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Respirator Effectiveness in an Enriched Uranium Plant

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Introduction

NUMEC processes uranium, enriched up to 97% U-235, in its Apollo, Pennsylvania Plant. Facilities include UF_6 to UO_2 conversion, ceramic fuel shape fabrication and unirradiated scrap reprocessing.

These processes each present potential exposure to airborne radioactivity, especially UO_2 powder handling. The plant designers recognized this and provided ventilation control for powder handling. This control consisted chiefly of fume hoods and local exhausts.

However, breathing zone air sampling studies revealed that localized exposure was occurring. Revised handling procedures and increased training did not reduce exposures below permissible limits. Consequently, early in 1966 NUMEC undertook a respiratory protection program to protect workers from the localized UO_2 dust exposure.

Since NUMEC operates the uranium plant under a special nuclear materials license issued by the U. S. Atomic Energy Commission, we had to obtain their approval of our respiratory program. The application covered equipment, fitting and operating procedures, maintenance, bioassay and training.

We received AEC approval in June, 1966. Because most affected workers were receiving weighted exposures of less than 10 MPCa,(1) we used half face respirators for every thing except emergencies.

We soon stumbled on one of the license criterion for respirator effectiveness. After each respirator use, we took nasal smears to demonstrate that protection had been provided. A high percentage of individuals showed up with nasal contamination exceeding our limit (50 d/m). No apparent correlation between personal air sampling and nasal smears developed. Consequently, we carried out a bioassay program to determine half face respirator effectiveness.

Method of Study

To compute respirator protection, two numbers are needed: (1) The potential radioactivity which would have been inhaled without respiratory protection and (2) the radioactivity actually inhaled.

Our uranium operators, working in exposure problem areas, routinely wear personal air samplers. This gave an excellent measure of potential exposure.

For an estimate of actual exposure, we had available urine and fecal excretion and whole body counting data. We decided on early fecal clearance (fecal samples collected during the first few days after an exposure), because our fecal sampling program, begun early in 1966, had shown us that urine sampling was misleading. Whole body counting was rejected because the method is not sensitive enough to detect small daily exposures. It is, however, an excellent indication of accumulated lung burdens.

Our method for studying respirator effectiveness was to correlate personal air sampling data with fecal sampling data. Only single, daily exposures were evaluated; we did not average data. Whenever an exposure exceeding 40 MPC-hours was detected, the operator was removed from radiation work and both fecal and urine samples were collected. Figure 1 shows how personal air samplers were worn by respirator wearers. A belt carries the air pump out of the way. We brought tygon tubing over the shoulder to the sampling head, which was fastened to the lapel or shoulder. We have experimented with a "bump" hat which carries both air pump and sampling head. This permits locating the sampling point within inches of the nose.

We were careful about fitting and field testing the respirators. Figure 2 shows the smoke tube technique, developed by Hyatt,[2] which we settled on for fitting and field testing. Our experience showed that the negative pressure test is a relatively poor indication of face seal. For the negative pressure test, we covered the canister inlet opening with the hands, held the breath for ten seconds and noted whether the face piece remained collapsed. Following this test with an MSA Stannous Chloride "Smoke Tube" test revealed an alarming frequency of inleakage. Even experienced Health and Safety tecnicians failed a third of the time to get a good face seal using the negative pressure test.

Much of our data comes from cases where the half face respirators were field tested by the negative pressure method. However, the protection afforded by the half face respirators was not substantially improved by changing to smoke testing. Smoke testing in the work place showed that the face seal would be lost, shortly after the original test.

The Importance of Personal Air Sampling

Almost all industrial radioaerosols are extremely localized in space. Concentrations vary drastically from place to place. This is because most radioaerosol sources are small; generally the worker's hands are the most common aerosol generator. The concentration gradient from a small source will be very steep, varying with the inverse square, and perhaps, the inverse cube of the distance.

Under such conditions, it is obvious that where an air sample is taken is critical, if you want to estimate the worker's exposure. The air sampling data in this report comes entirely from breathing zone sampling.

Figure 3 shows the log-normal distribution of the ratio of personal air sampler concentration to stationary air sampler concentration. When this ratio equals one, the personal air sampler agrees with the fixed position air sampler. We show distributions from three nuclear fuel plants. The UKAEA data is from Fraser[3]. The distribution slope of the NUMEC uranium plant data is similar to the UKAEA data. However, the distribution is displaced so that the ratio is about 2-1/2 times greater for a given percent of the data population.

The NUMEC plutonium plant data shows a very wide spread of ratios. We were able to show a good correlation of bioassay data with personal air samplers at the plutonium plant[4].

More than 50% of personal air samples in our uranium plant showed concentrations seven times that for stationary air samples. Ten percent of the time the factor was more than 20.

It is clear that personal air sampling is absolutely necessary, if you intend to determine respirator effectiveness under actual work conditions. Stationary air samplers underestimate exposures by considerable and widely varying margins. Even weighted exposure analyses with hand held air samplers will only give reliable data for that particular sampling period.

