Inference of Radionuclide Intakes and Doses from Workplace Indicators, Air Monitoring and Bioassay Results

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Tony James, Alan Birchall, and Dan Strom
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Some of the AAHP Course Participants

The course participant should understand

- the basic concepts of intakes of radioactive material due to inhalation, ingestion, entry through intact skin, or through a wound or injection
- the basic quantities and units
- the measurements and other data used to infer various dose quantities following intakes
- the elementary procedures for inferring intakes and doses
- the uncertainties and limitations inherent in the use of bioassay and workplace indicators for internal dosimetry

Recurrent Themes

- forward v. backward problems
  - intake $\rightarrow$ bioassay quantities
  - intake $\rightarrow$ dose
  - bioassay quantities $\rightarrow$ intake $\rightarrow$ dose
- variability
- uncertainty
- models
- calculational tools

Radiation Protection: The Big Picture

- Limit risk of stochastic health effects
  - cancer
  - heritable ill-health
  - non-cancer endpoints (heart disease, stroke, digestive diseases, & respiratory diseases; Preston et al. 2003)
- Prevent deterministic effects
- Deposition of ionizing radiation energy leads to
  - increased probability of stochastic health effects or
  - increased severity of deterministic health effects

Risk, Dose, Intake, and "Exposure"

- Radiation Protection Goal: Limit or prevent health effects
- Means: Limit irradiation from external sources and limit intakes and ontakes of radioactive material by limiting exposure
- Value judgment: primary and secondary dose limits and constraints
- Measure of achievement of goal: various kinds of dose

Absorbed Dose

- easy to define (ICRU 60)…

  The **absorbed dose**, D, is the quotient of $\mathrm{d}\bar{\epsilon}$ by $\mathrm{d}m$, where $\mathrm{d}\bar{\epsilon}$ is the mean energy imparted to matter of mass $\mathrm{d}m$, thus

  $$D = \frac{\mathrm{d}\bar{\epsilon}}{\mathrm{d}m}\,.$$

  Unit: $\mathrm{J\,kg^{-1}}$

  The special name for the unit of absorbed dose is gray (Gy).

- …but often harder to measure, infer, or invent!

Dosimetry

- "dose" + metry
  - root is *metron* (Greek: to measure)
- current usage: any dose number is presumed to be the result of "dosimetry"
- thesis
  - If measurement or observation is the dominant activity, and
  - uncertainties in results are predominantly due to measurement uncertainty,

  use the word "dosimetry." Otherwise, maybe new terms would be more appropriate!

Measuring the Quantity of Radiation

- observation of biological response (e.g., erythema, chromosome aberrations)
- cloud chambers
- film blackening
- appearance or sound of bubbles in superheated liquids
- analysis of activation or fission product yield
- scintillations
- Cherenkov radiation (light)
- thermoluminescence (TL) or optically stimulated luminescence (OSL)
- observation of radiation damage (e.g., chemically etching damage in film, radiochromic changes, thermal and electrical conductivity changes)
- chemical changes as quantitated by light absorption or nuclear magnetic resonance
- measurement of electric charge or current in solids (Ge and Si) or gases such as xenon, P10, or air, and
- calorimetry

Dosimetry for External Irradiation

- most measurements are *outside* of the human body
- want to know dose inside or at surface
- external irradiation: few inferential steps
  - absorption
  - albedo
  - spectrum changes
  - based on types, energies, directions of incident radiation
  - assumptions about person wearing dosimeter
  - neutrons still a challenge
- irradiation following intake or ontake of radioactive material
  - surgical implantation of dosimeters? no.
  - inference

Dosinference for Internal Irradiation

- blend of “dose” + “inference” (Strom 2002)
- uncertainties associated with inferential steps dwarf uncertainties of measurement steps
  - exceptions: ^{3}H and alkali metals, e.g., ^{137}Cs
- measurements tend to be of dose-rate like quantities, rather than dose-like quantities
  - rate of photon emission from regions of body (in vivo counting)
  - count rate or numbers of atoms (TIMS, ICP-MS) in excreta
  - count rates from air samples
  - exception: chromosome aberrations
- infer activity (and its uncertainty) in organs and tissues from measurements and biokinetic models

Non-Measured Inputs to Dosinference

- knowledge or guesses of time course and route(s) of intake
- identity of all radionuclides and proportions in a mixture
- particle size distribution and transportability for inhalation
- gastrointestinal (GI) tract absorption
- chemical and physical form for ingestion, injection, wound, or dermal absorption from an ontake
- true daily excretion rate for in vitro bioassay (non 24-h samples)
- biokinetic models
  - Reference Man usually used, not individual data
  - individual chest wall thickness and ^{40}K corrections
  - site-specific solubility, e.g., Y-12's Class Q uranium
- air sample data, stay time, respiratory protection data, respiratory tract model

What's Uncertain When Inferring Intake?

- Circumstances
  - time or time course of intake
  - route(s)
- Material characteristics
  - radionuclide mixture
  - particle size and shape
  - chemical form(s) and transportability (S, M, F, or real)
- Measurements
  - counting or measurement uncertainty
  - 24-h sample? simulated? adulterated or contaminated?
- Biological variability
  - availability and validity of model(s)
  - systematic differences between individual and models
  - among bioassay samples or measurements
- Interpretation
  - interference from environmental exposures
  - prior intakes

Dosinference from Radon Progeny

- short-lived decay products of radon & thoron
  - particle size
  - equilibrium factor
  - unattached fraction
  - smoking
  - nose breathing
  - level of exertion
  - diurnal variations
- ICRP (1995) “dose conversion convention”
  - 5 mSv/WLM rather than 12.5, based on epidemiology

Doswaggery

- blend of “dose” + “swag” (Strom 2002)
  - root is acronym for *scientific wild assumption guess* (US popular usage)
  - examples of *swags*
    - predicting the weather two weeks in advance
    - predicting the value of the stock market in a year
- uncertainties in assumptions dwarf even the uncertainties in the inferential steps, much less the uncertainties in the measurements
- may not rely on measurement at all, or may rely on measurements only tenuously associated with individual for whom a dose is being inferred

Imputed Values

- to "impute" has taken the meaning to "make up a number"
  - Reissland (1982) used the term "notional dose" for what today is termed an "imputed dose"
- lost or damaged external dosimeter, spoiled bioassay or air sample
- imputation commonly done for regulatory compliance
  - interview worker & colleagues, dose rates, time-in-area
  - average preceding and subsequent dosimeter results
- can be very accurate
  - CARI-6 for air travel

  http://www.cami.jccbi.gov/AAM-600/610/600Radio.html
- can be done for "less than detectable" results

Doswaggery to Impute Doses

- not all imputed doses are doswags
  - production lines
  - radiology department with steady caseload
  - careful dose reconstructions such as RERF DS02
- examples of doswaggery:
  - assigning historical uranium miners potential alpha energy exposures (J h m^{-3} or WLM) based on measurements in similar mines
  - historical dose reconstruction for litigation in U mining, milling, refining in absence of any concurrent workplace measurements
  - some projections of future (50-year "committed") doses
  - population doses from high level waste repositories

Uncertainty Is Not *Necessarily* Error

- "The result of a measurement (after correction) can unknowably be very close to the value of the measurand (and hence have a negligible error) even though it may have a large uncertainty. Thus the uncertainty of the result of a measurement should not be confused with the remaining unknown error." – ISO (1995)
- a doswag *may* be accurate but *is* highly uncertain
- long-range weather forecasts are sometimes correct!

