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SAMPLING METHODS AND REQUIREMENTS
FOR ESTIMATING AIRBORNE RADIOPARTICULATE HAZARDS

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Health Physics Division

November 21, 1952

OAK RIDGE NATIONAL LABORATORY
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II

SAMPLING METHODS AND REQUIREMENTS FOR ESTIMATING AIRBORNE RADIOPARTICULATE HAZARDS

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SAMPLING METHODS AND REQUIREMENTS III
FOR ESTIMATING AIRBORNE RADIOPARTICULATE HAZARDS

A B S T R A C T

A study was made of the proper criteria for a sampling and evaluation method with which to appraise the biological hazard from airborne radioactive material. Current instruments and techniques do not provide needed data in a satisfactory form for practical use.

Principal concern is with internal exposure from insoluble beta-emitting particulate air contaminants. Particle size distribution parameters are critical because of size selective lung site retention. Upper respiratory and alveolar clearance rates and mechanisms also differ. Given a mean particle diameter (0.3μ), variation in standard deviation from 2. to 3.66 increases the airborne mass and submersion dose 216 fold (particle number content). Upper respiratory retention increases 5.3x, alveolar retention decreases 16.2x, and percent exhaled decreases 30x.

Upper respiratory exposure rates (using a tissue cylinder model) are seen to be several hundred times the usually calculated values based on uniform distribution. Alveolar clearance to the lymph nodes gives similar exposure increases. A significant lung volume fraction (30% in the illustrative example) may receive varying intensity exposure as the aggregate effect of individual alveolar particles. Simple respiratory protection can decrease this 200 times or more depending on particle distribution, etc?

The recommended sample collection method uses two filters to separate size fractions simulating respiratory retention. Appropriate areas, flow rates, and sampling times are used. For evaluation, the comparative gross activity counts are indicative of particle size distribution and probable exposure levels. Counting with absorbers gives necessary energy-range data and recounts provide decay rates. The filter samples, in approximately 30 minutes X-ray film exposures, produce spots of diameters proportional to the significant particle activity sizes. A size count of such spots indicates the number and intensity of exposure foci. Leaching the filters permits the determination of soluble activity. Subsequent film exposures for longer times can provide further permanent data for future reappraisal.)

The non-uniform retention with size must be recognized in sampling particulate borne air activity. The non-uniformity of lung dosage must be recognized in the appraisal of hazard or establishing of tolerances for radio-particulates.

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SAMPLING METHODS AND REQUIREMENTS
FOR ESTIMATING AIRBORNE RADIOPARTICULATE HAZARDS

1

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This is a preliminary report* of a nearly completed survey conducted under the direction of Professor T. F. Hatch of the Graduate School of Public Health, University of Pittsburgh. It is most proper to acknowledge the helpful discussions on air activity hazards and sampling methods contributed by members of many of the project laboratories.

Purpose

The purpose of this study is to establish the proper criteria for an air sampling instrument or instruments with which to evaluate the biological hazard from airborne radioactive material.

Application

Such an instrument is of interest to AEC project personnel in connection with the operation of reactors, chemical processing plants, and laboratories handling large amounts of radioactive materials. Military applications include monitoring weapons tests and for civil and military defense in warfare. With possible modifications it could serve industrial users of radioisotopes.

Statement of Problems

Upon considering the objective of this study, there at once arise such questions as: What is the biological hazard from airborne radioactivity? What characteristics of the airborne material are significant in regard to the hazards? How do you evaluate the sample collected?

*Text of a paper presented October 16, 1952, at the AEC Health Physics Conference, Idaho Falls, Idaho. A series of comments, notes, and references has been added to supplement this text, and illustrative figures and calculation work sheet copies have been appended.

The characteristics and biological behavior of the airborne material to be sampled were seen to require integrated study in order to make a valid recommendation of the best method of sampling (if indeed, a suitable method existed). It was recognized from the outset that the gaps in our present knowledge are such that only interim recommendations could be made. However, such an interim technique should collect data of maximum future value to permit later re-examination. Much sampling that has been done in the past is of dubious value because of the lack of data on efficiency, particle size, concentration, etc.

This discussion will include: the importance of particle distribution parameters, the problems of non-uniform dose, and necessary radioactivity data. At the end, the interim recommendations for air sampling methods will be presented for your criticism.

Types of Hazard

The hazard from airborne radioactive material may include significant submersion and contamination exposures. However, this present study places primary interest on the internal hazard, especially that from insoluble particulates radioactive material. The hazards from soluble radioactive material have been given considerable study to date and will benefit from retention data developed herein. Principal attention will be directed to beta emitters, such as mixed fission products, for reasons to be brought out in a later discussion of alpha and gamma effects.

Pertinent Particle Parameters

Radioactive particles behave physically like other airborne material and in almost every case are associated with large numbers of inert particles of dust, organic debris, etc. The only differences which ordinarily can be observed in active particles are those which result when they are of higher

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¹ Examples are shown in Appendix A, pages 4, 6, and 8 for number and mass distributions with different standard deviations. Experimental data will frequently deviate at larger sizes due to failure to sample a few larger particles and at smaller sizes due to failure to resolve all the fine particles. Changes in the distribution due to settling will shift the median size (and possibly the deviation) while preserving the log-normal character of the distribution.

² The "effective" size considers differences in dynamic behavior of higher density components and of aggregates. These are influenced by the settling or impaction removal characteristics of their mass or composite diameter respectively. The electrostatic effect of particle surface charges in the lung passages is of relatively lesser importance due to saturation humidity.

³ An excellent discussion of the influence of breathing rate is given by C. N. Davies in the article "Dust Sampling and Lung Disease" published in the British Journal of Industrial Medicine Vol. 9, 1952, p. 123-125. When the differences in the breathing rates of experimental subjects are considered, the size-retention data of different observers is found in substantial agreement.

density. Depending on their origin, some active particles may be distinctive (visually) in color or shape.

Observations on the numbers of particles of different sizes show them to have a frequency distribution which is "normal" when the logarithms of the particle diameters are plotted versus their relative numbers. Such log-normal distributions are characterized by their median size, M_g , and standard deviation, σ_g . With increasing σ , the distribution becomes broader, particles occur over a wider spread of size ranges. The amount of deviation and the value of the median particle diameter will vary with the origin, composition, and method of particle formation. Simple fracture formation will tend to larger sizes and deviations than abrasive formation as in grinding. Thermal formation may lead to fine fumes, or in other cases to condensation on naturally occurring particles as nuclei. Special "logarithmic probability" graph paper yields a straight line plot for particle distributions, the slope of which is proportional to the standard deviation¹. The activity of particles will vary with the mass, if they are homogenous, and the distribution of mass versus particle diameter is also log-normal. For the same number median diameter, differences in standard deviation markedly affect the mass median diameter since a small increase in percent of larger sizes leads to considerable increase in relative mass.

Lung Retention of Particles

The size distribution of the active particles has been stressed because the natural protective mechanisms of different parts of the respiratory system vary in their efficiency of particle removal and retention with the "effective"² particle size, as well as with the individual. The effects of differences in breathing rate are most important for the larger sized particles which at higher breathing velocities tend to be removed more effectively by impingement in the upper respiratory system³.

4 Applicable physiological quantitative data on alveolar clearance rates is generally lacking or uncertain of interpretation. Alveolar retention may be weeks, months or permanent. Ciliary clearance motion is at a visible rate, which may be 3 to 4 cm/min (Brit. J. Industr. Med., 1949, 6, 246).

5 The radioactive materials absorbed in situ from alveolar, bronchial, or nasal deposition due to their solubility, and those absorbed from the gastro-intestinal tract will affect various body organs and tissues. The importance of such radioisotopes can be evaluated by the methods discussed in "Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water" by the Subcommittee on Internal Dose of the National Committee on Radiation Protection, to be published as National Bureau of Standards Handbook 52. The capillary bed in the alveolar lung is much more efficient for uptake to the blood than is the G-I tract. (Some calculations have been made for mixed fission products by Harvey in CRLIR-81 that may be of interest.)

6 In consequence, air sampling procedures need make no finer distinction in particle size than does the human body, so long as this degree of sample separation is effectively achieved.

7 The values used in these illustrative calculations were selected as being reasonably typical in respect to median size, deviation, density, and concentration. The specific activity was chosen at random, since this will be governed by the circumstances of the exposure. Variation in specific activity will introduce non-linear changes in the resultant tissue dosage volumes and is given appended discussion.

Of the several mechanisms for particle retention, filtration and impaction are paramount in the nasal cavities, impaction and sedimentation in the bronchial "tree", and sedimentation and diffusion in the alveolar spaces. Retention times and clearance methods also differ⁴. Mucous secretion and ciliary action respectively trap and with fair rapidity transport particles from their upper respiratory deposition sites to the throat where they may be expectorated or swallowed. Swallowed particulate activity is subject to action by the fluids of the G-I tract and possible absorption therefrom⁵. In the case of certain physiological disturbances the viscosity of the mucous may not be proper for ciliary action to be as effective as otherwise.** Insoluble particles deposited in the alveolar spaces are chiefly removed by phagocytes, whose action is stimulated by the irritation aroused. They engulf and carry particles through intercellular spaces and lymphatic channels to the lymph nodes where they are retained. As an alternate, the phagocytes may carry particles to the edge of the ciliated epithelium of the terminal bronchioles. Where a particle cannot be handled by the phagocytes due to size or toxicity, the alveolar sac may close in and wall it off with fibrous tissue.

We may then consider two main divisions of the respiratory system (upper respiratory and alveolar) which differ in the major particle retention mechanism, the particle sizes retained, and the particle clearance characteristics. These differences govern the duration and, therefore, the intensity of the exposures received, and affect any maximum permissible values which might be derived⁶.

Numerical Example

The importance of the particle distribution parameters is borne out by considering three cases having the same numbers of particles per unit volume of air, the same median number size of 0.3μ and different standard deviations⁷.

**Certain respiratory infections also damage the cilia.

Table 1

	Standard Deviation σ_g	Mass Median Size μ	Total Mass Mg/m ³	Activity (1%) $\mu\text{c/cc}$	Submersion Dose mrep/hr
A	2.0	1.27	0.074	1.5×10^{-5}	5.3
B	2.7	5.8	0.69	1.4×10^{-4}	49.
C	3.66	46.8	16.0	3.2×10^{-3}	1120.

All distributions have number median size of 0.3μ . Concentration = $2 \times 10^8/\text{m}^3$
 of $\rho = 2.6$, Sp. Act. = 20 c/g,

⁸See appended discussion of Case II.

Table 2

	Total Mass Mg/m ³	Percent Mass Retained			Percent Exhaled
		Upper Resp.	Alveoli	Total	
A	0.074	18.2	43.8	62.0	38.0
B	0.69	68.9	19.8	88.7	11.3
C	16.	96.1	2.7	98.8	1.2

Number median size for all = 0.3μ diameter, concentrations
 constant at,

$$2 \times 10^8/\text{m}^3$$

⁹ The data used in this study is that given by Brown, Cook, Ney, and Hatch in Amer. Journal of Public Health, Vol. 40, No. 4, April 1950, on p. 458 with extrapolation above 5μ diameter sizes. See also the reference in note (3) p. 121-123 for comparison with the work of other investigators.

The results may be compared in Table 1. The shift of the mass median size and increase of total mass present show the significance of the σ value. If 1% active particles of 20 curies per gram and effective energy 0.35 Mev are assumed, a considerable difference in submersion exposure is seen with the same total particle concentration. If the total air activity is constant, the numbers of particles represented would vary for different σ values⁸.

Several investigators have studied the percentage alveolar and upper respiratory retention for various particle sizes. When this data is applied to the size distributions considered, the results may be seen and compared Table 2⁹.

Non-Uniform Dose Problems

In the setting of maximum permissible concentrations for radioactivity in air the critical organ has been considered to receive not over 0.3 rem/wk exposure on the basis of uniform concentration in absorbed microcuries per gram of organ. Using approximately 1000 gm for the lungs has seldom led to their selection as the critical organ. Other factors are the biological elimination rate from different parts of the respiratory system and the solubility of the material. At the Chalk River Conference the approximation was suggested that of the inhaled particulates 25% was retained in the lungs, 50% discharged to the G-I tract and the remaining 25% exhaled. This has been used by the Subcommittee on Internal Dose of the National Committee on Radiation Protection for the calculation of their value of f_a^{***} in Handbook 52 for soluble material. For insoluble material with the lung as the critical organ, f_a has been taken as 0.12.

It has been shown in Table 2 that a change in standard deviation of the particle size distribution will produce a variation of greater than an order of magnitude in the mass or activity retained in the alveoli and a

*** f_a = fraction retained by inhalation

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Table 3

Respiratory Section	No. Each	Internal Diameter cm	Length cm	Sector Volume 350 μ r
Trachea	1	1.3	11.0	1.61 cc
Bronchi	2	0.75	6.5	1.12
1st Ord. Bronchi	12	0.4	3.0	1.72
2nd Ord. Bronchi	100	0.2	1.5	3.87
3rd Ord. Bronchi	770	0.15	0.5	7.82
Terminal Bronchioles	5.4 x 10 ⁴	0.06	0.3	(169.)
Resp. Bronchioles	1.1 x 10 ⁵	0.05	0.15	---
Alveolar Ducts	2.6 x 10 ⁷	0.02	0.02	---
Alveolar Sacs	5.2 x 10 ⁷	0.03	0.03	---

¹⁰ Values used are taken from "Respiratory System: Aerosol Therapy" by Harold A. Abramson, Medical Physics, Otto Glasser, Editor-in-Chief, Vol. 2, 1950, p. 829.

¹¹ The terminal bronchioles were not included since their dimensions approach the magnitude of the assumed range of 350 μ . It should be pointed out further that the tissues at the junctures of the cylinders of this model will receive multiple exposure. Bronchial structures include considerable amounts of cartilage, muscle and connective tissue as well as the more sensitive epithelium, etc. The trachea-bronchial lymph nodes are arranged along the interior (away from the air) surfaces of these upper respiratory members and might receive some exposure from transient upper respiratory retained activity.