Early Fecal Clearance as a Measure of Exposure

In 1964 Sill[5] pointed out the errors in using urinalysis as a routine monitoring method for internal radioactive contaminants. In his experience, radioactivity measured by whole body counting could not be detected in the urine. He found however that in all cases fecal samples showed measureable quantities of the radionuclide.

This can be easily understood if we consider the 1966 ICRP deposition and retention model shown in Figure 4[6]. Inhaled particles are deposited in three regions of the respiratory tract, the nasal-pharynx, tracheo-bronchial and pulmonary compartments. Almost 100 percent of the insoluble alpha emitters (UO_2, ThO_2 and PuO_2) deposited in the N-P and T-B regions are removed by ciliary mucous transport to the G.I. tract in a matter of minutes. This rapidly eliminated fraction, represented by (b) and (d), together with a similarly rapidly removed pulmonary fraction (f) make up an early clearance phase (Phase I). All Phase I insoluble alpha activity is eliminated in the feces. b and d represent 4 and 10 minute half times for actinide elements. f represents a 24 hour half time clearance rate. Effectively, Phase I clearance is over in 3 days.

A second clearance phase, with a half time of one year or greater from the pulmonary part of the lung, is represented by (e), (g) and (h). Only about 5 percent of the insoluble alpha emitters originally deposited in the pulmonary compartment are absorbed (e) into the circulating blood. Another 15 percent is removed to the lymph system (about 10% of which is later transferred to the blood). The remainder is eliminated by endocytosis and the ciliary escalator through the G.I. tract to the feces.

For one micron Median Aerodynamic Diameter particles, the expected early fecal clearance is 38% of those inhaled. Particle sizing studies in the UO_2 handling areas show that one micron MAD is a reasonable compromise value.

In-vivo or whole body gamma counting has demonstrated excellent results for the accurate assay of many radionuclides in the human body. The only requirement is the presence of an energetic gamma emitted with reasonable abundance from the radionuclide of interest.

Unfortunately, the actinide elements are not blessed with abundant energetic gamma radiation. ^{235}U is detected to levels as low as 7 nCi[7]. However, this is not sensitive enough to detect single daily exposures where the radioactivity inhaled may be less than 0.1 nCi.

To illustrate the importance of fecal sampling, we have included some of our uranium bioassay data (Figure 5). The excretion rates via feces and urine are plotted against each other for those cases where the samples were collected the same day. The dotted urine level line represents the excretion from a maximum permissible skeletal burden, after the 300 day[8] half life portion of the excretion curve has been reached. The dotted fecal line represents the excretion rate predicted for a permissible lung burden (17 nCi) after the 380 day half time[6] has been reached.

Many of the fecal data represent early clearance and are not necessarily unpermissible. However it is obvious that urine data by itself gives a false impression of actual exposure. We were able to use this data to estimate the effectiveness of half face respirators. We found that they are not very effective.

The Effectiveness of Half Face Respirators

Having reliable estimates of the radioactivity actually inhaled during respirator wearing, we were able to compare actual inhalation with potential inhalation for specific time periods, usually single shifts (Figure 6). The line of no protection equates potential with actual inhalation. The other lines show the factor by which the half face respirators reduced potential exposure.

Air-purifying half face respirators are supposed to provide better than a factor of 10 protection[9]. Figure 6 shows that this is an optimistic figure, at least under our conditions of use. The computed average for the data shown is 2.1. Those data above the No protection line were assumed to be on the N.P. line for the calculation of the average.

Theoretically, there should be no data above the no protection line. You can not inhale more than you were exposed to. Of course, there is a lot of potential error in both estimates and these data could represent the inherent error. But, we noted that each of these cases were similar. They are all from our uranyl nitrate crystallization operation. Before we installed this operation in glove boxes, we encountered a great deal of hand contamination. We believe that ingestion inflated the inhalation estimates.

The crystal operation also gave us another interesting experience. We had always held faith that high efficiency, particulate filters, (e.g. the Wilson R-520) were the strongest link in respirators. Face seal leakage, we believed, was the source of our problem. However, nasal contamination and bioassay results moved us to test the Wilson R-520 HEPA filter for penetrability of the uranyl nitrate crystal aerosol. The tests showed penetration over 20%. When the Wilson No. 43 chemical cartridge was substituted, the filtration of this particular aerosol was definitely improved. This observation is unique in our experience; the R-520 filter is highly efficient for UO_2 dust.

Most of the data points are for eight hour periods. The permissible inhalation line indicates 8 MPC-hours exposure. Where this line crosses the factor of 10 line is the potential inhalation for which more protection than half-face respirators was needed. Even though average exposures were less than 10 MPC, individual exposure actually reached the protection factor for full face respirators. This is an important point. It reinforced our decision to switch to full face respirators.