Word Choice Based on Uncertainty

Term	Typical Dominant Uncertainty				Ratio of 97.5%ile to 2.5%ile of Inferred Dose
	Measure-ments	Models	Model Parameters	Imputed Data	
Dosimetry	✓✓	✓	~	~	**1.01 to 2**
Dosinference	✓	✓✓	✓✓	~	**2 to 20**
Doswaggery	~	✓	✓	✓✓	**>20**

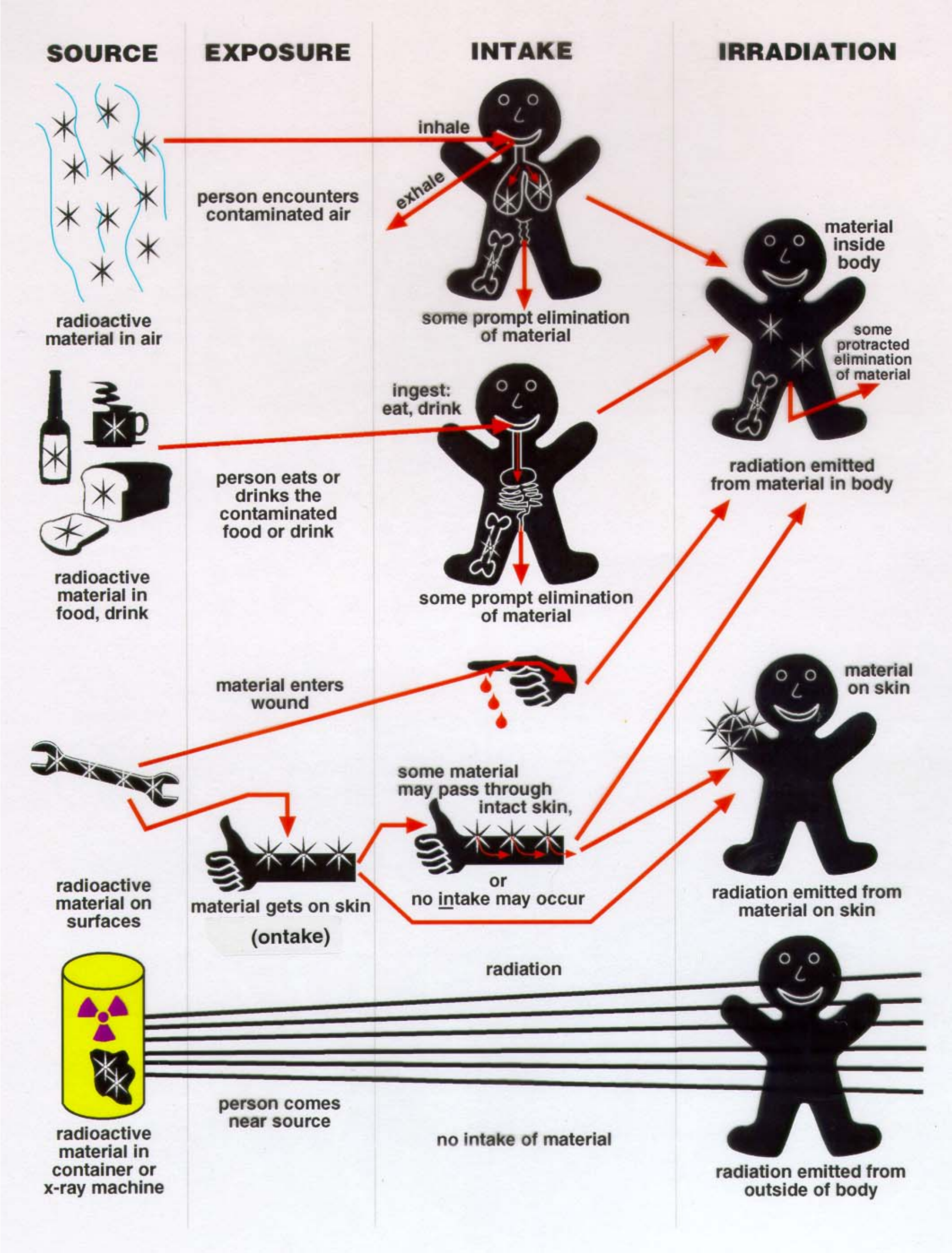
✓ denotes important; ✓✓ denotes very important; ~ relatively trivial