Table 4

	Retained Activity μ c		Average Tissue Dose Rates			
	Upper Resp.	Alveoli	Lung (HB52) mrep/hr	U. Resp. (16g) rep/hr	Alv (900g) rep/hr	L. Nodes (20g) rep/hr
A	2.73	6.6	1.5	0.14	5.8	0.26
B	96.5	27.8	13.5	4.8	24.8	1.1
C	3075.	86.5	308.	153.	77.	3.5

Concentration, number of particles, constant at $2 \times 10^8/\text{m}^3$
Number median size = 0.3 μ for each distribution

¹² Approximately an hour's exposure is assumed during which one cubic meter of air is breathed with resultant retention of particles and activity as shown. Different concentrations or lengths of exposure may be directly evaluated by the use of appropriate factors. For this type of exposure calculation the specific activity also introduces only linear variation.

¹³ Injury may take the form of abnormal cell wall permeability, derangement or malfunction of vital cellular enzyme systems, and impairment of cellular growth, division

difference of more than a factor of five in the upper respiratory retention. The amount exhaled will vary from 1.2 to 38%, a factor of 30. This indicates that the MPC values for airborne activity should be modified by a factor based on the particle size distribution where this can be determined.

Average Dosage Calculations

As a different approach, we may consider activity retained in the upper respiratory system as a uniform coating on the interior of a set of cylinders of tissue for calculating an average dose. To be conservative and include the possibility of mouth breathing, the tract from the trachea through the third order bronchi will be used. Table 3 gives some average dimensions of these organs from which their surface area can be calculated¹⁰. If an estimate is made that 90% of dose is expended within approximately 350 μ of the surface (this will vary with the energy), the volume of tissue affected may be calculated to be about 16 cubic centimeters¹¹.

The dose from the activity retained in the alveoli may be approximated on the basis of affecting 900 gm of tissue (the major remaining bulk of the lung). As an extreme alternate, one might consider the active particles entirely phagocytized to the lymph nodes, which vary widely in size and number with the health of the individual. A reasonable estimate is from 40 to 50 such nodes with a total mass of approximately 20 grams.

The values of average dosage obtained with these assumptions are given in Table 4 for the three particle size distributions considered¹².

Local Dosage Effects

The effects of radiation on the cell in vivo are death, damage, or stimulation (considered by some as a lesser form of damage¹³). Stimulated cells regenerate those tissues destroyed. At some degree of damage cells may become cancer foci, with a probability related to dose and damage the magnitude of which is not presently known. Radiation carcinogenesis is felt by some

and reproductive processes necessary for tissue regeneration and repair through breakage of chromosomes or destruction of genes. The relative hazard introduced when such effects are confined to comparatively small clusters of cells (10^2 to 10^5 cells) of different tissues is not presently known. This is also true of such effects as ageing, increased sensitivity to subsequent injury, and the possibility of carcinogenesis. With an increase of the numbers of such clusters of cells, receiving a wide range of exposure dosages and dose rates, the relative hazard may also increase (not necessarily in proportion). Specific activity and the range of radiations will be important dose rate variables in this connection.

¹⁴ No inference is made of the quantitative probability of cancer originating as a result of dosages produced by a single radioactive particle. Various values of increase in neoplasm incidence at different dosages are given by J. Furth and E. Lorenz in "Carcinogenesis by Ionizing Radiation" (as yet unpublished). Such dose-effect data for small areas of tissue must await further biological research. As none of the effects of radiation are beneficial, reasonable control measures significantly reducing the volumes of exposed tissue are felt to be warranted.

¹⁵ Work sheets of the formulae used and calculations made are appended.

Table 5

Percent Retained Particle Number		Volumes (μ^3) Receiving Indicated Dose Rates (rep/da) From Alveolar Retained Particles					
Upper Resp.	Alveoli	0.3-3.0	3.0-30	30-300	300-3000	> 3000	
A	0.37	37.5	1.6×10^{13}	8.5×10^{11}	3.9×10^{10}	1.5×10^9	5.6×10^7
B	2.25	36.2	8.5×10^{13}	5.7×10^{12}	3.2×10^{11}	1.5×10^{10}	6.2×10^8
C	5.26	34.8	3.2×10^{14}	2.5×10^{13}	1.5×10^{12}	8.3×10^{10}	3.8×10^9

Above is based on 1% active particles or 2×10^6 per cubic meter

Number median size = 0.3μ in each case. Spec. Act. = 20 c/gm

Inhalation of 1 m^3 is assumed (= approx. 1 hr exposure)

to become significant at or moderately below the LD-50 dose, with 5 to 10 fold increase in normal incidence¹⁴.

For a more precise hazard estimate it is necessary to consider the dosage rates in the immediate tissue vicinity of the dispersed alveolar particles. While the total active mass of the particles retained in the alveoli may be quite small in some particle distributions, the percent of the number of such particles is moderately high and less variable. The significance of this is that each such particle is a focus of radiation surrounded by a sphere of tissue in which the dosage will vary over a wide range. This variation results from both geometry and the beta energy spectrum.

Alpha emitting particles are not of comparable hazard since they are monoenergetic and increase in specific ionization at the end of their range, so as to largely compensate for geometry. This yields a sharply bounded sphere of heavily damaged or dead cells, to be replaced, rather than zones of lesser damaged cells, some small fraction of which can perhaps become cancer nuclei. Alpha emitting particles cannot be ignored and, when of the right specific activity and size, may produce critical dose rates in tissue spheres of about 40 microns radius (for 5 Mev alpha). Gamma radiation, especially when of moderate energy, can contribute a general dosage background on which the local high intensity particle dose rates are superimposed.

Zone Dosage Calculations

Using standard formulae, the volumes of tissue receiving dosages over ranges of different magnitude can be calculated for any particle activity. Multigroup calculations have been made using convenient particle size ranges and the corresponding percentages of alveolar retention and numbers of particles¹⁵. The results are presented for the three size distributions in Table 5. These consider the particles in one cubic meter or roughly an hour's exposure.

At present there is no valid biological data available that would give

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16 The effects of radiation exposure on the efficiency of ciliary transport are not known, although tests to give this data have been suggested by Dr. Marshall Brucer of the ORINS Medical Division. The larger particles handled here would have relatively much greater associated exposure rates. Due to the delay between exposure and effect, single or occasional particles should be readily handled. There is a valid uncertainty, however, in the case of numerous and repeated successions of such particles to be cleared.

the probability of cancer (or other harm) as a function of dose. If there were, one could apply these probabilities to the tissue volumes in the dose ranges as given in Table 5 and better estimate the hazard. Tissue cell volumes may fall in the range 500 to 5000 cubic microns. Thus there are many cells in the dose-rate ranges of 3 to 30 rep/day and 30 to 300 rep/day which may possibly represent the highest carcinogenic risk.

Radioactivity Parameters

In addition to the obvious hazard factors of length of exposure and concentration there are other important data which should be taken. The energy of the radiations is a highly significant factor directly bearing on their range in tissue and the volumes receiving different dosages.

Specific activity (curies/cc) is important since this will govern both the total activity borne by a given dust concentration and the activities of the particle sizes retained in each respiratory region. The ratio of active to inert particles is quite important, and like specific activity difficult to measure experimentally. This ratio may vary with particle size rather than being constant as assumed in these illustrative calculations. Similar variation of specific activity with particle size may occur. These nonlinearities can be handled by inserting appropriate factors for the size group in the calculations made. The decay rate of the activity present will govern the total dose received and should be measured.

Data on biological elimination rates is important to any estimate of total dose and in general is lacking. Estimates have been offered of around 24 hours for clearance of upper respiratory deposited particles by ciliary action, however, this transit rate is uncertain¹⁶. The rate and percent of phagocytic clearance is not known although it will certainly vary.

The lymphatic tissue to which alveolar particles are cleared is especially radiosensitive.

Sampling Recommendations

The most practical method of sampling air activity will favor simplicity, and speed of getting the right answer. The evaluation technique must be considered with the sampling method as a unified whole. The following method is the interim recommendation:

The sample is physically separated into two parts as collected, simulating the corresponding retention in the body. Probably the simplest way of achieving this is by the use of two filters and appropriate sampling conditions. The prefilter has an efficiency versus particle size retention characteristic which is reasonably close to that of the upper respiratory system. Such a filter may be available, or can be developed and might have relatively coarse or mixed size fibers or pores. The final filter will be of maximum efficiency, a satisfactory one being the now available molecular filter. Any non-aggregated ultra fine particles lost by penetration will be largely "soluble" due to their surface to mass ratio and in any case can diffuse through cell walls and be directly absorbed into the blood for possible concern to other organs. These normally contribute only a very small fraction of the total active airborne mass.

The two sample fractions are those handled differently by the respiratory system. A comparison of the separate gross activities of these two fractions gives some idea of the particle size distribution and permits an estimate of approximate tissue dosages.

These two samples are then exposed to X-ray film for a relatively short time. Absorption by inert components is not serious for the larger particles of higher activity on the prefilter nor for the surface held activity of the final filter. Filter areas can be chosen for the sampling times and flow rates to minimize particle overlap.

The diameter of the spot produced on the film by this exposure is a single valued monotonic function which may be measured precisely with a

- 17 This technique has been successfully employed by Dr. Julian H. Webb, Kodak Research Laboratories, Rochester, New York, in the investigation of the economic hazard of weapons test fall-out particles to X-ray emulsions.
- 18 Short-time exposures would readily display the concentration of higher activity particles of major biological hazard significance.
- 19 Some type of continuous gross air activity monitor would usefully indicate the need for collecting a sample for hazard evaluation. Warning from such a monitor might indicate the need for precautionary donning of respiratory protection. With suitable development, a dual filter continuous monitor could possibly be developed, but it is doubtful if it would be justified**.
- 20 The application of respirator filter removal efficiency vs particle size data to tissue volumes receiving significant exposure ranges as calculated for different particle size ranges will permit a more valid estimate of the degree of reduction of exposure afforded by various respirators. This could be applied also to the temporary expedients which might be recommended for civil defense usage.
- 21 Solution of activity in the pleural fluids will deplete the concentration present as an exposure focus as well as contributing (presumably a relatively small extent) to other body organ exposures. Diffusion of dissolved activity in adjacent cell tissues will enlarge the effective source of radiation from "point" dimensions and somewhat effect the more adjacent tissues receiving the higher exposure rates.
- 22 Plastic absorbers are to be preferred because of closer equivalence to tissue. Variations of the absorption range (effective energy) will introduce non-linear variations in affected tissue volumes.

** A simpler alternate might be two continuous air monitors using different grades of filter paper. The difference in readings could be indicative of the airborne radioactivity retained in the alveoli if proper choice of filter paper quality is made.

narrow slit densitometer to define the edge¹⁷. A simpler and usually adequate method would be to use a series of calibrated spots for comparison. This would permit rapid easy tabulation of the numbers of spots in various size ranges. A spot of one millimeter diameter corresponds roughly to 10^4 disintegrations, or a 30-minute exposure for particles of $1.5 \times 10^{-4} \mu$ c and larger. For the specific activity and density of the examples considered this would represent a diameter of 1.7μ . Subsequent exposures could be made for longer times¹⁸ for detailed study of size distributions if desired. A later exposure for the same length of time would disclose any non-uniformity of decay rates.

The presence of predominantly fine particles would be indicated by more diffuse film darkening and personnel should switch to masks from the respirators donned when the rise in gross air activity was first noted¹⁹. Respirators effective for particles greater than 0.5μ or 1.0μ are cheap and decrease the volume of exposed tissue by a factor of from 6 to over 200, depending on the particle distribution parameters²⁰. The respirator filters can likewise be filmed to show how much activity the wearers were protected from, and to give a large number of sample data showing far better than the otherwise few sampling points, the true distribution of air activity for the exposure.

Solubility data can be directly obtained by leaching for a suitable interval with an appropriate solution some of the sample material²¹. Range and energy data for the activity can be readily obtained by counting the filters with several absorber thicknesses (preferably plastic)²².

The above data on the air activity can be taken in a reasonably brief period of time. This is important when the estimate of hazard will be the basis for action. Such action might include evasion, the use of further personnel protection, or control of the source. In other cases, the hazard estimate may provide warning for others downwind or comparative data with which to anticipate conditions in future circumstances. There even may be

instances where the hazard estimates will be of value to claim commissions.

When further data is ultimately obtained that will permit more precise appraisal of the biological hazard, final improved recommendations can be offered. Meanwhile the interim method gives valuable data and a permanent set of records, as well as hazard estimates for present guidance.

(end of text of speech)

Thomas J. Burnett

October 14, 1952 (text)

November 15, 1952 (comments)

Supplement 1

Discussion of Calculations

Two salient points are emphasized in this study and illustrated in the accompanying calculations:

1. The non-uniform retention and deposition of airborne activity requires that the sampling method effectively recognize the particle sizes present.
2. The non-uniformity of dosage resultant to respiratory tissues must be recognized in the appraisal of potential hazard from particulate borne air activity.

The above conclusions are not invalidated despite occasional imperfections in the rigor of various assumptions used herein:

1. Nasal retention of activity, in the case of those not breathing through their mouths, would partially shift the effective tissue exposure. More tissue would be involved, some areas would receive lesser exposure.
2. Size (and activity) gradation along the bronchial tree would occur (with substantial overlap), relatively smaller particles tending to be retained farther down as the air progresses through smaller diameter ducts with lower linear velocity. This might permit extending the upper respiratory exposure model to the terminal or even respiratory bronchioles. Although more tissue is thus involved, there is concurrent greater non-uniformity.
3. The particle size vs percent retention curve used was that for maximum alveolar retention, while the true value is probably somewhere between the curves for maximum and minimum retention, due to differences from the assumed equality of upper respiratory retention in both directions. The differences between true values in any specific case and the assumed maximum retention would be relatively small, although affecting some particles of larger physical size. The assumed values are more conservative for certain size ranges and for these may somewhat overstate the affected tissue volumes. However, the variations between individuals are at least as great, as well as are differences introduced in the respiratory retention pattern by exertion, emotion, infections, etc.
4. The suggested prefilter collecting a sample representing upper respiratory retention will not effect a sharp size separation--but neither do the lungs. Its characteristics can at best be a reasonably close approximation since the air flow sampled will be constant in velocity and direction while that in the lungs is reciprocating in direction and variable in flow rate.
5. Loss of some small particles collected by the prefilter would be compensated for on the final filter by its retention of some that would be exhaled. The small particles retained on the first filter would contribute only relatively minor additional activity.