Although it's not shown here, we noticed that shorter wearing periods result in better respirator protection. This is probably because the worker can maintain procedural discipline better for short periods. The tendency to touch the mask, talk, wrinkle the face, etc. increases with the length of the wearing period.

Another rather subjective observation we have had is the superior protection some individuals get. We do not think this is entirely due to their face shape fitting the mask better. Wearing a respirator properly requires self-discipline. The worker, who has it, achieves better respirator protection.

We have tried 3 models: The Wilson, AO and the MSA Comfo. The Wilson model fits more individuals because of the pleated nose cups. It also gave slightly better, average protection. All three were made available to workers during the study.

This data clearly indicates that, under actual working conditions, with an AEC approved respirator program, half face respirators give inferior protection.

The Effect of Respirators on UO_2 Workers Exposure

It's often difficult to demonstrate psychological effects quantitatively. But we have evidence that respirator wearing increases the breathing zone concentration. Figure 7 shows personal air sampling data for three separate operator jobs. The abscissa has no units. The exposures occurred over the same six month period. The average concentration, over all three jobs, was 1532 $d/m/m^3$ for respirator wearers and 464 $d/m/m^3$ for those without respirator protection.

A unique situation existed for these three jobs. For the first six months of the respirator program, respirator wearing for these jobs was optional. We were concentrating on more severe exposure problem areas and did not enforce respirator wearing until the higher exposures began to occur with the respirator wearers.

Apparently, workers think they are protected by the respirators and use less care in handling uranium. Work in open front hoods and local exhaust ventilation is vulnerable to poor handling technique.

Taking the 3.3 increase in the exposure into account with the average 2.1 protection factor for half face respirators, leads us to the amazing conclusion that half face respirator wearers in our plant were actually exposed to 57% more radioactivity than non-respirator wearers.

Discussion

This effectiveness study prompted us to discontinue the use of half face respirators. The only instance where we still permit their use is where the worker must wear prescription eyeglasses. Where such an operator needs protection frequently, we obtain special mounted prescription glasses for a full face mask. Respiratory protection is restricted to full face respirators or supplied air in all other cases.

An even more major decision precipitated from the study: NUMEC converted from ventilation control (e.g. fume hoods) to process containment (e.g. gloved boxes) for enriched uranium processing. Of course, it was not the only reason for doing this. Reduction of process losses of valuable ($11/gram) fissile material was a by-product of the improved containment. Figures 8 and 9 illustrate the change in philosophy.

Fitting respirator dimensions to the human face has been dealt with so thoroughly[10], that we hesitate to comment. But it seems to us that half face respirators are inherently vulnerable to inleakage. The width of the seal is usually much narrower than for full face configurations. And this narrow seal is applied to the most awkward parts of the face, the nose ridge and chin. Indeed, a chemical engineer would despair of sealing processing piping under such conditions. Besides, process piping does not talk, scratch its nose, grow whiskers or chew tobacco.

There are a number of observations concerning respirator wearing we would like to pass on:

1. Training is obviously very important. But we found on-the-spot training gave better results than class room lectures. Our staff went out on the floor, did field testing and gave instructions on the job.

2. Smoke tube testing, especially in the work place, is an eye opener. Organizations using only negative pressure techniques or testing only during fitting would benefit from a field testing program.

3. Proper removal of contaminated respirators is critical. Often an individual can cancel an entire wearing period's effectiveness by a careless removal. A concentrated cloud of radioactivity can be generated right in the breathing zone. We recommend removal of contaminated protective clothing, thorough contamination monitoring and decontamination, before the mask is removed.

4. The initiation of a respirator program is not the time for relaxing the industrial hygiene or health physics monitoring programs. Air monitoring and bioassay programs are still essential.

5. Nasal smears have always indicated when an exposure has occurred. But we have not successfully correlated nasal smears to actual exposure. Our limits (25 d/m for plutonium and 50 d/m for uranium) have proven satisfactory. That is, nasal smears lower than these values have never been associated with unpermissible exposures.

6. Worker acceptance of respiratory devices is highest for supplied air respirators and lowest for full face respirators. As a consequence, we use supplied air often in cases where its superior protection factor is not actually needed.

7. Environmental stress, heat, humidity, hard work, drastically reduces respirator effectiveness. Supervision must take this very real factor into account when specifying the length of wearing periods.

8. Individual discipline varies widely and an effort must be made to spot the "exposure prone" individuals. Usually a string of high nasal smears is the first indicator.

9. The best respirator program in the world will not succeed without the floor supervisor's cooperation. The foreman must be made to appreciate all aspects of the program.

10. Preliminary effectiveness studies are showing that full face respirators give definitely better protection. But there are a significant number of occassions where the protection factor is less than 100. Supplied air wearing, which is more closely supervised, has shown excellent protection.

A final comment: A recently published article[11] showed a major nuclear facility placing primary reliance on half face respirators. We believe that the half mask gives inherently inferior protection and that they have limited utility in a modern industrial respirator program.

