed on recycled paper

Federal Recycling Program

E-54