6. The particles considered are not perfect spheres, but this would only introduce a constant for shape factor applying linearly throughout. Volumes would still vary as the cube of some composite equivalent linear dimension.
7. The effects of shape on particle retention are considered minor, and the particles involved in an exposure would probably depart from ideal spheres to an extent comparable to that of the particles used in the retention studies.

Values obtained in any case if not completely quantitative can, nevertheless, be of accuracy comparable to other health physics survey measurements and of considerably better certainty than present biological data.

The only alternate to a two stage collection system as discussed is a complete multiple stage instrument making sharp separation in sizes. The corresponding stages would have to be evaluated for numbers of particles and the activity associated with each in order ultimately to reconstruct a size - activity - lung tissue exposure distribution. The necessary multiple steps and tedious microscopy make such an alternate slow, impractical, and of little general use.

For some engineering studies other types of particle collecting instruments may have specific uses. Caution and careful consideration of the limitations of the instrument would be required before the data thus obtained could serve (if at all) as any indication of the radiation health hazards involved.

Necessity of Air Sampling

Field studies of activity releases generally show no dependable correlation between airborne activity and fall-out or external exposure rate measurements. This can be readily understood from the calculations for Case II where a constant air activity is considered with variation of particle size distributions (see pgs A29 et seq. of Appendix A). An hour's exposure to an air activity concentration giving 0.1 rep/hr submersion exposure rate leads to such internal exposure as upper respiratory dose rates of from 3 to 15 reps/hr, and even average alveolar exposure rates between 123 and 8 mrep/hr (lymph node dosages are correspondingly higher, of the order of reps/hr). This alone would deny the propriety of failure to sample air activity concentrations.

Since there is a reasonable probability of a unique hazard from radioparticulates it is felt that air sampling should be mandatory despite any presumed safety on the basis of minimal external exposure levels.

J.H.
November 3, 1952

22

Supplement 2

The Radioparticulate Hazard*

1. The assumption of a unique hazard associated with the inhalation of insoluble radioactive particles as compared with the different hazard from the intake of soluble materials rests upon the following two points of difference:

a The lung retention of the particulate material is not a constant fraction of the quantity inhaled but varies with the size distribution of the particles. The site of deposition in the upper respiratory tract or in the alveoli similarly varies with particle size. This means that a constant fraction must not be used in the equation for calculating permissible air concentration. On the contrary, it requires that the upper respiratory and deep lung retention values must be determined for any given exposure by suitable size analysis or by a sampling procedure which separates the particles into two fractions comparable to the separation which occurs in the respiratory system.

b The radioactive particle deposits in the lungs do not produce uniform radiation of the total organ. Therefore, particles may act as separate foci of relatively intense radiation (per gram of tissue) around each particle. In the same way, groups of particles resulting from natural processes of concentration of the dust in the lungs may produce a high dosage in a small fraction of the total lung. This may occur, for example, in the lymph nodes which are said to be more radio-sensitive than lung tissue.

2. There is no question about point a above. Radioactive particles do not behave differently from others in respect to deposition in the respiratory tract, and it is easy to show that the percentage of deposition in the upper respiratory tract and in the alveoli may vary widely depending upon the size distribution. It is not necessary, therefore, to accept the reality of the particle problem to justify the need for a sampling method which separates airborne particulate matter in accordance with the separation which takes place naturally in the respiratory tract. This procedure makes it unnecessary to employ an assumed constant fraction for lung deposition as is now done in the standard method of calculating the permissible atmospheric concentration.

3. The argument for a unique particle problem rests primarily upon the production of non-uniform radiation of the lungs. Permissible atmospheric concentration of radioactive materials are, in every case, calculated values. Starting with an assumed maximum permissible dosage rate per gram of tissue, the calculations are based upon an assumed relationship between the atmospheric concentration and the rate of deposition of the active material in the critical organ. In the case of soluble materials, the activity is transported from the lungs by solution into the blood stream and is then concentrated in the critical organ, where it is assumed to be uniformly distributed. This assumption may not be correct; but the non-uniformity, if it exists, is the result of natural processes within the organ and is not determined by the physical size of the particulate matter deposited in the lungs. With insoluble particles, on the other hand, the lung itself is the critical organ, and so long as the particles remain as such in the lungs the non-uniformity of radiation in the lung tissue must be accepted as a fact. This is true at the time of initial deposition and the radiation is bound to become less

*This presentation by T. F. Hatch, summarizes well the discussions on the "particle particle" at the recent Health Physics Conference. It is presented here for the interest and comments of health physicists and others.

uniform with time as the particles become concentrated through the natural process of handling of dust particles in the lungs. For example, there is a tendency toward the concentration of particles in lymph nodes. Depending upon the activity per particle and other energy characteristics, the intensity of radiation in the tissue immediately around each particle or group of particles will vary with distance from a high to a low level. In the case of radiation with limited penetrating power, the distance between the particle foci may be great enough to result in a non-hazardous dose of radiation to some portions of the lung tissue. It follows, therefore, that in the logical use of the standard equations for calculating dosage, it is not valid to assume uniform radiation of the lungs. To illustrate this point, consider the situation if all the dust were taken up by the lymph nodes. Since these weigh no more than 20 grams as compared with 1000 grams for the total lungs, there would be at once a 50 fold increase in the tissue dosage.

4. The argument against a unique particle hazard rests principally upon the point that only a few cells are affected by the localized radiation about particle foci, and with the small number of particles affected, an unusual hazard is not produced. If this is true, then it must logically follow that insoluble particles in the lungs constitute a lesser hazard than is estimated by the usual method of calculation, since non-uniform radiation is inevitably associated with these insoluble particles. It is obvious, however, that the number of cells exposed to excessive radiation will vary depending upon the activity per particle, form of radiation and energy level, and the number of active particles. For 1 - 1.5 micron particles with 20 curies per gram of β -radiation and $\sum bE = 0.35$ Mev., the volume of tissue around a single particle which receives more than 30 to 300 rep per day amounts to 3×10^5 cubic microns. Assuming the volume of a single cell to be 300 cubic microns, the number involved in this example will be 1000 cells per particle. Since many such particles may be deposited in the lung following a typical dust exposure, it is evident that large numbers of cells will receive radiation in excessive amounts.

5. There is no experimental evidence in support of or against the reality of the particle problem. It must be noted, however, that the accepted atmospheric tolerance levels for various soluble materials are based upon rather elaborate calculations involving some basic assumptions with respect to the biological aspects of the problem. These assumptions are logical and it seems only reasonable that they should be similarly applied to an analysis of the situation in the lungs. In order to accumulate the necessary evidence in support of or against the particle hazard, it will be necessary to measure exposures to insoluble radioactive particles in such a way as to permit an estimate of the nature and magnitude of the lung doses, including recognition of its non-uniform distribution. This means that the methods of sampling and analysis must be selected to give the required information with respect to size distribution and activity per particle. So long as particulate exposures are measured only in terms of total activity and without reference to the size and activity per particle, the necessary information will not be forthcoming.

6. The present assignment calls for the recommendation of appropriate methods of sampling and analysis for the appraisal of exposures to insoluble radioactive particulate materials. The first question which confronts us is whether or not a particle hazard exists. If it does not then the sampling needs are rather simple. Past practice has called only for the separation of all of the particles (without reference to size) from a known volume of

air and the measurement of activity in this collected material. This is not an acceptable procedure since it does not give a proper recognition to the fact that the amount of dust deposited in the lungs may vary widely depending upon the size distribution. Whether or not a unique particle hazard exists, it is necessary that the sampling procedure be carried out in such a way as to permit the estimation of the fraction of the inhaled dust which is deposited in the deep lung spaces. If a particle hazard does exist, then additional information is required concerning the distribution of activity among the particles, including the number of individual particles, the variation in activity per particle and the nature and energy level of the radiation from the particles. To obtain these added pieces of information, it is necessary that the particles be deposited by the sampling device with sufficient distance between them to permit individual measurements of activity, etc.

7. We may conclude from the foregoing:

a There is no firm evidence at present in support of or against the reality of a unique hazard associated with the inhalation of insoluble radioactive particles.

b There is no question about the role of particle size in determining the fraction of inhaled particulate matter which is deposited in the upper respiratory tract and in the alveoli. Differences in particle size distribution which may be encountered will result in wide differences in the fractions so deposited.

c It is not proper to employ a constant fraction for lung deposition in the equation used to calculate permissible atmospheric concentrations of particulate matter.

d Whether or not a unique particle hazard exists, it is, therefore, necessary in the sampling of radioactive particulate materials to employ techniques which will indicate how much of the dust is deposited in the upper respiratory tract and how much in the alveoli.

e In the absence of definite proof for or against a unique particle hazard, we believe that the wise procedure is to employ sampling and analytical methods which will determine the essential characteristics of particulate activity and, in turn, will provide a proper basis for the appraisal of the particulate hazard (if one exists). Only in this way will it be possible to accumulate the necessary evidence in support of or against the reality of the particle problem. So long as the present method of sampling (which gives no recognition to variation in particulate activity with size) continues in use, the necessary information will not be obtained.

8. Proper recognition of the role of particle size in determining the hazard does not require refined measurements of size distribution. Our interest in size itself does not extend beyond its influence upon the fractions of dust deposited in the upper respiratory tract and alveoli respectively. We recommend, therefore, the use of a relatively simple, two stage sampling apparatus. The collecting characteristics of the first stage will simulate those of the upper respiratory tract. This means that the efficiency of collection should be 80% or more for 5 micron particles and should drop off systematically to zero efficiency at about 1 micron. The second stage of collection must be 100% down to 1 or 2 microns. It may drop off for smaller sizes in accordance with the collecting characteristics of the alveoli but it would be simpler to employ a collecting medium with high

efficiency against these finer particles. As noted above, we believe that such a two stage apparatus or its equivalent is necessary for the sampling of radioactive particles without reference to a unique particle hazard.

The two stage apparatus must deposit the active particles with sufficient space between them to permit individual particle examination by radioautography. By this means it will be possible to determine the number of active particles and the activity per particle. By introducing known absorbing media it will be possible to determine the penetration characteristics of the radiation. Repeated measurements spaced in time will determine the decay rate of the particulate material.

T. F. Hatch
University of Pittsburgh
Pittsburgh, Pennsylvania

October 20, 1952

Sampling for Radioparticulate Hazards - Appendix ACalculations

1. The first step is the choice of assumptions relative to the retention of inhaled airborne materials as a function of particle size. (Pgs. A1, A2)
2. Three hypothetical sets of characteristics are chosen specifying the particle distributions A, B, and C. The corresponding mass concentrations are then calculated based on shape and density assumptions. The resultant amounts of activity retained in different parts of the lung as related to particle size are next developed using convenient (Case I) assumptions of concentrations, etc. (Pgs. A3 - A17)
3. Associated exposure values are calculated for the different particle distributions with the Case I assumptions. (Pgs. A18 - A28)
4. With modified assumptions (Case II) the changed exposure values are calculated for comparison. (Pgs. A29 - A30)
5. The relative influence of changes in the several variables is discussed. (Pgs. A31 - A34)

Comments - Appendix A

The data on lung retention vs particle size was replotted with reasonable care from Figure 5, Pg. 458, Vol. 40, No. 4, Apr. '50, American Journal of Public Health to include arbitrary extrapolation down to 0.1μ and above 5μ diameter particles. A systematic increase in efficiency was assumed for the upper respiratory retention following the curvature of the given plot to a value of 100% around 20μ . Alveolar retention was similarly extended using the curve for maximum retention, with care that the sum of ordinates approached systematically, but did not exceed, 100%.

28

NOT CLASSIFIED

1620 31

A-1

Comments - Appendix A

The data on lung retention vs particle size in A-1 has been replotted on log-log paper to determine the appropriate divisions of size range such that an average retention value for the range will be reasonably valid. Sections are chosen to include limiting regions (such as alveolar for $>15\mu$.)

Logarithmic abscissae permit convenient display of the range of particle sizes normally encountered. Logarithmic ordinates permit graphical application of retention factors to numbers (or mass) of particles in size ranges.

30PARTICLE DIAMETER, MICRONS (μ)

Comments - Appendix A

The distribution parameters of median size and standard deviation were arbitrarily selected to cover a reasonable range of typical standard deviations and a normal average value of median size.

The calculation of mass median diameters follows the methods in "Industrial Dust" by P. Drinker and T. Hatch Chapter 8. (McGraw-Hill Book Co., Inc., New York, 1936)

Log-normal dust distributions were assumed for the purpose of the illustrative cases considered.

These data are used in the preparation of Table 1.

The assumptions to be used in Case I are presented at this point. This case considers a constant concentration of numbers of particles. The case of a constant concentration of activity is considered on A29.

WORK SHEET - DISTRIBUTION PARAMETERS

DISTR:

"A" NUMBER MEDIAN PARTICLE DIAMETER $M_g = 0.3 \mu$

DEVIATION $\sigma_g = 2.0$

84.13% size = 0.6μ 15.87% size = 0.15μ

By: $\log M_g = \log M_g' - 6.9078 \log^2 \sigma_g$ (INDUSTRIAL DUST, Minkus + Hatch)

$\log M_g' = 9.47712 - 10 + 6.9078 (0.30103)^2 = 0.10301$

MASS MEDIAN DIAMETER $M_g' = \underline{1.27 \mu}$

"B" NUMBER MEDIAN PARTICLE DIAMETER $M_g = 0.3 \mu$

DEVIATION $\sigma_g = 2.7$

84.13% size = 0.81μ 15.87% size = 0.11μ

$\log M_g' = 9.47712 - 10 + 6.9078 (0.43136)^2 = 0.76245$

MASS MEDIAN DIAMETER $M_g' = \underline{5.79 \mu}$

"C" NUMBER MEDIAN PARTICLE DIAMETER $M_g = 0.3 \mu$

DEVIATION $\sigma_g = 3.66$

84.13% size = 1.1μ 15.87% size = 0.082μ

$\log M_g' = 9.47712 - 10 + 6.9078 (0.56348)^2 = 1.67041$

MASS MEDIAN DIAMETER $M_g' = \underline{46.8 \mu}$

ASSUMPTIONS - CASE I

Constant: Concentration / vol of air: $C = 2 \times 10^5$ particles/liter

Ratio $\frac{\text{active}}{\text{inert}}$ particles: $R = 1\%$ for all sizes

Shape - assumed spherical

Density: $P = 2.6 \text{ gm/cubic centimeters}$

Specific Activity: $A = 20$ curies/gram

Therefore varying: activity concentration in air
exposures and retentions
mass median diameters with distributions

This is a logarithmic probability plot of distribution A.