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Figure 1

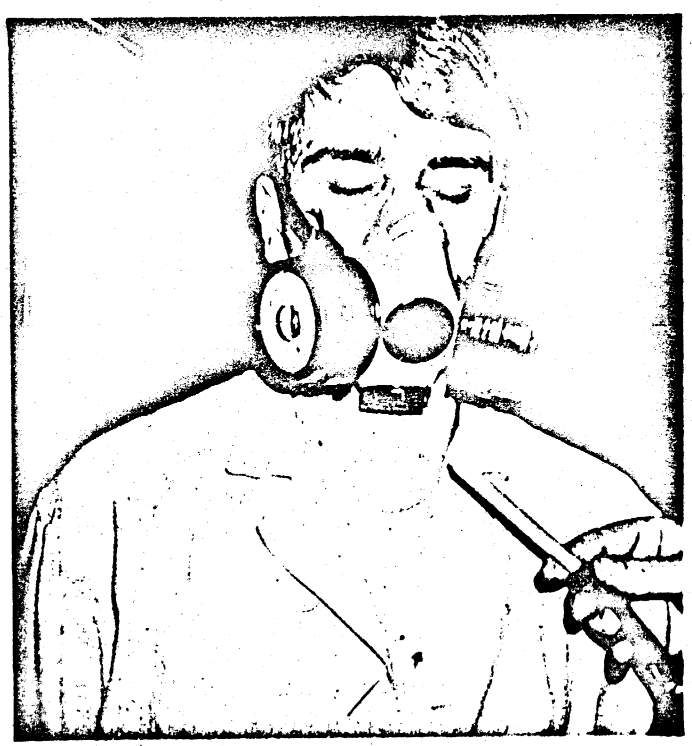


Figure 2

DISTRIBUTION OF RATIO

$$\frac{\text{PERSONAL AIR SAMPLER