Calling a Spade a Spade…

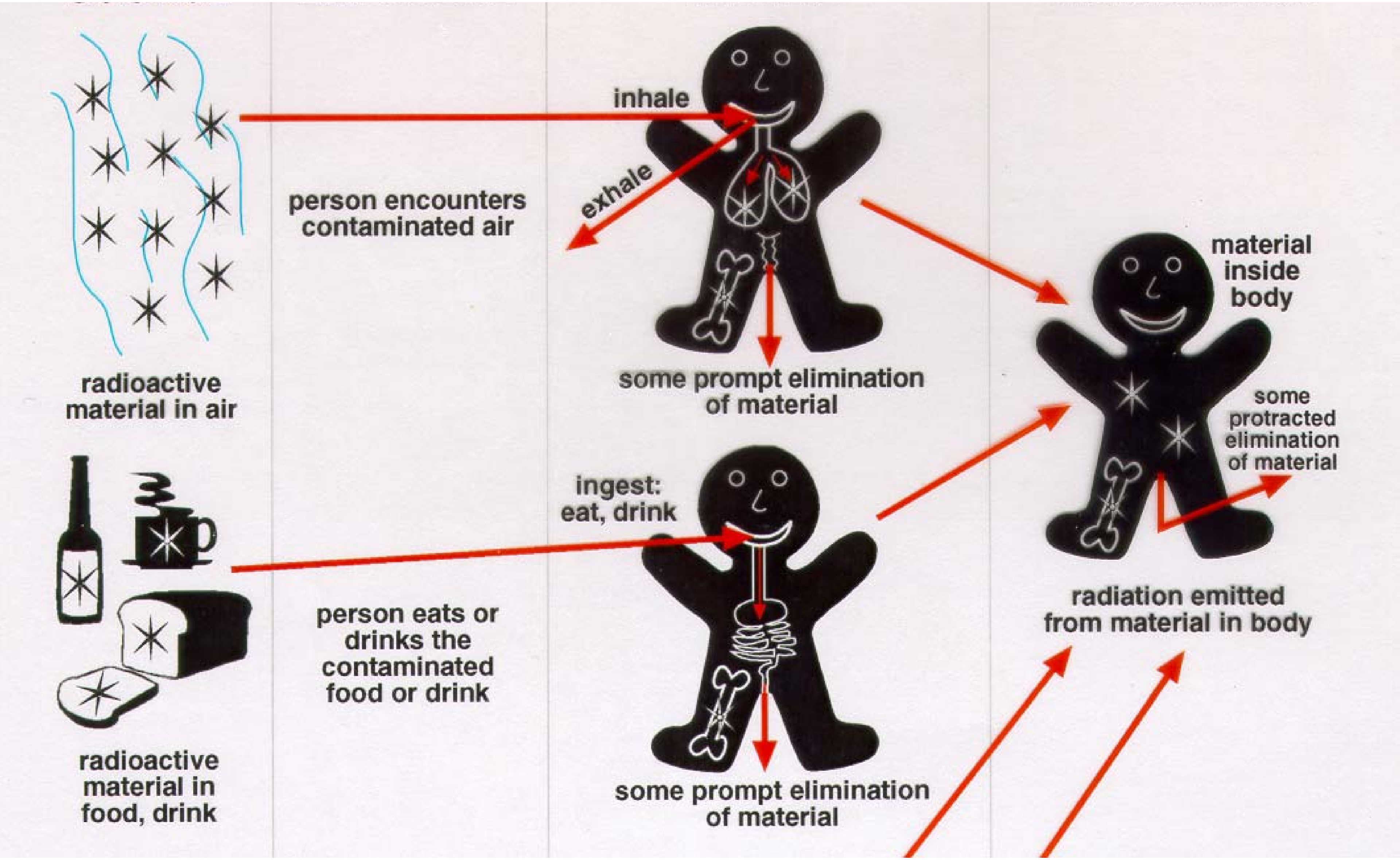
- maybe it's time to choose different words when the dose in question is measured, inferred, or essentially assumed
- *dosimetry* when measurement uncertainty predominates
- *dosinference* when model parameter uncertainty predominates
- *doswaggery* when assumption or imputed value uncertainty predominates