The number distribution is shown by the solid line with size ordinates at the left. The mass distribution is shown by the broken lines with size ordinates at the right.

NOT CLASSIFIED

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DISTRIBUTION

34

1620 37

The mass distribution of particles of distribution A in the size ranges selected is plotted as a histogram (total ordinates = 100%) on the graph shown on Page A2. It is seen how the amounts of mass (or activity) in the airborne contamination breathed are distributed by size relative to the retention characteristics of the lung.

The outer histogram is the distribution of (active) mass in the air breathed, the shaded overlapping inner ones are those giving the distribution of retained (active) mass of particles respectively for alveolar and upper respiratory lung regions.

For comparison, see distribution B on Page A7 and distribution C on Page A9.

36

PARTICLE DIAMETER, MICRONS (μ)

37

This is a logarithmic probability plot of distribution B.

The number distribution is shown by the solid line with size ordinates at the left. The mass distribution is shown by the broken line with size ordinates at the right.

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38

DISTRIBUTION "B"

The mass distribution of particles of distribution B in the size ranges selected is plotted as a histogram (total ordinates = 100%) on the graph shown on Page A7. It is seen how the amounts of mass (or activity) in the airborne contamination breathed are distributed by size relative to the retention characteristics of the lung.

The outer histogram is the distribution of (active) mass in the air breathed; the shaded overlapping inner ones are those giving the distribution of retained (active) mass of particles respectively for alveolar and upper respiratory lung regions.

For comparison see distribution A on Page A5 and distribution C on Page A9.

A7

Mass Distribution
"B"

40

PARTICLE DIAMETER, MICRONS (μ)

1620 43

Unclassified

41

This is a logarithmic probability plot of distribution C.

The number distribution is shown by the solid line with size ordinates at the left. The mass distribution is shown by the broken line with size ordinates at the right.

Reverse A7, facing A8

NOT CLASSIFIED

42

DISTRIBUTION "C"

1620 45

48

43

The mass distribution of particles of distribution C in the size ranges selected is plotted as a histogram (total ordinates = 100%) on the graph shown on Page A2. It is seen how the amounts of mass (or activity) in the airborne contamination breathed are distributed by size relative to the retention characteristics of the lung.

The outer histogram is the distribution of (active) mass in the air breathed, the shaded overlapping inner ones are those giving the distribution of retained (active) mass of particles respectively for alveolar and upper respiratory lung regions.

For comparison see distribution A on Page A5 and distribution B on Page A7.

A 9

Mass Distribution
"C"

44

PARTICLE DIAMETER, MICRONS (μ)

1620 47

Unclassified 3/15

45

The three mass distributions are plotted on Page A10 for ease of comparison and the shift of mass away from the smaller sized particles is readily seen.

Also plotted on this same figure are the alveolar and upper respiratory retentions, using the non linear percent scale. It can thus be visualized how the shift of significant mass percent (say the range from 10 to 90 percent) to larger sizes with increasing standard deviation and constant mean particle diameter produces a shift in retention from alveolar to upper respiratory.

NOT CLASSIFIED

46

% MASS GREATER THAN STATED SIZE

The three particle size distributions are plotted on Page A11 to show the variation of the standard deviation. These are true log-normal plots (as a frequency distribution histogram) using convenient size intervals of one tenth decade and values read from the graphs on Pages A4, A6, A8.

For comparison, and following the previous examples, the alveolar and upper respiratory retentions are also shown.

These are number distributions, the corresponding mass distributions are shown on Page A12.

NEUFEL & ESSER CO., N. Y. NO. 355-91
Semi-Logarithmic, 5 Cycles X 10 to the inch, 6th line ascended.
MADE IN U.S.A.

49

The three mass distributions corresponding to the number distributions plotted on Page All are here shown.

With the alveolar and upper respiratory retentions shown it is clearly seen how the shift of mass median size affects the retained activity.

In the previous graph (All), the change in standard deviation made relatively little difference in the number percent of retained particles, particularly those deposited in the alveoli. Hence, the local tissue dosage, affected by the number of foci, is less variable.

Reverse All, facing Al2

KEUFFEL & ESSER CO., N. Y. NO. 350-91
Semi-Logarithmic, 5 Cycles X 10 to the Inch, 5th lines accented.
MADE IN U.S.A.

The assumptions of A3 define the manner of distribution of the number and mass of particles among different size groups.

The approach made on A12 represents a manner of getting the total mass concentrations (in gm/l) of the hypothetical particle distributions from the assumed number concentrations. In a practical case the total mass concentration would be measured experimentally by sampling.

Having selected appropriate size groups it is necessary to assume an equivalent average diameter for the particles in the size range considered. This is done as a mass average diameter, to later calculate the local dosage from associated activity.

Subsequent to these calculations it was ascertained that the total mass for the distribution can readily be determined using this formula for the mass average diameter, D:

$$\log D = \log Mg + 3.4539 \log^2 \sigma_g$$

whence the;

$$\text{Total mass concentration} = \frac{\pi}{6} [D]^3 \times 10^{-12} \times \rho \times C$$

This is a more precise value than those obtained herein but the errors are sufficiently small (aver. 10%) and systematically high so that they do not affect the validity of the argument.

WORK SHEET - CALCULATION OF MASS CONCENTRATIONS

DEFINITIONS:

C = concentration of particles per unit volume of air
 = total number of particles per liter

ρ = density of particles in gm/cm^3

$\bar{\phi}$ = weighted average diameter of particles
 in a given size range, such that:

$\frac{\pi}{6} [\bar{\phi}]^3 \times 10^{-12}$ represents the average
 volume in cm^3 of ^{each of} the particles in this
 size range.

$N\%$ = the percent of the total number of particles
 in a given size range, hence

$N\%_j \times C$ = the number of particles/liter in a
 "size range j "

$M\%$ = the percent of the total mass of particles in a
 given size range.

$M\%_j$ = the percent of the total mass in range j

CALCULATION:

$\frac{\pi}{6} [\bar{\phi}_j]^3 \times 10^{-12} \times \rho$ = mass of an average particle in range j (gms)

$[N\%_j \times C] \times [\frac{\pi}{6} [\bar{\phi}_j]^3 \times 10^{-12} \times \rho]$ = mass concentration (gm/l) of the
 particles in the size range j

therefore:
$$\frac{\frac{\pi}{6} \times 10^{-12} \times [\bar{\phi}_j]^3 \times [N\%_j] \times \rho C}{M\%_j} = \text{mass concentration for the distribution}$$

$$= \text{gm/liter for the total number of particles}$$

and
$$[\bar{\phi}_j]^3 = \frac{\text{mass conc. (gm/l) of total} \times M\%_j}{\frac{\pi}{6} \times 10^{-12} \times \rho \times C \times N\%_j}$$
 for dosage calc.

Working from the graph of distribution A (Pg. A4) the number and mass percents are read off corresponding to the end points of the 13 selected size ranges. These readily yield the percent of mass or number of particles in each of the size ranges of interest. Since distribution A was worked first, a somewhat greater accuracy was attempted with B and C.

An average percent retention (both alveolar and upper respiratory) for application to each of the size ranges was determined by inspection of their graph (Pg. A2) versus size. The basis for selection of the size ranges was that within each the retentions varied in a manner permitting reasonably valid use of an average.

Application of the average retention percents to the corresponding mass or number percents yields for each range its retention as a percent of the distribution total. The sum of these thus gives overall retention, distributed between upper respiratory and alveolar.

A summary of these data results is given (Pg. A17) wherein the three distributions can be compared.

An average diameter is selected from the mass distribution graph (A4) to correspond to the average or mid-mass percent of a size range having significant percents of both mass and number. Using the formulae of Pg. A13 values are calculated for the total mass concentration of distribution A. Three such determinations are averaged and Case I assumptions used to yield activity concentrations.

WORK SHEET DISTRIBUTION "A"

MASS DISTRIBUTION:

SIZE RANGE μ	RANGE LIMITS: %	% IN RANGE	UPPER RESP. RETEN. FACTOR	RETEN. %	ALVEOLAR RETENTION FACTOR	%
<0.1	0.01				<.20	
0.1-0.2	0.01-0.4	0.4			.26	0.105
.2-.3	0.4-1.9	1.5			.33	.50
.3-.5	1.9-9.0	7.1			.41	2.95
0.5-1.0	9.0-36	27.			.51	13.7
1.0-1.5	36-59	23.	<.01	.23	.54	12.4
1.5-2.0	59-74	15.	.23	3.45	.45	6.8
2-.4	74-95	21.	.51	10.6	.31	6.5
4-7	95-99.25	4.3	.76	3.25	.19	.81
7-10	99.25-99.85	0.6	.88	.52	.12	.071
10-15	99.85-99.98	0.1	.95	.10	.037	.004
15-30		100.0	.99	18.2 TOTAL	<.001	43.8 TOTAL
>30			1.00			

NUMBER DISTRIBUTION:

SIZE RANGE μ	RANGE LIMITS: %	% IN RANGE	UPPER RESP. RETEN. FACTOR	RETEN. %	ALVEOLAR RETENTION FACTOR	%
<0.1	5.5	5.5			<.20	1.1
0.1-0.2	5.5-28	22.5			.26	5.85
.2-.3	28-50	22.0			.33	7.26
.3-.5	50-76.5	26.5			.41	11.28
0.5-1.0	76.5-95.7	19.2			.51	9.8
1.0-1.5	95.7-98.9	3.2	<.01	<.032	.54	1.73
1.5-2.0	98.9-99.66	0.8	.23	.184	.45	.36
2-.4	99.66-99.99	0.3	.51	.153	.31	.09
4-7			.76	TOTAL .37	.19	37.5 TOTAL
7-10			.88		.12	
10-15			.95		.037	
15-30			.99		<.001	
>30			1.00			

Size range 0.3-0.5 μ , 7.1% mass $1.9 + \frac{7.1}{2} = 5.45\%$ mass midpoint $\Rightarrow$ 0.415 av. diameter
 $\{0.3-0.5\}: \frac{\pi}{6} \times 10^{-12} \times [4.15]^3 \times .266 \times f_{xc} = 0.140 \times 10^{-12} f_{xc}$
 .071

Size range 0.5-1.0, 27% mass $9 + \frac{13.5}{2} = 22.5\%$ mid mass $\Rightarrow$ 0.745 av. diameter
 $\{0.5-1.0\}: \frac{\pi}{6} \times 10^{-12} \times [7.45]^3 \times .191 \times f_{xc} = 0.154 \times 10^{-12} f_{xc}$
 .27

Size range 1.0-1.5, 23.1% mass $36.2 + \frac{23.1}{2} = 47.75\%$ mid mass $\Rightarrow$ 1.23 μ av. diam
 $\{1.0-1.5\}: \frac{\pi}{6} \times 10^{-12} \times [12.3]^3 \times .032 \times f_{xc} = 0.136 \times 10^{-12} f_{xc}$
 .231

$$\text{AVERAGE} = \frac{1}{3} (140 + 154 + 136) = .143 \times 10^{-12} f_{xc}$$

$$\text{FOR } P=2.6 \text{ AND } G=2 \times 10^5 / l$$

$$\text{CASE I } 0.143 \times 10^{-12} \times 5.2 \times 10^5 = 0.744 \times 10^{-7} g/l$$

$$f_{xc} = 5.2 \times 10^5$$

$$\text{MASS} = 7.44 \times 10^{-8} g/l$$

$$7.44 \times 10^{-8} \mu g/l$$

$$0.074 \mu g/m^3$$

$$\text{FOR } 20 \text{ } \mu\text{m} = 14.9 \times 10^{-8} c/l = 1.5 \mu c/l = 1.5 \times 10^{-3} \mu c/cc$$

ACTIVITY (IF ALL ACTIVE)

IN RANGE .5 to 1.5 μ ARE 11.53% OF 23000/LITER RETAINED OF 43000 PRESENT

WITH 1% OF PARTICLES ACTIVE.

$$1.5 \times 10^{-3} c/l = 1.5 \times 10^{-2} \mu c/l = 1.5 \times 10^{-5} \mu c/cc$$

(1% ACTIVE)

THEN

230 ACTIVE PARTICLES .5 TO 1.5 μ DIAMETER/LITER

LUNG RETAINS:

$$2.3 \times 10^5 \text{ ACTIVE PARTICLES}/M^3 (0.5 \text{ TO } 1.5 \mu \phi)$$

$$2.35 \times 10^5 / m^3 (0.3 \text{ TO } 0.5 \mu \phi)$$

Working from the graph of distribution B (Pg. A6) the number and mass percents are read of corresponding to the end points of the 13 selected size ranges of interest.

An average percent retention (both alveolar and upper respiratory) for application to each of the size ranges was determined by inspection of their graph (Pg. A2) versus size. The basis for selection of the size ranges was that within each the retentions varied in a manner permitting reasonably valid use of an average.

Application of the average retention percents to the corresponding mass or number percents yield for each range its retention as a percent of the distribution total. The sum of these thus gives overall retention, distributed between upper respiratory and alveolar.

A summary of these data results is given (Pg. A17) wherein the three distributions can be compared.

An average diameter is selected from the mass distribution graph (A6) to correspond to the average or mid-mass percent of a size range having significant percents of both mass and number. Using the formulae of Page A13 values are calculated for the total mass concentration of distribution B. Three such determinations are averaged and Case I assumptions used to yield activity concentrations.