CONCENTRATION}}{\text{STATIONARY AIR SAMPLER CONCENTRATION}}$$

FOR THREE NUCLEAR FUEL PLANTS

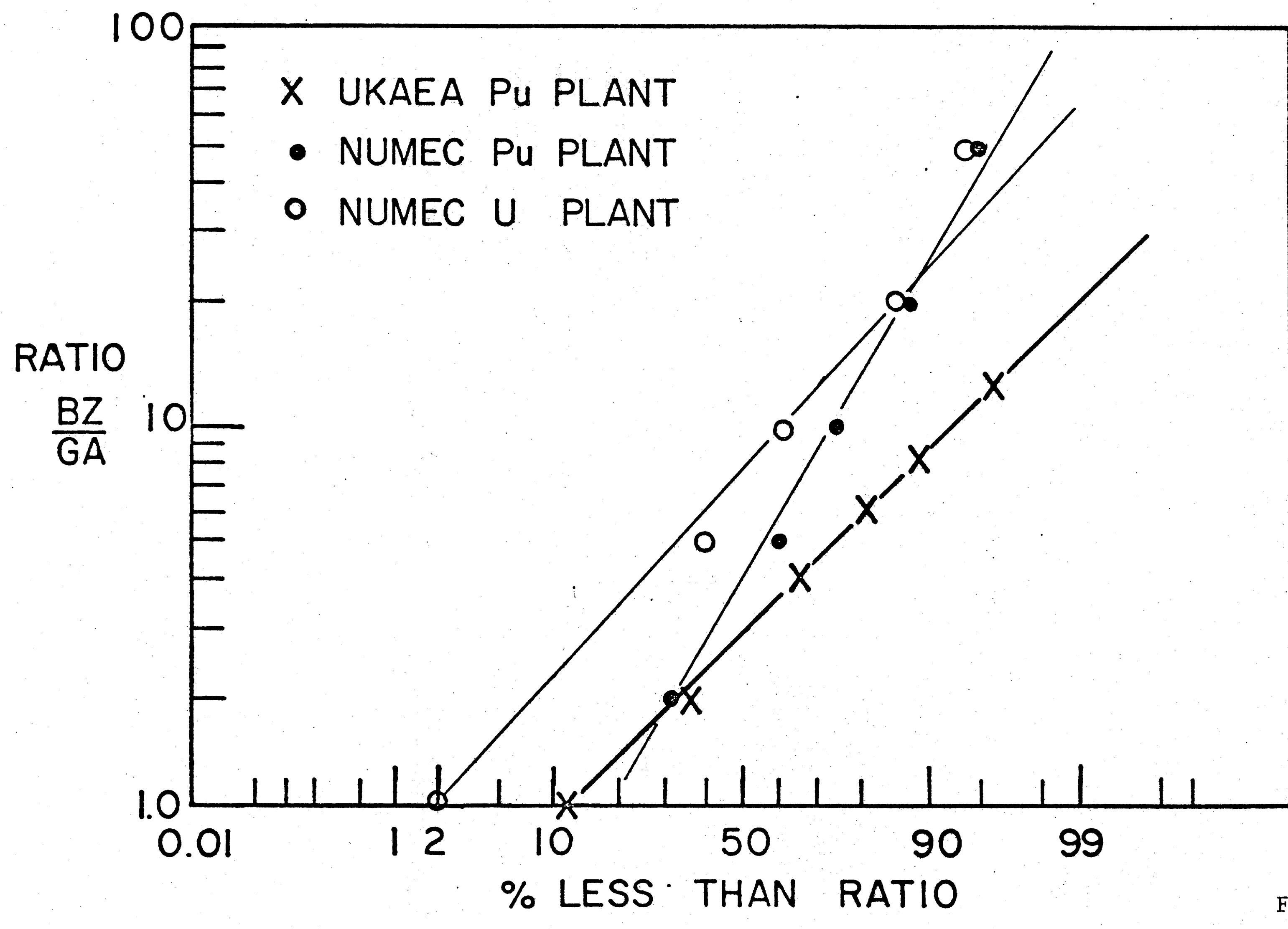
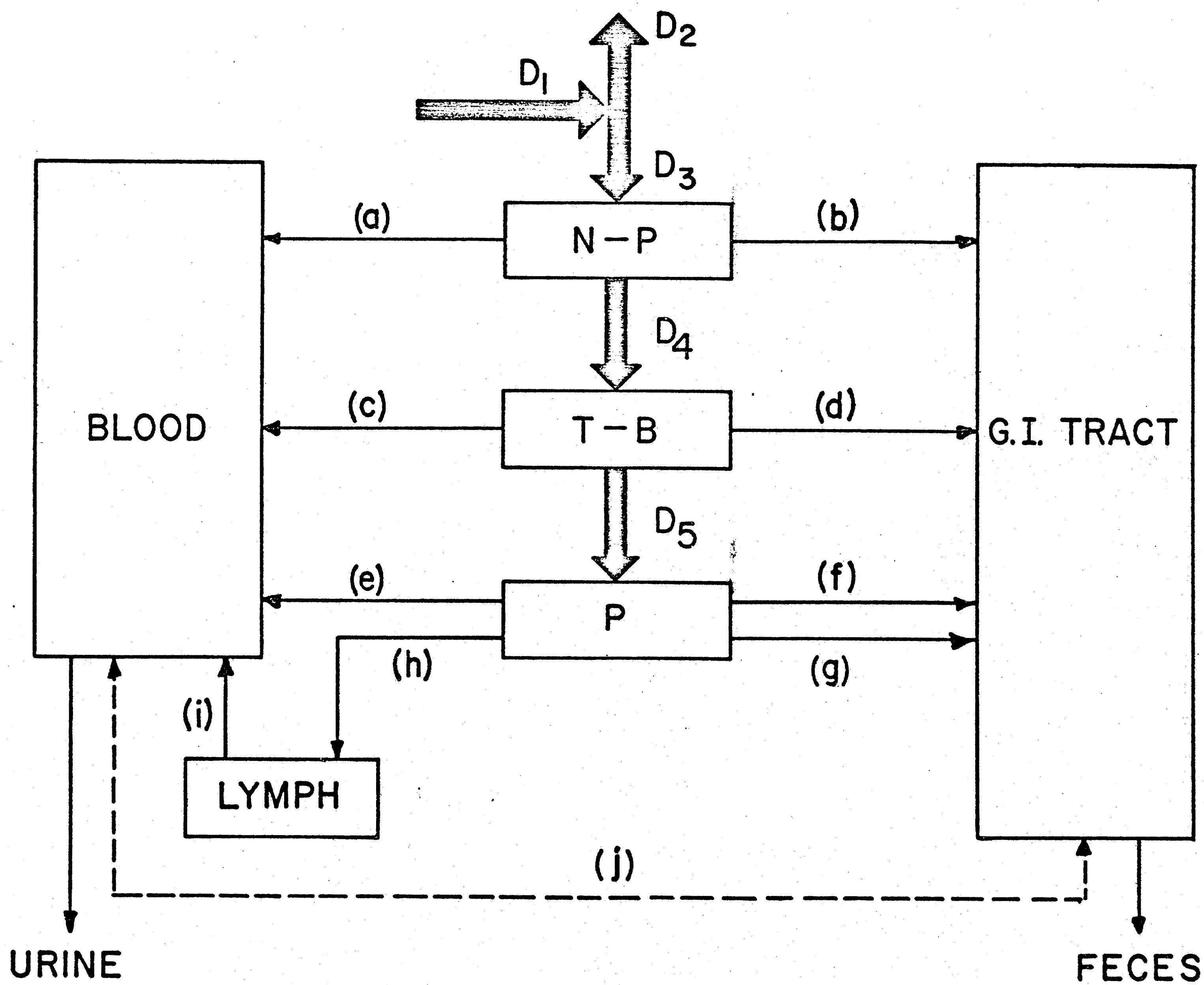