Sources, Exposures, Intakes & Ontakes, and Irradiation

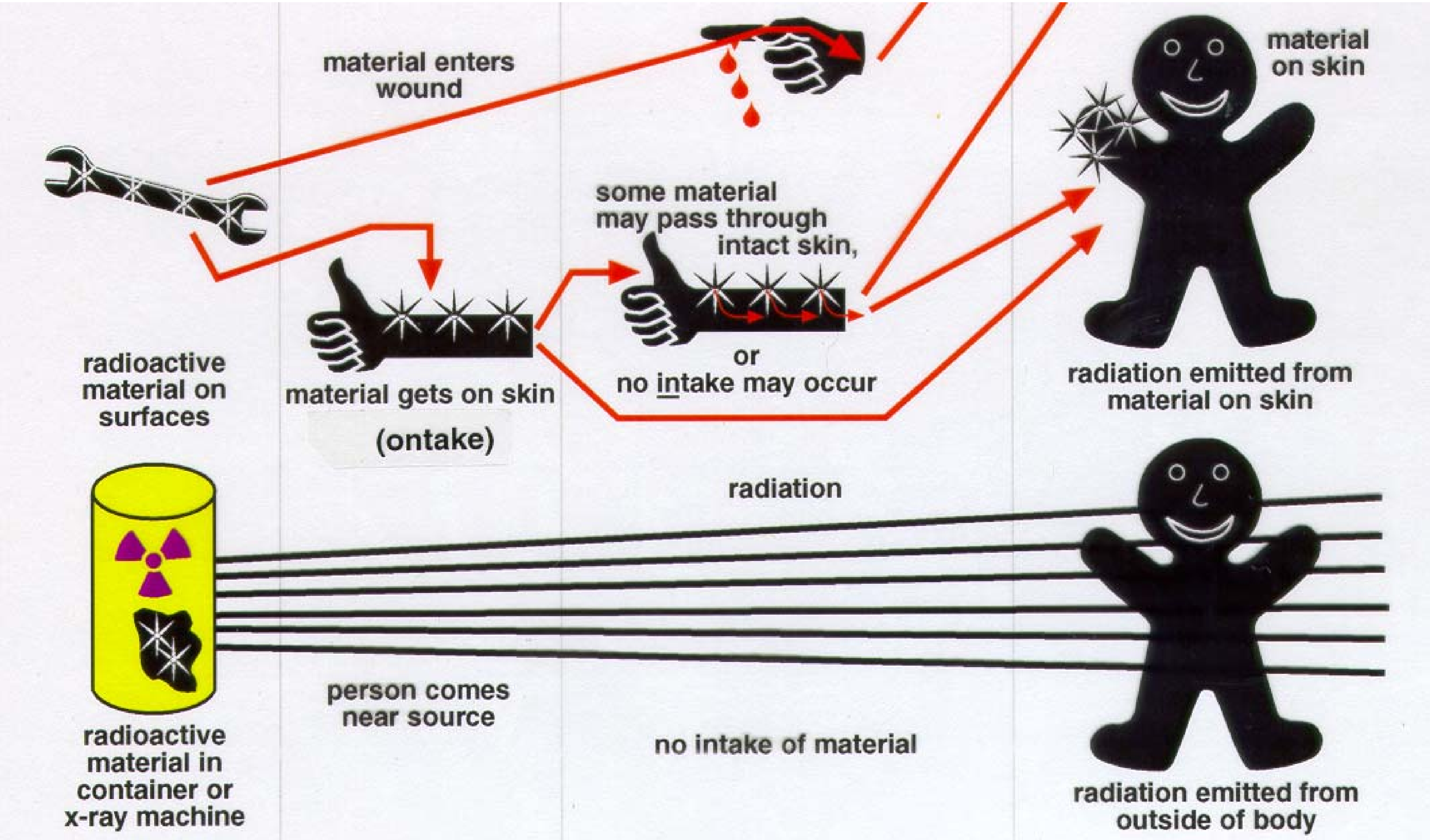
Strom & Watson 2002



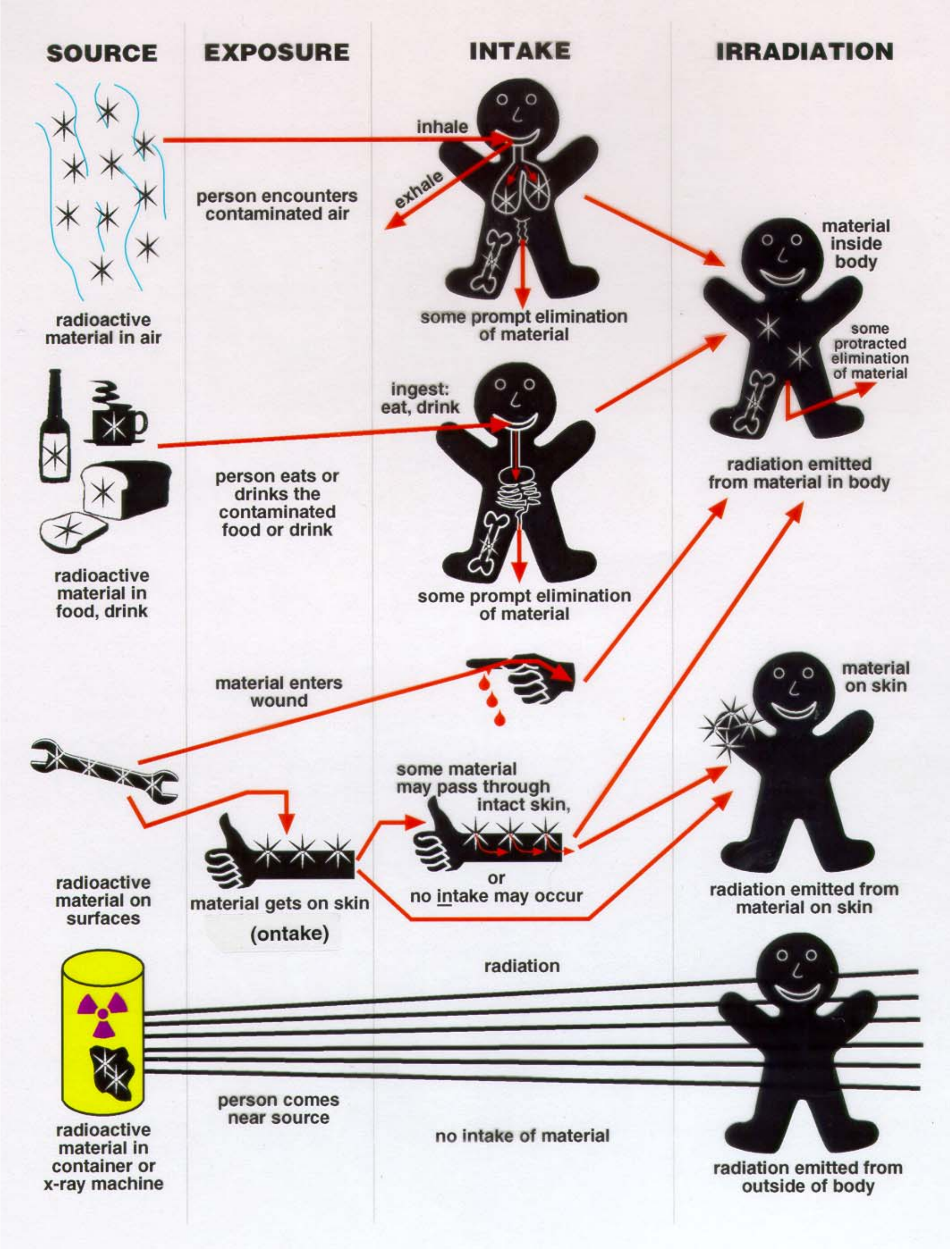
Source Exposure Intake Irradiation



Source Exposure Intake Irradiation



Any place you can intervene on an arrow, you can do radiation protection.



Exposed Portions of the Body

- uniform, whole-body irradiation is the exception:
  - ^{3}H
  - alkali metals: ^{22}Na, ^{40}K, ^{137}Cs
- self- & cross-irradiation: organ or tissue irradiated by radioactivity within organ or tissue, & by radioactivity elsewhere in body
- non-uniform, partial body irradiation is the rule:
  - radioactive iodines (e.g., ^{131}I, ^{125}I, ^{123}I) target the thyroid against a concentration gradient of as much as 500:1
  - calcium analogs (Ca, ^{90}Sr, ^{226}Ra) are bone-seekers
  - heavy metals (e.g., Th, U, Pu, Am) target liver, bone, blood-forming organs
  - insoluble forms may target lung (if inhaled) & gastrointestinal (GI) tract (if inhaled and cleared to GI tract or if ingested)
  - short-lived forms may target lung or GI tract and decay prior to translocation
- differences in tissue or organ radiosensitivity

Nature of the Irradiation

- Fate of radioactive material:
  - *intake* (route): getting into the body
  - *uptake*: getting from lung, GI tract, or wound into systemic circulation
  - *translocation:* moving from one part of the body to another, or within organs (e.g., bone remodeling)
  - *retention*: staying somewhere for a while
  - *elimination*: removal from the body
    - radioactive decay
    - biological clearance
- ingestion: solubility
- inhalation: transportability
- metabolism: changing chemical, physical form; relocation

Occupational Internal Dosimetry Programs

- workplace monitoring and workplace indicators
- personnel monitoring: personal air samplers
- baseline, routine, special, and termination bioassays
- ensuring worker selection and participation
- performance criteria: minimum detectable activity, concentration, intake, and dose
- quality assurance of radiobioassay laboratory (HPS-ANSI N13.30-1996)
- timely sample analysis (routine, special, emergency)
- analysis of bioassay and other results
- recording and reporting
- ANSI N13.39-2001, Strom 1994

Quantity of Irradiation: Absorbed Dose

1. How many atoms undergo radioactive transitions?
2. How much energy is emitted per transition (in joules)?
3. What fraction of that energy is absorbed?
4. In what mass is the energy absorbed (in kilograms)?