WORK SHEET DISTRIBUTION "B"

MASS DISTRIBUTION:

SIZE RANGE	RANGE LIMITS: %	% IN RANGE	UPPER RESP. RETEN. FACTOR	RETEN. %	ALVEOLAR RETENTION FACTOR	%
<0.1					<2.20	
0.1-0.2	20.039	20.039			.26	2.01
.2-.3	20.39-0.165	0.126			.33	.04
.3-.5	0.165-0.73	0.565			.41	.23
0.5-1.0	.73-4.0	3.27			.51	1.67
1.0-1.5	4.0-8.9	4.9	<1.01	<1.05	.54	2.64
1.5-2.0	8.9-14.6	5.7	.23	1.31	.45	2.56
2.-4.	14.6-35.5	20.9	.51	10.66	.31	6.48
4-7	35.5-57.5	22.0	.76	16.71	.19	4.18
7-10	57.5-70.6	13.1	.88	11.52	.12	1.57
10-15	70.6-82.7	12.1	.95	11.49	.037	.45
15-30	82.7-94.9	12.2	.99	12.07	<.001	<1.01
730	94.9-100.0	5.1	1.00	5.1		
		TOTAL 100.00			TOTAL	19.84

NUMBER DISTRIBUTION:

SIZE RANGE μ	RANGE LIMITS: %	% IN RANGE	UPPER RESP. RETEN. FACTOR	RETEN. %	ALVEOLAR RETENTION FACTOR	%
<0.1	13.5	13.5			<2.20	<2.70
0.1-0.2	13.5-34.3	20.8			.26	5.41
.2-.3	34.3-50.0	15.7			.33	5.18
.3-.5	50.0-69.5	19.5			.41	7.99
0.5-1.0	69.5-88.6	19.1			.51	9.74
1.0-1.5	88.6-94.6	6.0	<1.01	<1.06	.54	3.24
1.5-2.0	94.6-97.1	2.5	.23	.58	.45	1.12
2.-4.	97.1-99.51	2.41	.51	1.23	.31	0.75
4-7	99.51-99.915	0.405	.76	.31	.19	.08
7-10	99.915-99.975	0.060	.88	.05	.12	<.01
10-15	99.975-100.0	0.025	.95	.02	.037	
15-30			.99		<.001	
730		TOTAL 100.00	1.00	42.25 TOTAL		436.22 TOTAL

SIZE RANGE: [0.5-1.0] 2.27% mass, mid % = 2.365 $\bar{\phi} = 0.776$ $\frac{\pi}{6} \times 10^{-12} [0.776]^3 \times .191 \times P \times C = 1.42 \times 10^{-12} PC$

[1.0-1.5] 4.9% mass, mid % = 6.45 $\bar{\phi} = 1.26$ $\frac{\pi}{6} \times 10^{-12} [1.26]^3 \times .060 \times P \times C = 1.28 \times 10^{-12} PC$

[1.5-2.0] 5.7% mass, mid % = 11.75 $\bar{\phi} = 1.76\mu$ $\frac{\pi}{6} \times 10^{-12} [1.76]^3 \times .025 \times P \times C = 1.25 \times 10^{-12} PC$

AVERAGE = $\frac{1}{3} [1.42 + 1.28 + 1.25] = 1.32 \times 10^{-12} PC$, FOR $P = 2.6$ AND $C = 2 \times 10^5/L$
 $P \times C = 5.2 \times 10^5$

CASE I $1.32 \times 10^{-12} \times 5.2 \times 10^5 = 6.86 \times 10^{-7} \text{ gm/L}$

MASS = $6.86 \times 10^{-7} \text{ GM/LITER} = 0.69 \mu\text{g/L} = 0.69 \text{ mg/m}^3$

FOR 20 CURIES/GM, $= 137 \times 10^{-3} \text{ g/L} = 13.7 \mu\text{C/L} = 0.014 \mu\text{C/cc}$ ACTIVITY (IF ALL ACTIVE)

IN RANGE .5 to 1.5 μ an 12.98% or 26000/LITER RETAINED IN ALVEOLI OF THE 50200 PRESENT

With 1% of particles active, $1.4 \times 10^{-3} \text{ g/L} = 0.14 \mu\text{C/L} = 1.4 \times 10^{-4} \mu\text{C/cc}$ (1% ACTIVE)

THEN
LUNG
RETAINS

260 ACTIVE PARTICLES 0.5 TO 1.5 μ DIAMETER/LITER

2.6×10^5 ACTIVE PARTICLES/ M^3 (0.5 TO 1.5 μ ϕ)

$1.6 \times 10^5 / \text{M}^3$ (0.3 TO 0.5 μ ϕ)

Working from the graph of distribution C (Pg. A8) the number and mass percents are read off corresponding to the end points of the 13 selected size ranges. These readily yield the percent of mass or number of particles in each of the size ranges of interest.

An average percent retention (both alveolar and upper respiratory) for application to each of the size ranges was determined by inspection of their graph (Pgs. A2) versus size. The basis for selection of the size ranges was that within each the retentions varied in a manner permitting reasonably valid use of an average.

Application of the average retention percents to the corresponding mass or number percents yield for each range its retention as a percent of the distribution total. The sum of these thus gives overall retention, distributed between upper respiratory and alveolar.

A summary of these data results is given (Pg. A17) wherein the three distributions can be compared.

An average diameter is selected from the mass distribution graph (A8) to correspond to the average or mid-mass percent of a size range having significant percents of both mass and number. Using the formulae of Pg. A13 values are calculated for the total mass concentration of distribution C. Four such determinations are averaged and Case I assumptions used to yield activity concentrations.

WORK SHEET DISTRIBUTION "C"

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MASS DISTRIBUTION:

SIZE RANGE μ	RANGE LIMITS: %	% IN RANGE	UPPER RESP. RETEN. FACTOR	RETEN. %	ALVEOLAR RETENTION FACTOR	RETEN. %
<0.1					<.20	
0.1-0.2				<96.12 TOTAL	.26	<2.70 TOTAL
.2-.3					.33	
.3-.5	<.025	2.025			.41	<.01
0.5-1.0	.025-.155	.13			.51	.07
1.0-1.5	.155-.41	.255	2.01	2.01	.54	.14
1.5-2.0	.41-.77	.36	.23	.08	.45	.16
2.-4.	.77-2.93	2.16	.51	1.10	.31	.67
4-7	2.93-7.2	4.27	.76	3.24	.19	.81
7-10	7.2-11.8	4.6	.88	4.05	.12	.55
10-15	11.8-19.0	7.2	.95	6.84	.037	.27
15-30	19.0-36.5	17.5	.99	17.3	<.001	<.02
>30	36.5-100.0	63.5	1.00	63.5		
		100.00 TOTAL				

NUMBER DISTRIBUTION:

SIZE RANGE μ	RANGE LIMITS: %	% IN RANGE	UPPER RESP. RETEN. FACTOR	RETEN. %	ALVEOLAR RETENTION FACTOR	RETEN. %
<0.1	19.9	19.9			<.20	<3.99
0.1-0.2	19.9-37.8	17.9			.26	4.65
.2-.3	37.8-50.0	12.2		<5.26 TOTAL	.33	4.63
.3-.5	50.0-65.4	15.4			.41	6.32
0.5-1.0	65.4-82.4	17.0			.51	8.67
1.0-1.5	82.4-89.3	6.9	<.01	2.07	.54	3.72
1.5-2.0	89.3-92.8	3.5	.23	.81	.45	1.57
2.-4.	92.8-97.65	4.85	.51	2.47	.31	1.51
4-7	97.65-99.23	1.58	.76	1.20	.19	0.30
7-10	99.23-99.64	0.41	.88	.36	.12	0.05
10-15	99.64-99.87	0.23	.95	.22	.037	<0.01
15-30	99.87-99.98	0.11	.99	.11	<.001	
>30	99.98-100.0	0.02	1.00	.02		<34.81 TOTAL
		TOTAL 100.00				

SIZE RANGE [1.5-2.0] 0.36% mass, mid % = 59 $\bar{\phi} = 1.77 \mu$ $\frac{\pi}{6} \times 10^{-12} [1.77]^3 \times .035 \times P \times C = 28.3 \times 10^{-12} PC$
 [2.-4.] 2.16% mass, mid % = 1.85 $\bar{\phi} = 3.07 \mu$ $\frac{\pi}{6} \times 10^{-12} [3.07]^3 \times .0485 \times P \times C = 33.9 \times 10^{-12} PC$
 [4-7]: 4.27% mass, mid % = 5.06 $\bar{\phi} = 5.5 \mu$ $\frac{\pi}{6} \times 10^{-12} [5.5]^3 \times .0158 \times P \times C = 32.4 \times 10^{-12} PC$
 [7-10]: 4.6% mass, mid % = 9.5 $\bar{\phi} = 9.45 \mu$ $\frac{\pi}{6} \times 10^{-12} [9.45]^3 \times .0041 \times P \times C = 28.1 \times 10^{-12} PC$
AVERAGE = $\frac{1}{4} [28.3 + 33.9 + 32.4 + 28.1] = 30.7 \times 10^{-12} PC$ FOR $P = 2.6$ AND $C = 2 \times 10^5 / \text{liter}$
 $PC = 5.2 \times 10^5$
CASE I $30.7 \times 10^{-12} \times 5.2 \times 10^5 = 159.6 \times 10^{-7} \text{ gm/l}$
MASS = $1.6 \times 10^{-5} \text{ gm/liter} = 16. \mu\text{g/l} = 16. \text{ mg/m}^3$
FOR 20 CURIES/GM = $32 \times 10^5 \text{ c/g} = 320 \mu\text{c/l} = 0.32 \mu\text{c/cc}$ **ACTIVITY (IF ALL ACTIVE)**
IN RANGE .5 to 1.5 μ are 12.39% or 24800/LITER RETAINED IN ALVEOLI OF THE 47800 PRES.
with 1% of particles active: $3.2 \times 10^{-6} \text{ c/l} = 3.2 \mu\text{c/l} = 3.2 \times 10^{-3} \mu\text{c/cc} (1\% \text{ ACTIVE})$
THEN LONG RETAINS 248 ACTIVE PARTICLES 0.5 TO 1.5 μ DIAMETER/LITER
 $2.48 \times 10^5 \text{ active particles/m}^3 (0.5 \text{ to } 1.5 \mu)$
 $1.24 \times 10^5 / \text{m}^3 (0.3 \text{ to } 0.5 \mu)$

The summarized results show for each of the thirteen selected ranges of particle size:

1. The percents of the number of particles of each illustrative distribution in each size range.
2. The percents of the mass of particles of each illustrative distribution in each size range.
3. The average retention percentages for each size range of the upper respiratory and alveolar sections of the respiratory system.
4. The percents of mass retained of each size range for upper respiratory and alveolar retention, with totals at the left.
5. The percents of the number of particles retained for each size range for upper respiratory and alveolar retention, with totals at the left.

The total retention percents for mass are used in Table 2 and the total retention percents for numbers in Table 5.

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SUMMARY SHEET

CODER BOOK COMPANY, INC. NORWOOD, MASSACHUSETTS.

NO. 31.302. DATA SHEET, ONE YEAR BY MONTHS. (WITHOUT NAMES OF MONTHS)

SIZE RANGE:	<0.1μ	0.1-0.2	.2-.3	.3-.5	.5-1.0	1.0-1.5	1.5-2.0	2-4	4-7	7-10	10-15	15-30	>30μ
PERCENTS OF NUMBERS OF PARTICLES IN EACH SIZE RANGE													
DISTRIB. "A"	5.5	22.5	22.0	26.5	19.2	3.2	0.8	0.3					
DISTRIB. "B"	13.5	20.8	15.7	19.5	19.1	6.0	2.5	2.41	0.41	.06	.02		
DISTRIB. "C"	19.9	17.9	12.2	15.4	17.0	6.9	3.5	4.85	1.58	.41	.23	.11	.02
PERCENTS OF MASS OF PARTICLES IN EACH SIZE RANGE													
DISTRIB "A"		0.4	1.5	7.1	27	23	15	21	4.3	0.6	0.1		
DISTRIB "B"		.04	.13	.56	3.27	4.9	5.7	20.9	22.0	13.1	12.1	12.2	5.1
DISTRIB "C"				.02	.13	.26	.36	2.16	4.27	4.6	7.2	17.5	63.5
PERCENTS RETAINED BY SIZE RANGE IN PARTS OF RESPIRATORY SYSTEM:													
UPPER RESP.						41	23	51	76	88	95	99	100
ALVEOLAR	<20	26	33	41	51	54	45	31	19	12	3.7	<0.1	
PERCENTS MASS RETAINED - NET													
UPPER RESP.:													
TOTAL	18.2					0.23	3.45	10.6	3.25	.52	.10		
A	68.91					0.05	1.31	10.66	16.71	11.52	11.49	12.07	5.1
B	96.12					0.01	0.08	1.10	3.24	4.05	6.84	17.3	63.5
ALVEOLAR:													
TOTAL	43.8	0.105	0.50	2.95	13.7	12.4	6.8	6.5	.81	0.071	0.004		
A	19.84	0.01	0.04	0.23	1.67	2.64	2.56	6.48	4.18	1.57	0.45	0.01	
B	2.70			0.01	0.07	0.14	0.16	0.67	0.81	0.55	0.27	0.02	
PERCENTS NUMBERS RETAINED - NET													
UPPER RESP.:													
TOTAL	0.37					0.032	0.184	.153					
A	2.25					0.06	0.58	1.23	0.31	0.05	0.02		
B	5.26					0.07	0.81	2.47	1.20	0.36	0.22	0.11	0.02
ALVEOLAR:													
TOTAL	37.5	1.1	5.85	7.26	11.28	9.8	1.73	0.36	0.09				
A	36.22	2.7	5.41	5.18	7.99	9.74	3.24	1.12	0.75	0.08	0.01		
B	34.81	3.98	4.65	4.03	6.32	8.67	3.72	1.57	1.51	0.30	0.05	0.01	

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The formulae used for calculation of exposure values are given following an explanation of the terms and a simple derivation which includes units so that proper dimensions of the results can be verified.

Both submersion and average tissue exposures are based on equilibrium conditions in which the energy absorbed per gram of tissue is assumed equal to that emitted per gram of medium or tissue. For gamma exposure contributions in particular, the volume of adjacent contaminated air or tissue may be less than necessary with the consequent need of a reduction factor. It is not the purpose of this paper, however, to discuss at length the rigor of the exposure calculation formulae. If it were, the use of an average value for specific ionization (ion pairs/cm) might require more extensive treatment since it is a function of energy or range.

Since the primary interest has been with beta exposure the effective energy used has been considered as beta only. Any application of these calculations to actual rather than illustrative cases should give proper consideration to accompanying gamma exposures.