Figure 3



1966 ICRP LUNG MODEL

Figure 4

URINE vs FECAL EXCRETION RATES
CHRONIC ^{234}U OXIDE EXPOSURES
NUMEC URANIUM PLANT

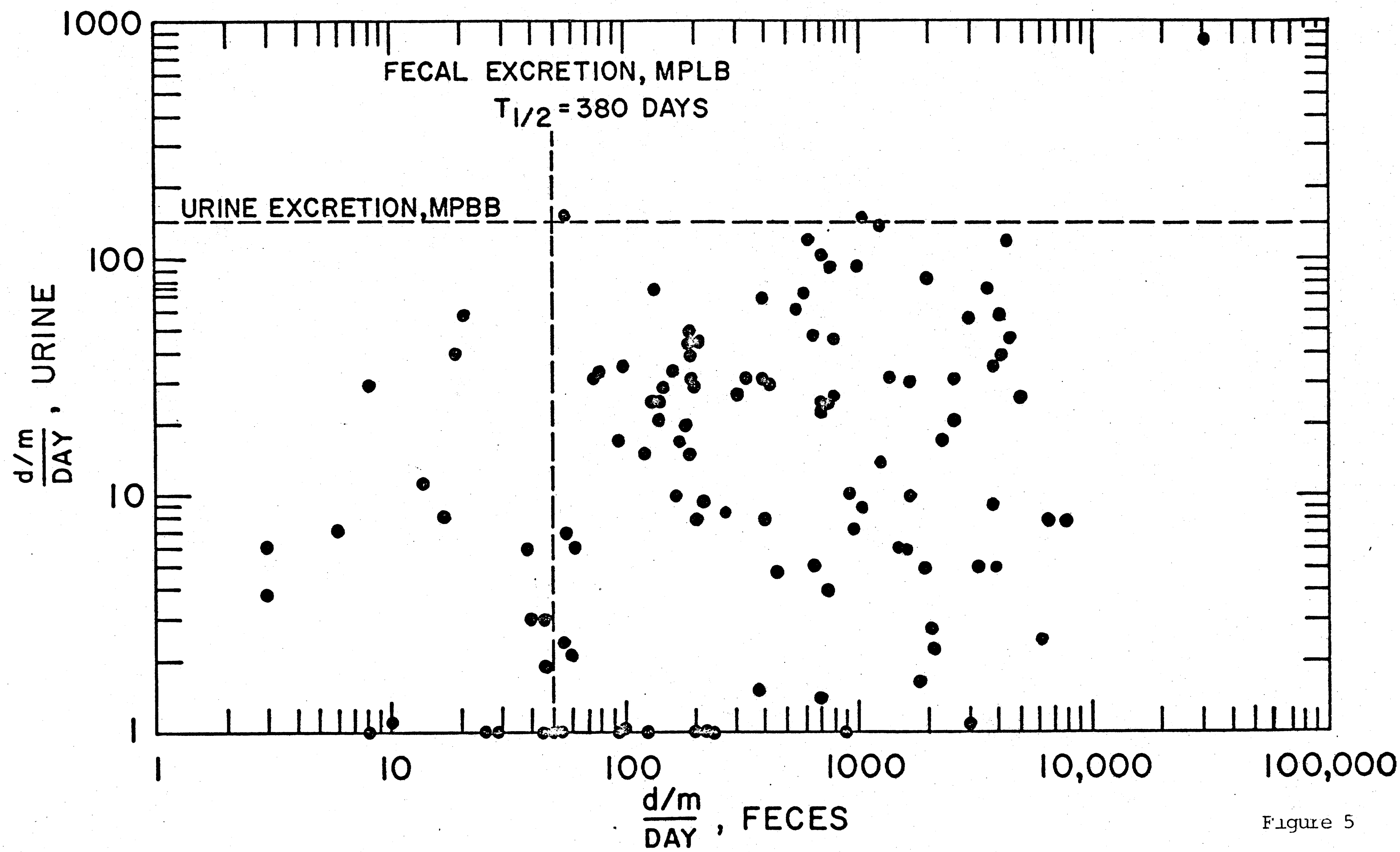


Figure 5

HALF FACE RESPIRATOR PROTECTION

NUMEC URANIUM PLANT

POTENTIAL INHALATION EST. BY PERSONAL AIR SAMPLER