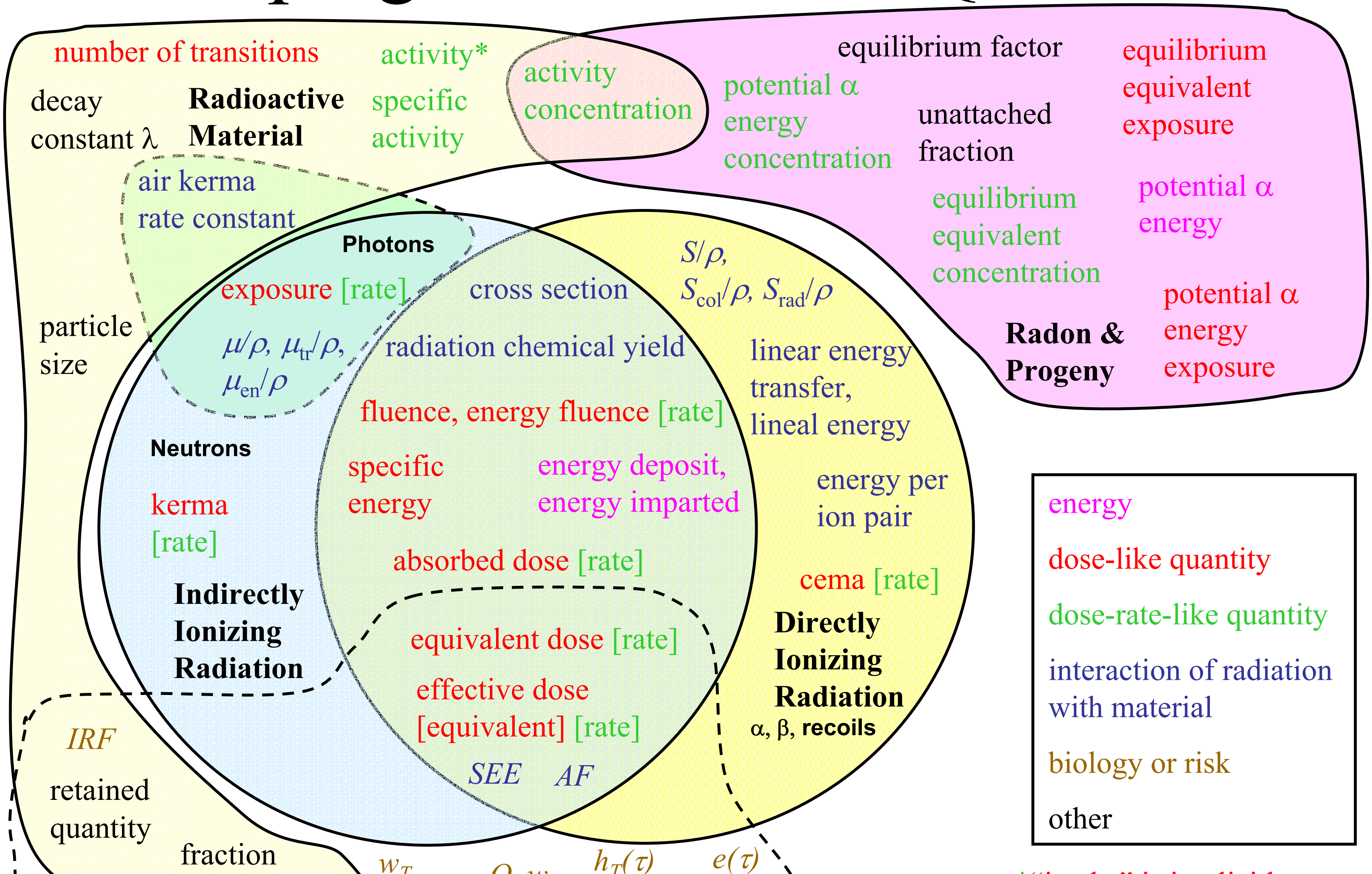
$$\mathit{Absorbed\ Dose} = \frac{[\mathit{No.\ of\ Transitions}][\mathit{Energy}/\mathit{Transition}][\mathit{Fraction\ Absorbed}]}{[\mathit{Mass\ in\ Which\ Energy\ Is\ Absorbed}]}$$

5. Sum dose in each target tissue or organ over contributions from each source tissue or organ

Types of Radiation Quantities

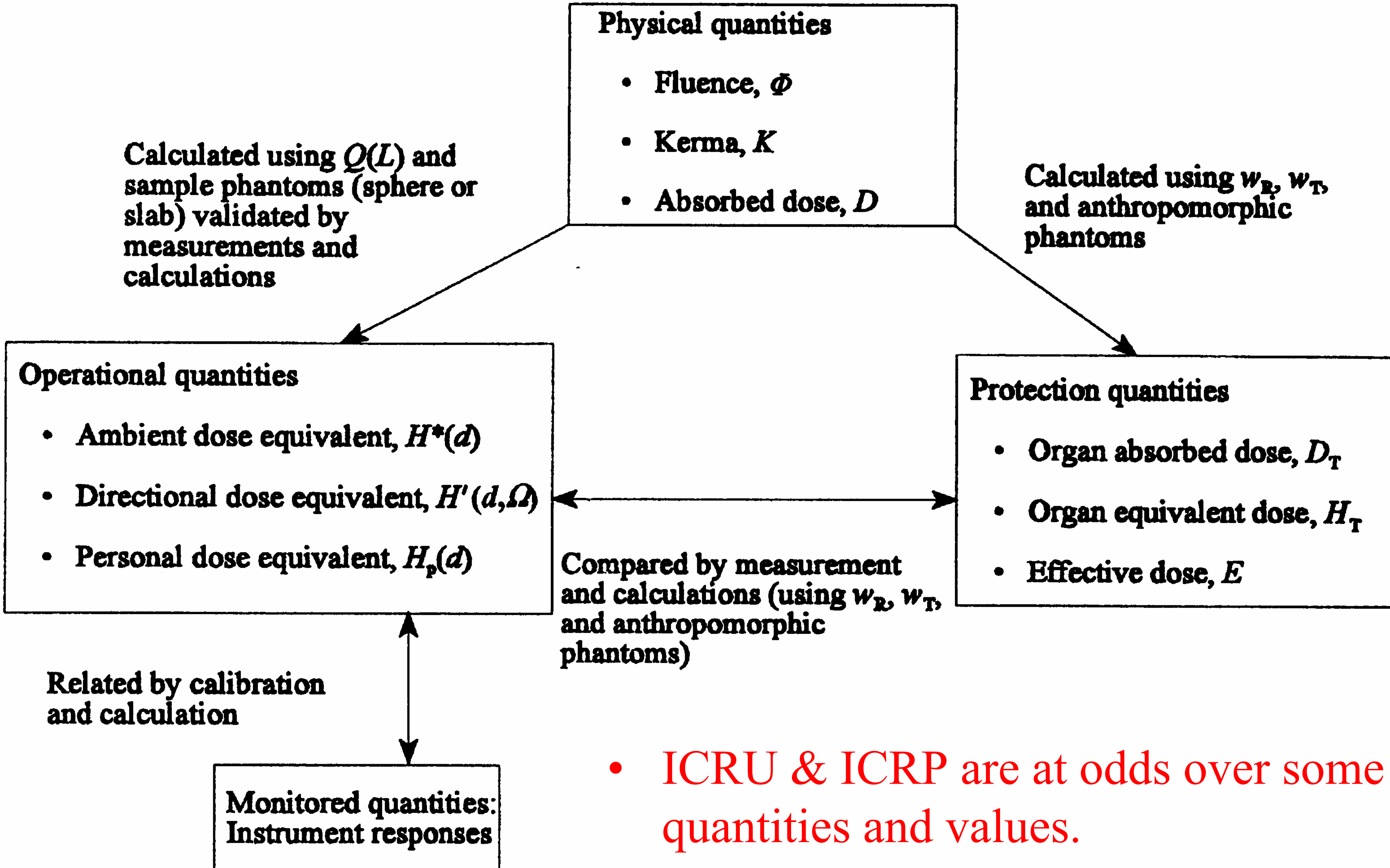
- energy
- dose-like quantities (energy/mass)
- dose-rate-like quantities (power/mass)
- interaction of radiation with material (various)
- biology or risk (various)
- other