WORK SHEET - EXPOSURE CALCULATION FORMULAE

*acknowledgment is extended to Dr. K. Z. Morgan, ORNL from whose works these formulae were abstracted and modified - his terminology is also used wherever consistency permits

Literature Reference:

- MDDC 240
- NBS HB52
- TID 5031

DEFINITIONS:

- Z = exposure rate for SUBMERSION EXPOSURE
- W = exposure rate for AVERAGE TISSUE EXPOSURE
- D_r = exposure rate for LOCAL TISSUE EXPOSURE, r from a source
- $\Sigma (bE)$ = effective or average energy per disintegration - Mev.
- q = unit quantity of radioactive material - microcuries per as $\mu\text{C/cc}$ of air or $\mu\text{C/gm}$ of tissue
- Q = total quantity of radioactive material - microcuries as $Q\mu\text{C}$ per particle, $Q\mu\text{C}$ absorbed in an organ -
- ρ_m = density of medium (- air = 0.001293 gm/cc)
- P_m = stopping power of medium
- P_t = stopping power of tissue (relative to air = 1.13 for β)
- μ = linear absorp. coeff. same units (reciprocal) as lengths
- r = distance from the center of an active particle, cm. or micron
- S_a = specific ionization (ionpairs/cm of forward direction of path) of radiations in air {this has been assumed constant. thru the range and with energy - an average value of 100 p/cm is used}

ASSUMPTIONS: (in part, others also implied)

- SUBMERSION assumes equilibrium in cloud: energy absorbed = energy released
- AVERAGE TISSUE EXPOSURE assumes uniform distribution
- LOCAL TISSUE EXPOSURE assumes homogenous tissue density

DERIVATION

$$Z = \frac{q \left(\frac{\mu\text{C}}{\text{cc}} \right) \times \Sigma (bE) \left(\frac{\text{Mev}}{\text{dis}} \right) \times 3.7 \times 10^{10} \left(\frac{\text{dis}}{\text{sec}} \right) \times 3600 \left(\frac{\text{sec}}{\text{hr}} \right) \times 1.6 \times 10^{-6} \left(\frac{\text{erg}}{\text{Mev}} \right)}{\rho_m \left[0.001293 \left(\frac{\text{gm}}{\text{cc}} \right) \right] \times \frac{P_m}{P_t} \left[\frac{1}{1.13} \right] \times 93 \frac{\text{erg}}{\text{gm}} \frac{1}{\text{rep}}} = 2002.7 q \Sigma (bE) \text{ rep/hr}$$

(1) $Z = 10^3 q \Sigma (bE) \text{ rep/hr}$ (considering γ from xrt radiaons and self shieldg of β)
(range of 1 Mev β = 3.7 m in air, 4.23 mm in tissue)

$$W = \left[\frac{Q (\mu\text{C})}{m (\text{gm of organ})} \right] \times \frac{\Sigma (bE) \frac{\text{Mev}}{\text{dis}} \times 3.7 \times 10^{10} \frac{\text{dis}}{\text{sec}} \times 3600 \frac{\text{sec}}{\text{hr}} \times 1.6 \times 10^{-6} \frac{\text{erg}}{\text{Mev}}}{93 \frac{\text{erg}}{\text{gm}} \frac{1}{\text{rep}}}$$

(2) $W = 2.29 \frac{Q}{m} \Sigma (bE) \text{ rep/hr}$

$$D_r = \frac{Q (\mu\text{C}) \times S_a \times \frac{P_t}{P_a} \left(\frac{\text{ip}}{\text{cm}} \right) \times 3.7 \times 10^{10} \left(\frac{\text{dis}}{\text{sec}} \right) \times 32.5 \left(\frac{\text{eV}}{\text{ip}} \right) \times 8.64 \times 10^4 \left(\frac{\text{da}}{\text{hr}} \right) \times 1.6 \times 10^{-12} \left(\frac{\text{erg}}{\text{eV}} \right)}{4\pi r^2 (\text{cm}^2) \times \rho_a \left[0.001293 \frac{\text{gm}}{\text{cm}^3} \right] \times 93 \left(\frac{\text{erg}}{\text{gm}} \right) \frac{1}{\text{rep}}} \times e^{-\mu r}$$

$D_r = \frac{0.11 P_t S_a Q e^{-\mu r}}{r^2} \text{ rep/hr}$ using $P_t = 1.13, S_a = 100$

(3) $D_r = 12.43 Q \frac{e^{-\mu r}}{r^2} \text{ rep/hr}$ at r cm for center of particle
1620 65 {or $.52 Q \{r\} \text{ rep/hr}$ }

The data in this table, while subject to variations both among individuals and other references in the literature, are considered reasonable as a whole and adequate for the illustrative calculations made for this study.

Table 3 of the text presents part of this information directly. The Sector volume values of Table 3 were calculated using the radii determined from here assuming ideal cylindrical geometry. The Sector areas were found as:

$$\text{Sector Area} = \pi \left[r^2 - (r + \Delta r)^2 \right]$$

where Δr was taken as 350 microns (= 0.035 cm), the volume values were then taken as the product of the total length of the branches in the respiratory section and the corresponding Sector area.

It is recognized that there is a degree of particle size separation introduced in passing down the bronchial tree. However, the complications introduced in assignment of appropriate activity values to each bronchial section were felt to be unjustified in view of the present lack of information on clearance rates or ciliary particle mobility.

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	Branching Factor	No.	Internal Diameter Cm	Length, Cm	Gross- Section, Cm ²	"Turbu- lence"	Streaming Periods, in Sec (Resi- dence Times)
Trachea	1	1	1.3 .6500	11.0 11.0	1.3	150	0.07
Bronchi	2	2	0.75 .3750	6.5 13.0	1.1	180	0.04
1st order bronchi	6	12	0.4 .2000	3.0 36.0	1.5	130	0.02
2d order bronchi	8	100	0.2 .1000	1.5 150.0	3.1	65	0.02
3d order bronchi	8	770	0.15 .0750	0.5 385.	11	11	0.04
Terminal bronchioles	70	5.4 x 10 ⁴	0.06 .0300	0.3 16200	150	1.3	0.22
Respiratory bronchioles	2	1.1 x 10 ⁵	0.05	0.15	220	0.9	0.17
Alveolar ducts	240	2.6 x 10 ⁷	0.02	0.02	8200	0.025	0.82
Alveolar sacs	2	5.2 x 10 ⁷	0.03	0.03	117000	0	1.2

radius total length

* Respiratory System: Aerosol Therapy by Harold A. Abramson, MEDICAL PHYSICS - Otto Glasser, Editor-in-Chief. Vol. 2, 1950. P. 829

$$\Delta r = 350\mu$$

$$= .0350 \text{ cm}$$

$$\pi(6500^2 + 6850^2) = .0467\pi = .146 \times 11. = 1.61 \text{ cc} = \text{gm, } 4 \text{ Paine} = 1.$$

$$\pi(4100^2 - 3750^2) = .0275\pi = .0863 \times 13. = 1.12$$

$$\pi(2350^2 - 2000^2) = .0152\pi = .0477 \times 36. = 1.72$$

$$\pi(1350^2 - 1000^2) = .00823\pi = .0258 \times 150. = 3.87$$

$$\pi(70750^2 + 1100^2) = .00648\pi = .0203 \times 385. = 7.82$$

$$\pi(.0650^2 - .0300^2) = .00333\pi = .0104 \times 16200.$$

$$= 169.0$$

SCHEME OF BRONCHIAL TREE *

1620

64

NOT CLASSIFIED

A19

65

The formulae of A18 are applied assuming an effective energy per disintegration of 0.35 mev and approximately one hour's exposure during which one cubic meter of air is inhaled.

The submersion exposure results are presented in Table 1 and the average tissue exposure results in Table 4 of the text.

Calculations are made after the present manner in HB52 using a constant retention percentage. Further calculations assume reasonable tissue masses and consider the retentions of the respiratory system divisions. No adjustment is made for non uniform distribution of activity along the bronchial tree or within the alveolar tissues.

As a supplementary "worst case", the alveolar retained activity is considered affecting 20 gm of lymph nodes, again assuming uniform distribution among and within the lymph nodes.

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WORK SHEET - EXPOSURE CALCULATIONS

ASSUMPTIONS: CASE I (repeated from A3)

Conc $C = 2 \times 10^5$ part/l ; 200 part/cc ; 2×10^8 part/m³
 Dens. $P = 2.6$ gm/cc
 $\frac{\text{active}}{\text{inert}}$ $R = 0.1$
 Spec. Act. $A = 20$ c/gm ; 2×10^7 μ C/gm

} constant with particle size

SUBMERSION EXPOSURE CALCULATIONS assume $\Sigma(6E) = 0.35$ mrad/dio.

DISTRIBUTION CONCENTRATION DATA from A14A15, A16 EXPOSURE RATE, Z

	TOTAL MASS MG/M ³	ACTIVE MASS gm/m ³	ACTIVITY CONC. μ C/cc (μ m ³)	$= 10^3 g \Sigma(6E)$ $= 350 g \text{ or } 3.5 \times 10^2 g$	
A	0.094 mg/m ³	1.4×10^{-7}	1.5×10^{-5}	5.25×10^{-3} rep/hr	5.25 mrad/hr
B	0.69 "	6.9×10^{-6}	1.4×10^{-4}	4.9×10^{-2}	49.
C	16.	1.6×10^{-4}	3.2×10^{-3}	11.2×10^{-1}	1120.

AVERAGE TISSUE EXPOSURE RATE CALCULATIONS assume: $\Sigma(6E) = 0.35$ mrad/dio.

assume: activity is retained from inhalation of 1 cubic meter of air, contaminated as per Case I = approx. 1 hour's exposure

GROSS LUNG CASE

DISTRIBUTION	ACTIVITY CONC. μ C/cc (μ m ³)	TOTAL ACTIVITY IN 1 M ³ μ C	LUNG RETENTION PER NBS HB52 $f_R = 0.12$ μ C	Q using $m = 1000$ gm μ C/gm	Aves Tissue Exposure Rate - W $\frac{2.29 g \Sigma(6E)}{m} = .802 \frac{g}{m} \text{ rep/hr}$
A	$1.5 \times 10^{-5} \mu$ C/cc	15 μ C	1.8 μ C	0.018 μ C/gm	1.4×10^{-3} rep/hr 1.45 mrad/hr
B	1.4×10^{-4} "	140	16.8 "	16.8×10^{-3} "	13.47 "
C	3.2×10^{-3} "	3200	384. "	$384. \times 10^{-3}$ "	308. "

UPPER RESPIRATORY CASE

DISTRIB.	g, μ C/cc $\times 10^{-6}$ TOTAL μ C ACT.	TOTAL % RETAINED U. RESP. FROM A17 %	Q ACTIVITY U. RESP. RET. μ C	Q using $m = 16.14$ gm μ C/gm from A19	Aves Tiss. Exp Rate $.802 \frac{g}{m} \text{ rep/hr}$ W
A	15 μ C	18.2 %	2.73 μ C	0.169 μ C/gm	0.135 rep/hr
B	140 "	68.91 "	96.5 "	5.98 "	4.79 "
C	3200 "	96.12 "	3075. "	190.5 "	152.6 "

ALVEOLAR CASE

DISTRIB.	TOTAL ACT IN M ³ μ C	TOTAL % RETAINED ALVEOLI FROM A17 %	Q ACTIVITY ALV. RETEN. μ C	Q using $m = 900$ gm μ C/gm	Aves Tiss Exp Rate $.802 \frac{g}{m} \text{ rep/hr}$ W $\text{or } .802 \frac{g}{m} \times 10^3 \text{ mrad/hr}$
A	15 μ C	43.8 %	6.58 μ C	0.0073 μ C/gm	5.8 mrad/hr
B	140 μ C	19.84 "	27.75 "	7.3×10^{-3} "	24.8 mrad/hr
C	3200 μ C	2.7 "	86.5 "	$96. \times 10^{-3}$ "	76.9 mrad/hr

assuming total phagocytosis to lymph nodes
with 100% retention there, gives the

LYMPH NODE CASE

DISTRIBUTION	Q ALVEOLAR RETAINED ACTIVITY μ C	Q using $m = 20$ gm μ C/gm	Aves Tiss Exposure Rate $.802 \frac{g}{m} \text{ rep/hr}$ W
A	6.58 μ C	0.329 μ C/gm	0.264 rep/hr
B	27.75 "	1.39 "	1.11 "
C	86.5 "	4.32 "	3.46 1820 69

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The dosage formula is used as a function of particle activity Q and distance r . The value of Q is a function primarily of diameter, ϕ , and specific activity.

The activity of a 1 micron diameter particle is calculated for the chosen value of $A (= 20 \text{ curies/gm})$. By substitution, this gives D_r as a function of particle diameter and distance.

Exposure rates can be readily calculated for a specific particle of given diameter, or the equivalent mass average diameter of the particles of a given size range can be used with the number of particles in that range to get total effects.

WORK SHEET EXPOSURE CALCULATIONS [CASE I]

LOCAL AND NON-UNIFORM EXPOSURE RATES

This considers the inhaled particles as separate foci of radiation exposure. with 5.2×10^7 alveoli, the probability of more than one particle being retained in a single alveolus is ignored

$C = 2 \times 10^8$ total particles or 2×10^6 active particles and the maximum retention (Distrib. A) is 37.5% of the number of particles. Hence there are at most 7.5×10^5 active particles to be distributed among 5.2×10^7 alveoli or an average of one active particle (of some size) per 69 alveoli. However, all sections of the lung are not used equally and certainly some alveoli might, by their location adjacent to terminal bronchioles, etc., become deposition sites for several particles. This case is not considered here

From A, 18 $D_r = \frac{0.11 P_t S_a Q}{r^2} e^{-\mu r}$ gives the rep/da to the tissue in the shell at distance r cm. from the center of a particle of activity Q μ c, diameter ϕ microns specific activity A curies/gram.

using $P_t = 1.13$
 $S_a = 100 \text{ } \mu\text{c/cm}^2$ $D_r = 12.43 Q \frac{e^{-\mu r}}{r^2}$

While this indicates D_r as a function of Q and r , if μ is considered constant (only approximately true), since S_a is a function of the energy, and so also is μ , $D_r = f(Q, r, E)$. For this study however an average value will be used for S_a and exponential absorption will be assumed for the β particles so μ is constant.

$$Q = \mu\text{c of particle} = f(\phi, \rho, A) \text{ or } f(\phi, A) \text{ assuming } \rho \text{ constant among active particles}$$

$$= Q(\phi, A)$$

$Q(1, 20) =$ for a 1μ ϕ particle with 20 c/g specific activity $= 0.524 \times 10^{-12} \text{ cc} \times 2.69/\text{cc} \times 20 \text{ c/g} = 27.2 \times 10^{-12} \text{ C} = 27.2 \times 10^{-6} \mu\text{c}$

$Q(\phi, 20) = 27.2 \times 10^{-6} [\phi]^3 \mu\text{c}$ $Q(1, A) = 1.36 \times 10^{-6} A \mu\text{c}$

defining $\xi(r) = \frac{e^{-\mu r}}{r^2}$, $D_r = 3.4 \times 10^{-4} [\phi]^3 \xi(r)$ rep/da at r from particle center

From A13 the values of $[\phi]^3$ for various size ranges can be readily calculated 1620 7/1

$\xi(r)$ is plotted for a semi-hypothetical case on log-log paper for direct graphical combination of $e^{-\mu r}$ (experimental values or old μ (p)) with r^{-2}

Using log-log paper the plot of r^{-2} is a convenient straight line with which the plotted experimental data for $e^{-\mu r}$ can be readily combined graphically to yield the product function $\xi(r)$. For some of the subsequent calculations it was necessary to extrapolate the plotted $e^{-\mu r}$ beyond the experimental data taken. This was done using other similar data of wider range for guidance.