ACTUAL INHALATION EST. BY EARLY FECAL CLEARANCE

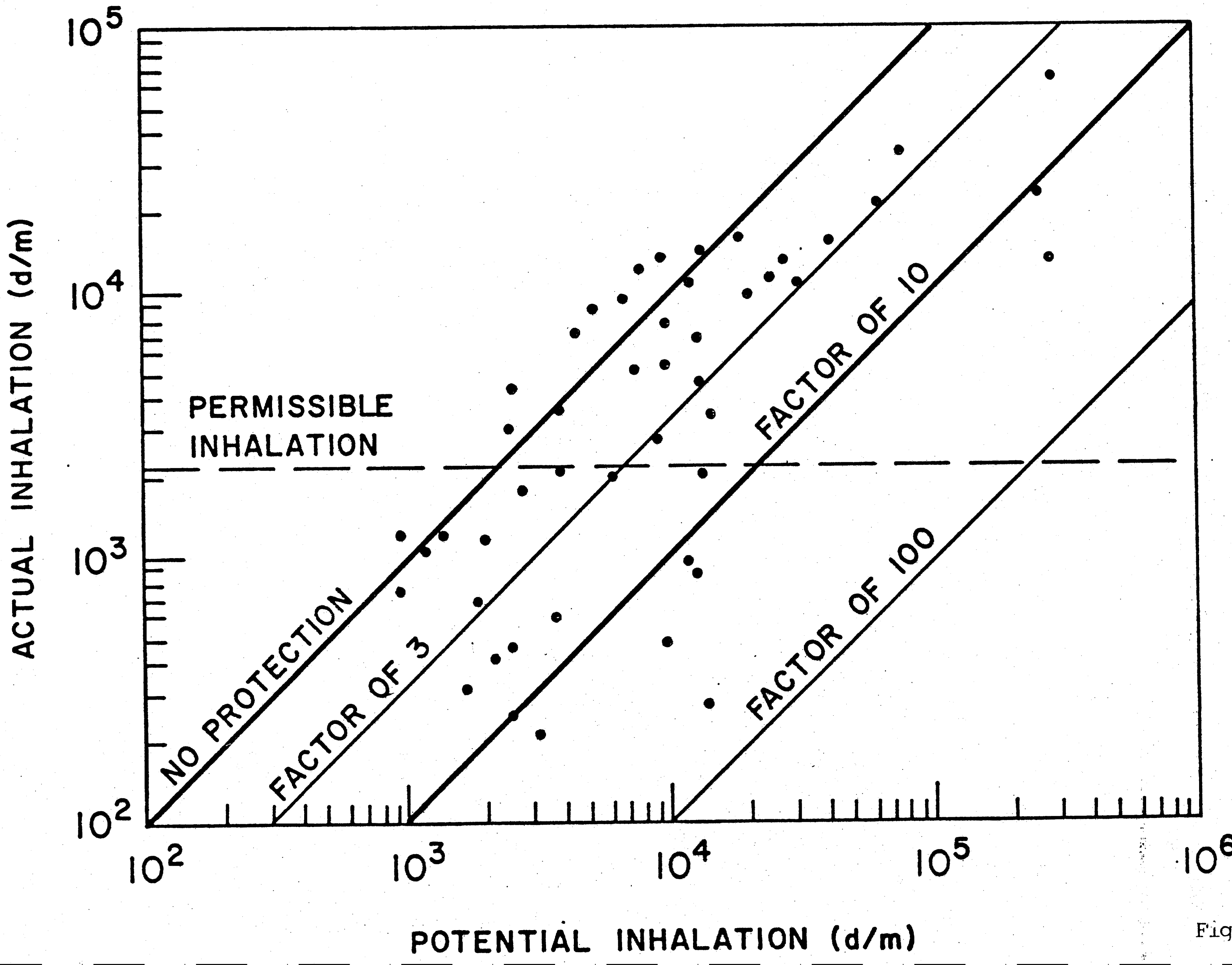


Figure 6

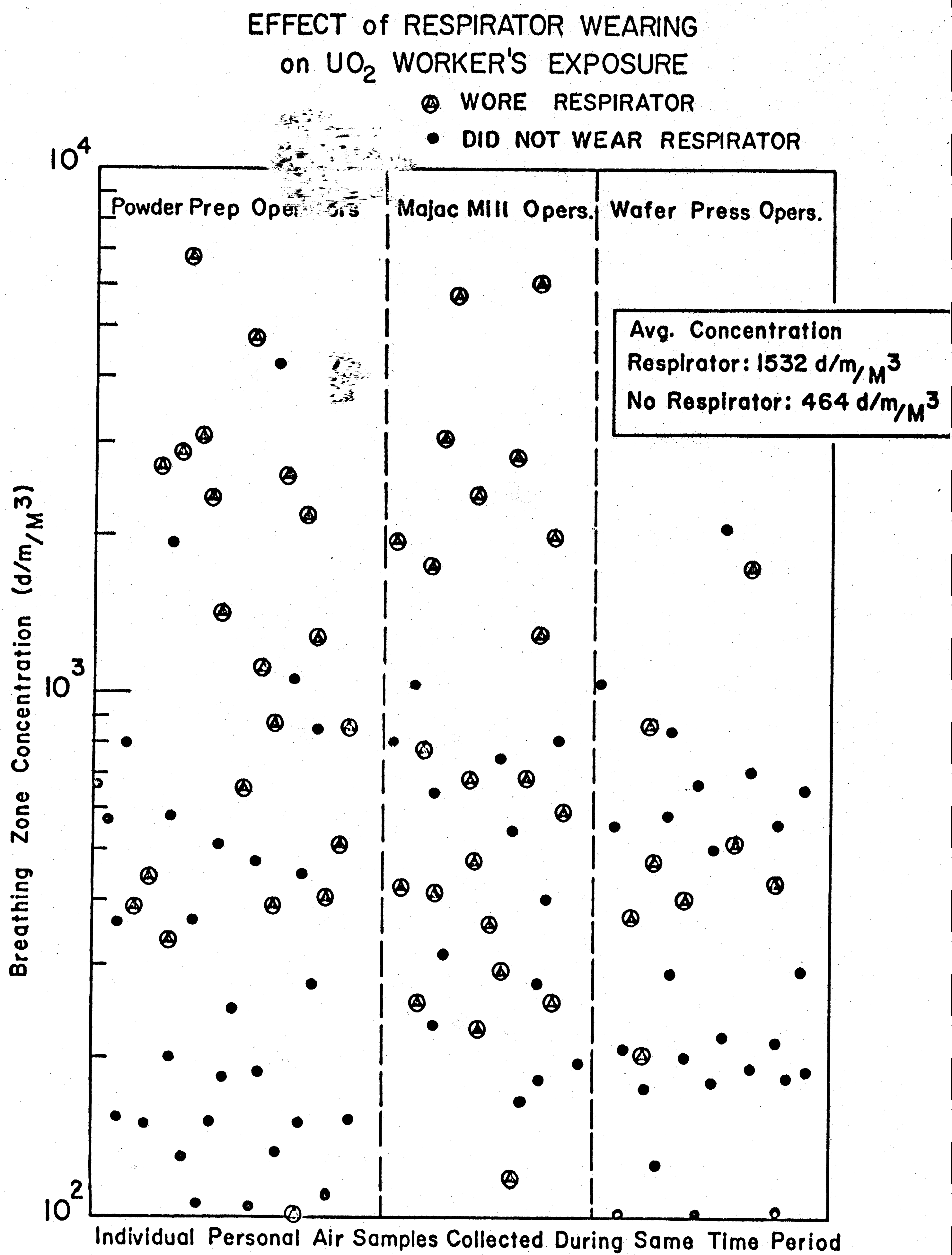

EFFECT of RESPIRATOR WEARING
on UO_2 WORKER'S EXPOSURE
WORE RESPIRATOR
DID NOT WEAR RESPIRATOR
Powder Prep Oper...s
Majac Mill Opers.