Groupings of Radiation Quantities



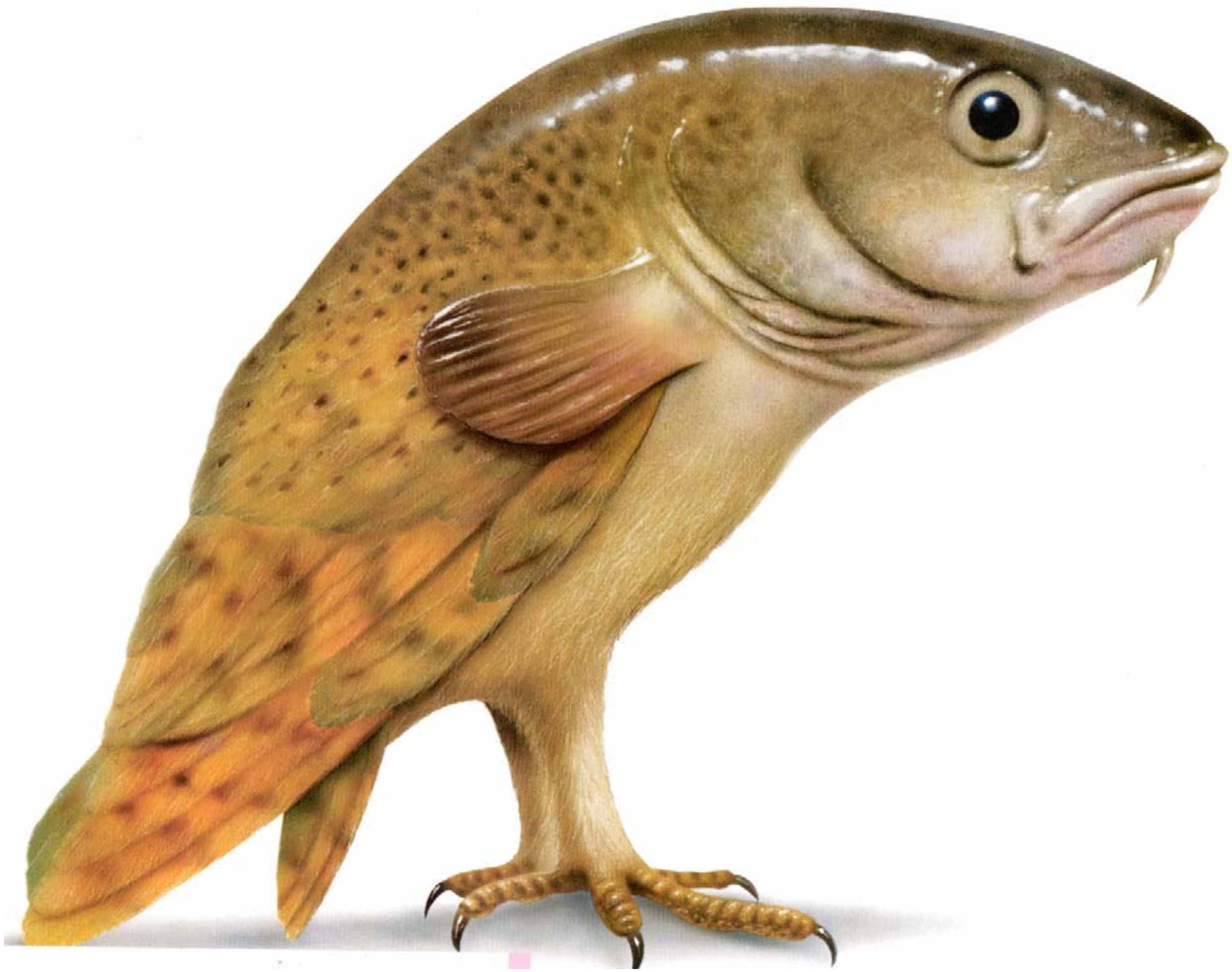
*"intake" is implicitly "dose-like" due to retention

Relationships among Physical, Operational, and Protection Quantities (ICRP 74, 1996)



- ICRU & ICRP are at odds over some quantities and values.

ICRP and ICRU are working together to build a coherent set of quantities and units for radiation protection



Activity

The **activity**, A, of an amount of a radionuclide in a particular energy state at a given time, is the quotient of $\mathrm{d}N$ by $\mathrm{d}t$, where $\mathrm{d}N$ is the number of spontaneous nuclear transformations from that energy state in the time interval $\mathrm{d}t$, thus

$$A = \frac{\mathrm{d}N}{\mathrm{d}t} .$$

Unit: s^{-1}

The special name for the unit of activity is becquerel (Bq).

- *Should this read, "…is* **the expectation value of** *the quotient of* dN *by* dt, *…" ? – D. Strom*

Number of Transitions

- "transitions" preferable to transformations, disintegrations, or decays…
- in ICRP 30 Supplement to Part 1, "number of transformations"

$$U(T) = \int_0^T A(t)\,\mathrm{d}t$$

- MIRD calls this "cumulated activity" $\tilde{A}$
- "dose"-like quantities are proportional to U
- radioactive decay, ingrowth, and other removal or addition processes affect U
- limited in NCRP Report 106 to 10^{10} βs for a hot particle on the skin; superceded by NCRP 130

Number of Transitions - 2

- transitions is dimensionless, 1 Bq s = 1
- there are lots of disguises for this dimensionless quantity
  - μCi-h (133,200,000)
  - μCi-d (3,196,800,000)
  - pCi-d (3196.8)
  - Bq-h (3600)

For Limitation Purposes: 1990 Equivalent Dose

- The equivalent dose in a tissue or organ is

$$H_T = \sum_R w_R D_{T,R}$$

1990 ICRP and 1993 NCRP Radiation Weighting Factors[a], w_R

Type and energy range[b]	Radiation Weighting Factor, w_R
Photons, all energies	1
Electrons and muons, all energies[c]	1
Neutrons:	
< 10 keV	5
10 kev to 100 kev	10
>100 kev to 2 MeV	20
> 2 MeV to 20 MeV	10
> 20 MeV	5
See also Figure A-1; $w_{R=neutron} = 5 + 17e^{-[\ln(2E)]^2/6}$	
Protons, other than recoil protons, energy > 2 MeV	5
Alpha particles, fission fragments, heavy nuclei	20

[a]All values relate to the radiation incident on the body or, for internal sources, emitted from the source.
[b]The choice of values for other radiations is discussed in ¶A14.
[c]Excluding Auger electrons emitted from nuclei bound to DNA (see ¶A13).