In simulation of an actual case, some experimental absorption measurements were used to give $e^{-\mu r}$ for these illustrative calculations. However, values of $\xi(r)$ could be plotted from experimental data on several energies of β to permit calculations, similar to these herewith, for ready evaluation of an actual sample.

Absorption measurements were made on a 100 day old sample of air activity from a weapon test to get the data here used for mixed fission product betas. The half thickness of 34 mg Al/cm² at 103 da compared reasonably well with a record of 28 mg Al/cm² at 4 da post shot. This gives a value of $\mu = 25.6 \text{ cm}^{-1}$ which however is not constant throughout the range.

Abscissae are given in microns of tissue and the conversion from the aluminum absorber data was made using 1.27 for the ratio of stopping power of tissue to that of aluminum. The use of microns as the unit of distance from the particle center assists in the visualization. Ordinates are in units of percent for the $e^{-\mu r}$ curve and otherwise in reciprocal sq.cm. $\left(\frac{1}{(10^{-3}\text{cm})^2} = 10^6 \text{ cm}^{-2} \right)$ at the left of the r^{-2} and $\xi(r)$ curves.

The superimposed addition of a graph of $4.18 r^3$ with ordinates at the right in cubic microns (10^{-12} cc) is of considerable value to read off the tissue volumes enclosed within different radii of interest.

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(c^{-pr} experimental, from bomb mfp @ 100d)

$e^{-\mu t}$ ORDINATES: % as decimal
VOLUME ORDINATES: μ^3

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From A14 are taken the mass of the distribution and the percents of mass and numbers of particles in each size range. Using the formula on A13 the mass average particle diameter cubed is readily obtained since the factors 10^{-12} μC cancel. With the relationship developed on A21 the corresponding values of Q in micro-curies are calculated and also the coefficient of the function of r for each size range (called "dose constant").

The next step is to solve for r to give a chosen exposure rate. Five values of D_r are chosen: 0.3, 3.0, 30., 300, and 3000 rep/da. These permit the designation of five (decade) exposure ranges:

0.3 to 3.0 rep/da
 3.0 to 30. rep/da
 30 to 300 rep/da
 300 to 3000 rep/da
 greater than 3000 rep/da

For a given values of D_r the resultant value of $\xi(r)$ is calculated and the corresponding value of r is read from the graph of A22. The volume within this radius also can be directly read off for this abscissae. The graphical volume values may be occasionally less accurate but they are quickly obtained.

For compactness of volume notation the power of ten is put in parenthesis: $2.56(7) = 2.56 \times 10^7$ cubic microns.

The resultant data is the volume within which the dose rate is greater than or equal to the selected rate D_r .

Volume Dose - Prelim

Work Sheet - Distribution "A"

$$M_g = 0.3 \mu \quad \sigma_g = 2.0 \quad M_g' = 1.27 \mu$$

$$\text{mass of distribution} = 0.143 \times 10^{-12} \text{ PC} = 0.074 \text{ mg/m}^3 = 7.44 \times 10^{-8} \text{ g/l}$$

$$\text{Case I } p=2.6 \quad C=2 \times 10^5 / l$$

$$C^* = \text{ACTIVE} = 2 \times 10^6 / \text{m}^3$$

PARTICLE SIZE RANGES: <0.1 0.1-0.2 0.2-0.3 0.3-0.5 0.5-1.0 1.0-2.0 2.0-4

PERCENT MASS EA SIZE 0.4 1.5 7.1 27.2 23.1 14.7 2.1

PERCENT NUMBERS OF PART. 5.5 22.5 22.0 26.6 19.1 3.2 0.8 0.3

 $\bar{\phi}$ MASS AVERAGE PARTICLE DIAM. <0.1 .169 .265 .418 .73 1.253 1.71 2.67 $[\phi]^3$ $\times 10^{-3}$ 4.96×10^{-3} 1.86×10^{-3} 7.2×10^{-3} .389 1.993 5.02 19.18

MASS AVERAGE PARTICLE ACTIVITY

$$Q(\phi, 20) = 27.2 \times 10^{-6} [\phi]^3 \mu \quad <2.7 \times 10^{-3} \quad 1.3 \times 10^{-3} \quad 5.1 \times 10^{-3} \quad 2.0 \times 10^{-3} \quad 1.06 \times 10^{-3} \quad 5.4 \times 10^{-3} \quad 1.36 \times 10^{-3} \quad 5.2 \times 10^{-3}$$

$$D_A = 3.4 \times 10^{-4} [\phi]^3 \text{ } \left\{ \begin{array}{l} (1) \end{array} \right.$$

$$\text{DOSE CONSTANT: } 3.4 \times 10^{-4} [\phi]^3 \quad <3.4 \times 10^{-4} \quad 1.65 \times 10^{-4} \quad 6.32 \times 10^{-4} \quad 2.48 \times 10^{-4} \quad 1.32 \times 10^{-4} \quad 6.7 \times 10^{-4} \quad 1.71 \times 10^{-3} \quad 6.5 \times 10^{-3}$$

FOR DOSES: r = radius in microns V = volume in μ^3 ; numbers in parenthesis are for power of 10

$$D_A = 0.3 \text{ rep/ds: } \xi(r) = >8.8 \times 10^5 \quad 1.81 \times 10^5 \quad 4.75 \times 10^4 \quad 1.21 \times 10^4 \quad 2.27 \times 10^3 \quad 4.47 \times 10^2 \quad 1.75 \times 10^2 \quad 4.6 \times 10^1$$

$$(\neq 3 \text{ beyond } r) \quad \lambda = <10.4 \mu \quad 22.1 \quad 41.6 \quad 77 \quad 163 \quad 320 \quad 463 \quad 790 \mu$$

$$V = 4.71(3) \quad 4.52(4) \quad 3.01(5) \quad 1.91(6) \quad 1.82(7) \quad 1.65(8) \quad 4.2(8) \quad 2.05(9)$$

$$\left(\begin{array}{l} 3.01(5) = 3.01 \times 10^5 \\ 10.16 \times 10^4 \end{array} \right)$$

$$D_A = 3.0 \text{ rep/ds: } \xi(r) = >8.8 \times 10^5 \quad 1.81 \times 10^5 \quad 4.75 \times 10^4 \quad 1.21 \times 10^4 \quad 2.27 \times 10^3 \quad 4.47 \times 10^2 \quad 1.75 \times 10^2 \quad 4.6 \times 10^1$$

$$\left\{ \begin{array}{l} \neq 3 \text{ beyond } r \\ \geq 3 \text{ within } r \end{array} \right\} \quad \lambda = <3.3 \mu \quad 7.2 \quad 14 \quad 26.8 \quad 58 \quad 121 \quad 182 \quad 315 \mu$$

$$V = 1.5(2) \quad 1.57(3) \quad 1.15(4) \quad 8.05(4) \quad 8.17(5) \quad 7.43(6) \quad 2.56(7) \quad 1.5(8)$$

$$D_A = 30 \text{ rep/ds: } \xi(r) = >8.8 \times 10^5 \quad 1.81 \times 10^5 \quad 4.75 \times 10^4 \quad 1.21 \times 10^4 \quad 2.27 \times 10^3 \quad 4.47 \times 10^2 \quad 1.75 \times 10^2 \quad 4.6 \times 10^1$$

$$(\text{as above}) \quad \lambda = <10.4 \mu \quad 2.3 \quad 4.5 \quad 8.8 \quad 20 \quad 42.8 \quad 66 \quad 119 \mu$$

$$V = 5.0(1) \quad 3.8(2) \quad 2.9(3) \quad 3.4(4) \quad 3.27(5) \quad 1.2(6) \quad 7.15(6)$$

$$D_A = 300 \text{ rep/ds: } \xi(r) = 1.21 \times 10^4 \quad 2.27 \times 10^3 \quad 4.47 \times 10^2 \quad 1.75 \times 10^2 \quad 4.6 \times 10^1$$

$$\lambda = 2.85 \mu \quad 6.5 \quad 14.4 \quad 22.6 \quad 42 \mu$$

$$V = 9.5(1) \quad 1.16(3) \quad 1.26(4) \quad 4.81(4) \quad 3.07(5)$$

$$D_A = 3000 \text{ rep/ds: } \xi(r) = 2.27 \times 10^3 \quad 4.47 \times 10^2 \quad 1.75 \times 10^2 \quad 4.6 \times 10^1$$

$$\lambda = 2.1 \mu \quad 4.6 \quad 7.4 \quad 14.3 \mu$$

$$V = 3.6(1) \quad 4.1(2) \quad 1.71(3) \quad 1.24(4)$$

The volumes of tissue receiving exposure rates within the indicated ranges are obtained by serial subtraction of the values on A23:

For an average particle in the range 0.5 to 1.0 μ

the volume for $D_r \geq 0.3$ rep/da = 1.82(7)

the volume for $D_r \geq 3.0$ rep/da = 8.17(5)

hence, the volume for 0.3 - 3.0 rep/da = $1.74 \times 10^7 \mu^3$

It was at first considered of interest to examine the exposed tissue volumes local to upper respiratory retained particles as well as those in the alveoli. It became quickly evident that this would involve a number of estimates to try to evaluate the dose to tissue on the other side of the bronchial passage and this effort was abandoned for this present study.

The number of alveolar retained particles for each size range for this exposure condition (1 m³ air inhaled) is obtained using distribution percent retentions from A17. The product of the volume about an average particle and the number of particles retained gives a total volume for each size range, and these when summed give the total for the exposure. These totals from A24, A26, and A28 are presented in Table 5.

Work Sheet - Distribution "A"

$Mg = 0.3 \mu$ $\sigma_g = 2.0$ $Mg' = 1.27 \mu$

Transf. Distribution: $0.148 \times 10^{-12} pc = 0.074 \text{ mg}/\text{m}^3$

Case I $P = 2.6$ $C = 2 \times 10^5/l$ $C^* = 2 \times 10^6/\text{m}^3$

Numbers in parenthesis are exponents of 10
 $4.36(4) = 4.36 \times 10^4$

PARTICLE SIZE RANGES: <0.1 0.1-2 2-3 3-5 5-10 10-15 15-20 2-4

DOSE VOLUMES PER EACH (volumes are given in μ^3 , $1 \mu^3 = 10^{-12} \text{ cc}$)
MASS AVERAGE PARTICLE

0.3 TO 3.0 $\mu\text{m}/\text{da}$	<4.36(3)	4.36(4)	2.9(5)	1.83(6)	1.74(7)	1.58(8)	3.94(8)	1.9(9)
3.0 TO 30. $\mu\text{m}/\text{da}$	<1.5(2)	1.52(3)	1.1(4)	7.76(4)	7.83(3)	7.1(6)	2.44(7)	1.43(8)
30 TO 300 $\mu\text{m}/\text{da}$	<4.4	50	3.8(2)	2.8(3)	3.3(4)	3.14(5)	1.15(6)	6.84(6)
300 TO 3000 $\mu\text{m}/\text{da}$			95	1.12(3)	1.22(4)	4.64(6)	2.95(5)	
>3000 $\mu\text{m}/\text{da}$				36	4.1(2)	1.71(3)	1.24(4)	

Adjusted UR
dose vol.

3-3
3-30
30-300
300-3000
>3000

UPPER RESPIRATORY NET %
RETAINED (NUMBERS)

ACTIVE PARTICLES - RETAINED IN U.R.
(PER $M^3 = 2 \times 2 \times 10^6$)

UPPER RESP. DOSE VOLUMES

0.3 TO 3.0	1.01(11)	1.45(12)	5.81(12)
3.0 TO 30.	4.55(9)	8.97(10)	4.37(11)
30 TO 300	2.01(8)	4.23(9)	2.09(10)
300 TO 3000	1.71(8)	9.03(8)	
>3000	2.62(5)	6.29(6)	3.80(7)

TOTAL

7.36×10^{12}
 5.31×10^{11}
 2.53×10^{10}
 1.28×10^9
 4.46×10^7

Because of geometry consider 30%
as calc. other 30% next lower range
of dose for approximation. But
val of 30% equiv. to 50% at lower dose.

ALVEOLAR NET % RETAINED
(OF NUMBER)

1.1 5.85 7.26 11.28 9.8 1.73 0.36 0.09 T=37.5

ACTIVE ALVEOLAR RETAINED
PARTICLES (PER $M^3 = 2 \times 2 \times 10^6$)

2.2×10^3 1.17×10^3 1.45×10^3 2.25×10^3 1.96×10^3 3.46×10^3 7.2×10^3 1.8×10^3

ALVEOLAR DOSE VOL'S:

0.3 TO 3.0	1.00(8)	5.10(9)	4.21(10)	4.12(11)	3.41(12)	5.47(12)	2.84(12)	3.42(12)
3.0 TO 30.	3.3(6)	1.78(8)	1.61(9)	1.75(10)	1.53(11)	2.46(11)	1.76(11)	2.57(11)
30 TO 300.	9.7(4)	5.85(6)	5.51(7)	6.3(8)	6.47(9)	1.09(10)	8.28(9)	1.23(10)
300 TO 3000.				2.14(7)	2.2(8)	4.22(8)	3.34(8)	5.31(8)
>3000.					7.1(6)	1.43(7)	1.23(7)	2.23(7)

TOTAL

1.56×10^{13}
 8.51×10^{11}
 3.86×10^{10}
 1.53×10^9
 5.59×10^7

From A15 are taken the mass of the distribution and the percents of mass and numbers of particles in each size range. Using the formula on A13 the mass average particle diameter cubed is readily obtained since the factors 10^{-12} ρ C cancel. With the relationship developed on A21 the corresponding values of Q in microcuries are calculated and also the coefficient of the function of r for each size range (called "dose constant").