Wafer Press Opers.
Avg. Concentration
Respirator: 1532 d/m/M3
No Respirator: 464 d/m/M3
Breathing Zone Concentration (d/m/M3)
Individual Personal Air Samples Collected During Same Time Period
10^4
10^3
10^2

Figure 7

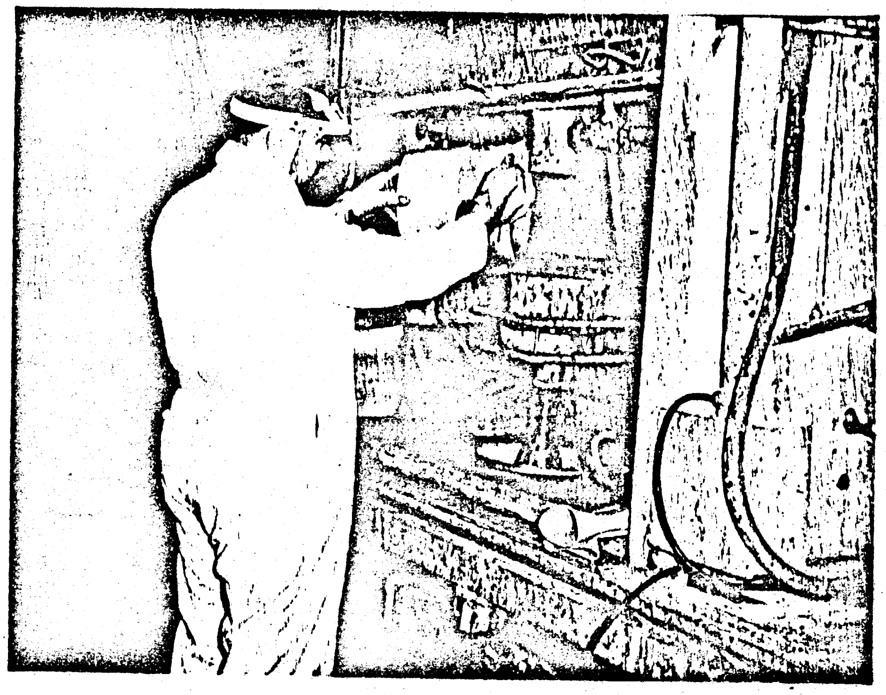


Figure 8

Figure 9