For Limitation Purposes: 1990 Effective Dose

- The effective dose is

$$E = \sum_T w_T H_T \text{ or}$$

$$E = \sum_T w_T D_T \sum_R \frac{D_{T,R}}{D_T} w_R$$

  where w_T is the tissue weighting factor
- Accounts for non-uniform irradiation

Committed Equivalent Dose and Committed Effective Dose

- The committed tissue or organ equivalent dose is

$$H_T(\tau) = \int_{t_0}^{t_0+\tau} \dot{H}_T(t)\,\mathrm{d}t$$

for a single intake of activity at t_0

- The committed effective dose is

$$E(\tau) = \sum_T w_T H_T(\tau)$$

- $E(50)$ is 50-year committed effective dose
- *Typically, these are doses that Reference Man would receive…*

ICRP's 1990 and 1977 Tissue Weighting Factors

Tissue or organ	1990 *w(T)*	1977 *w(T)*
Gonads	0.2	0.25
Bone marrow (red)	0.12	0.12
Colon	0.12	0.06**
Lung	0.12	0.12
Stomach	0.12	0.06**
Bladder	0.05	0.06**
Breast	0.05	0.15
Liver	0.05	0.06**
Esophagus	0.05	0.06**
Thyroid	0.05	0.03
Skin	0.01	(0.01)
Bone surface	0.01	0.03
Remainder*	0.05	[0.30 *see above*]
TOTAL	1	1.01

*1990: adrenals, brain, upper large intestine, small intestine, kidney, muscle, pancreas, spleen, thymus and uterus.

**1977: each of 5 highest dose organs included in remainder with *0.06* weighting factors; stomach, small intestine, upper and lower large intestine each count as 0.06 if receiving high doses. $w_{skin} = 0.01$ was added 1985.

Some Quantities Needed for Dosimetry of Intakes

- absorbed fraction, $AF(T \leftarrow S)_R$
  - the fraction of energy emitted as a specified radiation *R* in a specified source tissue *S* which is absorbed in a specified target tissue *T*
- specific effective energy, $SEE\ (T \leftarrow S)_R$
  - the energy (MeV), suitably modified for radiation quality, imparted per gram of a target tissue *T* as a consequence of the emission of a specified radiation *R* from a [transition] occurring in source tissue *S*
- fractional absorption in the GI tract, f_1
  - the fraction of an element entering the gastrointestinal tract which reaches body fluids

"Dose Coefficient"

- committed tissue equivalent dose per unit intake at age t_0
  - $h_T(\tau)$ in Sv/Bq
- committed effective dose per unit intake at age t_0
  - $e(\tau)$ in Sv/Bq
- time $\tau = 50$ y for adults, $\tau = 70 - t_0$ for children
- depends on
  - sex, route of intake

Inhalation

–particle size
–breathing rate
–clearance parameter
  •ICRP 2 soluble or insoluble (S or I)
  •ICRP 30 lung class (D, W, [Q,] Y)
  •ICRP 66 material type (S, M, F)
–fractional absorption in the GI tract f_1

Ingestion

–chemical form:
  GI uptake f_1

Air Sampling for Dosinference

- activity concentration, $\chi = A/V$ (Bq m^{-3})
- personal (breathing zone, BZ) air samplers
  - lapel
  - fixed head for glove box locations
- general area (GA) air samplers
- presumed to be representative of what worker inhaled
- may be way off for high-specific activity aerosols where one particle can be a significant fraction of an *ALI* (Birchall et al. 1991)
- For *average* inhalation exposures to high specific activity $^{238}PuO_2$ particles (10 g/cm^3, 5 μm AMAD, lognormal distribution GSD = 2.5) of 1, 2, 4, and 8 DAC-hours, ITRI's Monte Carlo analysis showed that most folks have zero intake, while some will exceed 2000 DAC hours (Scott et al. 1997)

Inhalation Exposure of Individuals

- The **exposure** Y (Bq h m^{-3}) over a period of time T (h) is

$$Y(T) = \int_0^T \chi(t)\,\mathrm{d}t$$

- Y is commonly normalized to the derived air concentration, DAC

$$Y_{\mathrm{norm},\,i}(T) = \int_0^T \frac{\chi_i(t)}{DAC_i}\,\mathrm{d}t$$

- *inhalation exposures* often given in DAC-h

Respiratory Protection

- Assigned Protection Factor, *APF*

$$APF = \frac{\chi_{\text{outside respirator}}}{\chi_{\text{inside respirator}}},$$

- *APF* is determined by regulator
- the **adjusted inhalation exposure** becomes

$$Y_{\text{norm, adjusted}, i}(T) = \frac{1}{APF} \int_0^T \frac{\chi_i(t)}{DAC_i} \, \mathrm{d}t$$

- *adjusted inhalation exposures* often given in *DAC*-h
- If stochastic *DAC*s are used, 1 *DAC*-h is a surrogate for 2.5 mrem of $H_{\text{E},50}$, so *DAC*-hours from different radionuclides can be added

Disguises for “Dose Coefficient”

- maximum permissible concentration, *MPC* (μCi cm^{-3})
  - ICRP 2
  - nothing maximum about it
  - *MPC*-hours
- annual limit on intake, *ALI* (Bq)
  - ICRP 30
  - stochastic ($H_{E,50}$ = 50 mSv)
  - non-stochastic (deterministic; $H_{50,T}$ = 500 mSv)
    - I like Skrable’s suggested *SALI*s and *NALI*s
- derived air concentration, *DAC* (Bq m^{-3})
  - stochastic or non-stochastic (deterministic)
  - DOE has only one value, the most restrictive

$$DAC = \frac{ALI}{(1.2\ \mathrm{m^3 h^{-1}})(2000\ \mathrm{h\ y^{-1}})}$$

Intake via Inhalation

- Intake, I (Bq)

$$I = \int_{start}^{stop} \chi \dot{V} \, \mathrm{d}t,$$

where

χ is the airborne radioactive material concentration (Bq/m^3);

$\dot{V}$ is the breathing rate (typically 1.2 m^3/hour); and

the integral is over the exposure time.

Measurements Used for Assessment of Doses from Intakes of Radioactive Material: Bioassay

- ***in vitro* assessment of internal radioactivity**
  - nasal swipes or smears: immediately after a suspected or verified accident
  - smears of skin or wash water
  - urinalysis
  - fecal analysis
  - analysis of other tissue material
  - analysis of swipe sample or air sample for particle size, solubility, and isotopic composition
- ***in vivo* assessment of internal radioactivity**
  - direct monitoring of skin
  - direct monitoring of wound
  - lung counting
  - whole body counting

Two Ways to Determine Intake *I*

- use bioassay result and knowledge of time of intake
  - intake retention fraction (*IRF*)
    - for a given "bioassay compartment," e.g., urine, feces, lung retention
    - as a function of time since intake t_I (Potter 2002)

$$I(\text{Bq}) = \frac{Activity\ in\ Bioassay\ Compartment}{IRF(t_I)}$$

- use air sample, stay time, breathing rate, and assigned protection factor

$$I(\text{Bq}) = \frac{\chi(\text{Bq m}^{-3})\, t(\text{hours})\, (1.2\text{m}^3\ \text{h}^{-1})}{APF}$$

From Intake to Effective Dose: *IRF* and *e*

- multiply *I* by effective dose per unit intake factor $e(\tau)$ (IAEA SS 115 or ICRP 68, 71, etc.)
- $e(\tau)$ depends on
  - route of intake
  - particle size (inhalation only)
  - chemical form
  - age
  - person (worker or public)

$$E(50) = I\, e(50)$$

Bioassay to Effective Dose Example

- routine 24-hour urine sample: 0.022 $\pm$ 0.005 dpm of $^{239+240}$Pu
- *DL* = 0.010 dpm
- Pu contamination near where he was working 200 days before
- Assume acute inhalation intake, 5µm AMAD Type S particles
- What *E*(50) would you assign to the worker?

Answer

- IRF_{urine}(200 d) = 1.61E-7 (Potter 2002 p. 772)
- *e*(50), 5µm = 8.3E-6 Sv/Bq (workers; IAEA SS 115 p. 153)
- Convert dpm to Bq (1 dpm = 1/60 Bq)
- 24-h urine excretion = (3.67 $\pm$ 0.83)E-4 Bq
- *(24-h Urine Bioassay Quantity)* ÷ *IRF* = 2280 $\pm$ 580 Bq
- $I \times e = E(50)$ = 0.0189 $\pm$ 0.0043 Sv = 18.9 $\pm$ 4.3 mSv
- uncertainty is doubtless ***much*** larger than the counting uncertainty

A "Quantity" That Never Occurred to the ICRP: Total Effective Dose (Equivalent)

- USA regulators explicitly *named* the sum of doses from external sources and committed doses from intakes of radionuclides *TEDE*

$$E_{\mathrm{T}} = E_{\mathrm{external}} + E(50)$$

- USA regulators also explicitly *named* the implicit whole body tissue weighting factor ($w_{(T = \text{whole body})} = 1$)
- also have cumulative or lifetime *TEDE*
- also have operational (personal) *TEDE* in contrast

Personal* Total Effective Dose, E_T

- IAEA SS 115 (1996): for verification of compliance with dose limits, use

  $$E_T = H_p(d) + \sum_j e(t_0)_{j,\text{ing}} I_{j,\text{ing}} + \sum_j e(t_0)_{j,\text{inh}} I_{j,\text{inh}},$$

  where the sums are over radionuclides *j*, ing means ingestion, and inh means inhalation
- intakes *I* (Bq) and personal dose equivalent H_p, are within a specified time period, e.g., 1 y

*Strom 2004

Radon and Radon Progeny

- ^{222}Rn (radon), ^{220}Rn (thoron), ^{219}Rn (actinon)
- a unique problem that requires special quantities & units
  - short-lived noble gasses in natural decay series with α- and β-emitting progeny
  - non-equilibrium mixtures
  - plateout
  - ultrafine-aerosol
- ICRU is utterly silent
- ICRP-65 (1993) quantities follow
- ICRP-65 ignores thoron
- practical primer in DOE standard on Internal Dosimetry (DOE-STD-1121-98), esp. pp. 78-84
  - http://tis.eh.doe.gov/techstds/standard/std1121/std112198.pdf

Potential Alpha Energy & Energy Concentration

- The **potential alpha energy**, ε_p (J) (a.k.a. *PAE*), of an atom in a decay chain of radon is the total alpha energy emitted during the decay of this atom to stable ^{210}Pb. (^{208}Pb for ^{220}Rn decay chain)
- *PAE* per unit of activity (J Bq^{-1}) is $\varepsilon_p / \lambda_r$, where λ_r is the radioactive decay constant
- The **potential alpha energy concentration**, c_p (J m^{-3}), of any mixture of short-lived radon progeny in air is the sum of the *PAE* of these atoms present per unit volume of air

$$c_p = \sum c_i (\varepsilon_{p,i} / \lambda_{r,i})$$

- 1 J m^{-3} = 6.242×10^{12} MeV m^{-3}
- 1 Working Level = 1.3×10^5 MeV L^{-3} = 2.08×10^{-5} J m^{-3}

Equilibrium Equivalent Concentration and Equilibrium Factor

- The **equilibrium equivalent concentration**, c_{eq} (Bq m^{-3}), of any non-equilibrium mixture of short-lived radon progeny in air is the activity concentration of radon in radioactive equilibrium with its short-lived progeny that has the same c_p as the actual non-equilibrium mixture
- The **equilibrium factor**, *F*, is defined as the ratio of the equilibrium equivalent concentration to the activity concentration of the parent nuclide, radon, in air
- The **ultrafine fraction** is that fraction of radon progeny activity that is not attached to ambient aerosols. This activity deposits disproportionately in the upper airways

Inhalation Exposure of Individuals – Radon Progeny

- The **potential α energy exposure** over a period of time T is

$$P_{\mathrm{p}}(T) = \int_0^T c_p(t)\,\mathrm{d}t$$

- The unit of P_{p} is J h m^{-3}
- P_{p} is often expressed in the historical unit of the Working Level Month (WLM)
- 1 "occupational month" = 170 hours (exactly)
- 1 WLM = 3.54 mJ h m^{-3}
- The **equilibrium equivalent exposure** over time T is

$$P_{\mathrm{eq}}(T) = \int_0^T c_{eq}(t)\,\mathrm{d}t$$

- The unit of P_{eq} is Bq h m^{-3} (really should be transitions m^{-3}!)
- Inhalation exposures of other radionuclides often given in DAC-h

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