The next step is to solve for r to give a chosen exposure rate. Five values of D_r are chosen: 0.3, 3.0, 30., 300, and 3000 rep/da. These permit the designation of five (decade) exposure ranges:

0.3 to 3.0 rep/da
 3.0 to 30. rep/da
 30 to 300 rep/da
 300 to 3000 rep/da
 greater than 3000 rep/da

For a given value of D_r the resultant value of $\xi(r)$ is calculated and the corresponding value of r is read from the graph of A22. The volume within this radius also can be directly read off for this abscissae. The graphical volume values may be occasionally less accurate but they are quickly obtained.

For compactness of volume notation the power of ten is put in parenthesis: $2.56(7) = 2.56 \times 10^7$ cubic microns.

The resultant data is the volume within which the dose rate is greater than or equal to the selected rate D_r .

Volume Dose
Prelim.

Work Sheet - Distribution "B"

$M_g = 0.3 \mu$

$\sigma_g = 2.7$

$M_g' = 5.77 \mu$

mass of distribution = $1.32 \times 10^{-12} \text{ PC} = 0.69 \text{ mg/m}^3 = 6.86 \times 10^{-7} \text{ g/l}$

CASE I $P = 2.6$ $C = 2 \times 10^5 / \text{L}$
 $C^* = \text{ACTIVE PART} = 2 \times 10^6 / \text{m}^3$

PARTICLE SIZE RANGES:

	<0.1	1-2	2-3	3-5	5-10	10-15	15-20	20-40	40-70	70-100	100-150
PERCENT MASS EA. RANGE		.04	.13	.57	3.27	4.9	5.7	20.9	22.0	13.1	12.1
PERCENT NUMBER PART. EA.	13.5	20.8	15.7	19.5	19.1	6.0	2.5	2.41	0.405	0.06	0.025
$\bar{\phi}$, MASS-AVER. PART. DIAM. μ	<0.1	.169 μ	.275	.419	.756	1.27	1.79	2.18	5.16	8.19	10.7
$[\bar{\phi}]^3$	10^{-3}	4.85×10^{-3}	2.09×10^{-2}	7.37×10^{-2}	4.32×10^{-1}	2.06	5.75	21.85	137	550	1220
ACTIVITY, MASS-AVER. PART.											
$Q(\phi, 20) = 27.2 \times 10^6 [\bar{\phi}]^3 \mu\text{C}$	2.7×10^5	1.3×10^6	5.68×10^6	2.0×10^7	1.17×10^8	5.6×10^8	1.56×10^9	5.94×10^9	3.72×10^{10}	1.5×10^{11}	3.32×10^{11}
$D_A = 3.4 \times 10^{-4} [\bar{\phi}]^3 \xi(\lambda)$											
DOSE CONSTANT: $3.4 \times 10^{-4} [\bar{\phi}]^3$	4.3×10^{-7}	1.65×10^{-6}	7.1×10^{-6}	2.5×10^{-5}	1.467×10^{-4}	7.0×10^{-4}	1.95×10^{-3}	7.43×10^{-3}	4.65×10^{-2}	1.87×10^{-1}	4.15×10^{-1}
FOR DOSES ξ :	$\xi(\lambda) = \frac{P}{\lambda}$; λ = radius in microns, μ ; V = volume in μ^3 , numbers in () are power of 10										
$D_A = 0.3 \text{ rep/da}$	$\xi(\lambda)$	$> 8.8 \times 10^5$	1.81×10^5	4.235×10^4	1.2×10^4	2.04×10^3	4.28×10^2	1.54×10^2	4.03×10^1	6.45×10^0	1.6×10^0
{ $\neq 0.3$ beyond λ $\cong 0.3$ within λ }	λ	$< 10.4 \mu$	22.1	43.9	78	170	327	490	840	1600	2750
	V	4.71 (3)	452 (4)	3.5 (5)	2.0 (6)	2.1 (7)	1.46 (8)	4.9 (8)	2.6 (9)	1.7 (10)	8.5 (10)
$D_A = 3.0 \text{ rep/da}$	$\xi(\lambda)$	$> 8.8 \times 10^6$	1.81×10^6	4.235×10^5	1.2×10^5	2.04×10^4	4.28×10^3	1.54×10^3	4.03×10^2	6.45×10^1	1.6×10^1
	λ	$< 3.3 \mu$	7.2	14.6	26.8	62	124	192	335	700	1160
	V	1.5 (2)	1.57 (3)	1.34 (4)	8.2 (4)	1.0 (6)	8.0 (6)	3.0 (7)	1.56 (8)	1.45 (9)	6.8 (9)
$D_A = 30 \text{ rep/da}$	$\xi(\lambda)$	$> 8.8 \times 10^7$	1.81×10^7	4.235×10^6	1.2×10^6	2.04×10^5	4.28×10^4	1.54×10^4	4.03×10^3	6.45×10^2	1.6×10^2
	λ	$< 1.04 \mu$	2.3	4.75	8.8	21	43.5	70	126	275	480
	V		5.0 (1)	4.5 (2)	3 (3)	3.9 (4)	3.45 (5)	1.45 (6)	8.6 (6)	8.75 (7)	8.3 (8)
$D_A = 300 \text{ rep/da}$	$\xi(\lambda)$		4.235×10^7	1.2×10^7	2.04×10^6	4.28×10^5	1.54×10^5	4.03×10^4	6.45×10^3	1.6×10^3	7.23×10^2
	λ		1.53	2.85	6.8	14.7	24	44.9	104	189	263
	V		1.5 (1)	9.5 (1)	1.35 (3)	136 (4)	5.9 (4)	3.8 (5)	4.75 (6)	2.86 (7)	7.75 (7)
$D_A = 3000 \text{ rep/da}$	$\xi(\lambda)$				2.04×10^7	4.28×10^6	1.54×10^6	4.03×10^5	6.45×10^4	1.6×10^4	7.23×10^3
	λ				2.2	4.75	7.9	15.2	36	68	95
	V				4.4 (1)	4.5 (2)	2.0 (3)	1.5 (4)	1.95 (5)	1.35 (6)	3.65 (6)

NOT CLASSIFIED

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The volume of tissue receiving exposure rates within the indicated ranges are obtained by serial subtraction of the values on A25:

For an average particle in the range 0.5 to 1.0 μ

the volume for $D_r \geq 0.3$ rep/da = 2.1(7)

the volume for $D_r \geq 3.0$ rep/da = 1.0(6)

hence, the volume for 0.3 - 3.0 rep/da = $2.0 \times 10^7 \mu^3$

The number of alveolar retained particles for each size range for this exposure condition (1 m³ air inhaled) is obtained using distribution percent retentions from A17. The product of the volume about an average particle and the number of particles retained gives a total volume for each size range, and these when summed give the total for the exposure. These totals from A24, A26, and A28 are presented in Table 5.

Volume
Dose-
Recap

Work Sheet - Distribution "B"

$$M_g = 0.3 \mu \quad \sigma_g = 2.7 \quad M_g' = 5.79 \mu$$

$$\text{Mass of Distribution: } 1.82 \times 10^{-12} \text{ g/cm}^3 = 0.69 \text{ mg/m}^3$$

$$\text{Case 1 } \rho = 2.6 \quad C = 2 \times 10^3 / \text{L} \quad C^* = 2 \times 10^6 / \text{m}^3$$

$$4.71(3) = 4.71 \times 10^3$$

PARTICLE SIZE RANGES: <0.1 0.1-0.2 0.2-0.3 0.3-0.5 0.5-1.0 1.0-1.5 1.5-2 2-4 4-7 7-10 10-15

DOSE VOLUMES PER
EA. MASS-AVERAGE PARTICLE

0.3 TO 3.0 $\mu\text{m}/\text{da}$ <4.56(3) 4.56(4) 3.37(5) 1.92(6) 2.0(7) 1.38(8) 4.6(8) 2.44(9) 1.55(10) 7.82(11)

3.0 TO 30. $\mu\text{m}/\text{da}$ <1.5(2) 1.52(3) 1.29(4) 7.9(4) 9.6(5) 7.66(6) 2.85(7) 1.47(8) 1.36(9) 5.97(9)

30 TO 300 $\mu\text{m}/\text{da}$ <4.4 5.0(1) 4.35(2) 2.9(3) 3.76(4) 3.31(5) 1.39(6) 8.22(6) 8.27(7) 8.01(8)

300 TO 3000 $\mu\text{m}/\text{da}$ 1.5(1) 9.5(1) 1.31(3) 1.31(4) 5.69(4) 3.65(5) 4.55(6) 2.72(6)

> 3000 $\mu\text{m}/\text{da}$ 4.4(1) 4.5(2) 2.06(3) 1.5(4) 1.95(5) 1.35(6)

UPPER RESP. NET %
NUMBERS RETAINED

<0.6 .58 1.23 .31 .05 .02 $\Sigma = <2.25$

ACTIVE PARTICLES - RETAIN U.R.
(PER $M^3 = 70 \times 2 \times 10^6$)

U. RESP. DOSE VOLUMES

0.3 - 3.0
3.0 - 30
30 - 300
300 - 3000
> 3000

ALVEOLAR NET %

NUMBERS RETAINED

<2.7 5.41 5.18 7.99 9.74 3.24 1.12 0.75 0.08 <0.01

$\Sigma = <36.22$

ACTIVE ALV. RETAINED

PART. (PER $M^3 = 70 \times 2 \times 10^6$)

<5.4 $\times 10^4$ 1.08 $\times 10^5$ 1.04 $\times 10^5$ 1.6 $\times 10^5$ 1.95 $\times 10^5$ 6.48 $\times 10^4$ 2.24 $\times 10^4$ 1.5 $\times 10^4$ 1.6 $\times 10^3$ <2 $\times 10^2$

ALVEOLAR DOSE VOL'S:

0.3 TO 3.0

2.46(8) 4.71(9) 3.50(10) 3.07(11) 3.9(12) 8.95(12) 1.03(13) 3.66(13) 2.48(13) <1.56(13)

3.0 TO 30

8.1(6) 1.64(8) 1.34(9) 1.26(10) 1.87(11) 4.97(11) 6.38(11) 2.2(12) 2.18(12) <1.19(13)

30 TO 300

2.38(5) 5.4(6) 4.52(7) 4.64(8) 7.33(9) 2.15(10) 3.12(10) 1.23(11) 1.32(11) <1.6(11)

300 TO 3000

1.56(6) 1.52(7) 2.55(8) 8.5(8) 1.27(9) 5.47(9) 7.28(9) <5.45(9)

> 3000

8.58(6) 2.92(7) 4.62(7) 2.25(8) 3.12(8) <2.7(8)

TOTAL

8.49 $\times 10^{13}$

5.72 $\times 10^{12}$

3.16 $\times 10^{11}$

1.51 $\times 10^{10}$

6.21 $\times 10^8$

↑
NOT
COUNT,
UNCERT.

From A16 are taken the mass of the distribution and the percents of mass and numbers of particles in each size range. Using the formula on A13 the mass average particle diameter cubed is readily obtained since the factors 10^{-12} ρ C cancel. With the relationship developed on A21 the corresponding values of Q in microcuries are calculated and also the coefficient of the function of R for each size range (called "dose constant").

The next step is to solve for r to give a chosen exposure rate. Five values of D_r are chosen: 0.3, 3.0, 30., 300, and 3000 rep/da. These permit the designation of five (decade) exposure ranges:

0.3 to 3.0 rep/da
3.0 to 30. rep/da
30 to 300 rep/da
300 to 3000 rep/da
greater than 3000 rep/da

For a given value of D_r the resultant value of $\xi(r)$ is calculated and the corresponding value of r is read from the graph of A22. The volume within this radius also can be directly read off for this abscissae. The graphical volume values may be occasionally less accurate but they are quickly obtained.

For compactness of volume notation the power of ten is put in parenthesis: $2.56(7) = 2.56 \times 10^7$ cubic microns.

The resultant data is the volume within which the dose rate is greater than or equal to the selected rate D_r .

The data on mass % in the small sized particles, $< 0.5\mu$ is not reliable enough from the graph of A8 to permit ready calculation of the three smaller size ranges. Values of $(\phi)^3$ vary somewhat but a fair approximation could be made using the higher of the corresponding values on A23 and A25.

Work Sheet - Distribution "C"

$$M_g = 0.3 \mu \quad \sigma_g = 3.66 \quad M_g' = 46.8 \mu$$

$$\text{mass of distribution} = 30.7 \times 10^{-12} \text{ PC} = 15.96 \text{ mg/m}^3 = 1.6 \times 10^{-5} \text{ g/L}$$

$$\text{Calc } P = 2.6 \quad C = 2 \times 10^5 / L$$

$$C^* = \text{ACTIVE PART.} = 2 \times 10^6 / m^3$$

PARTICLE SIZE RANGES

<0.1 0.1-0.2 0.2-0.3 0.3-0.5 0.5-1.0 1.0-1.5 1.5-2 2-4 4-7 7-10 10-15

PERCENT MASS EA. RANGE

<0.25 .13 .255 .36 2.16 4.27 4.6 7.2

PERCENT NUMBER PART.

19.9 12.9 12.2 15.4 17.0 6.9 3.5 4.85 1.58 0.41 0.23

$\bar{\phi}$ <0.1 1.765 1.295 1.82 2.97 5.41 8.7 12.25

$[\bar{\phi}]^3$ <10⁻³ .448 2.17 6.04 26.2 158 659 1835

$Q(\bar{\phi}, 20) = 2.72 \times 10^3 [\bar{\phi}]^3 \mu L$ 42.7x10³ 1.22x10⁵ 5.9x10⁵ 1.64x10⁶ 7.12x10⁶ 4.3x10⁷ 1.79x10⁸ 5.0x10⁸

DOSE CONSTANT $34 \times 10^4 [\bar{\phi}]^3$ 43.4x10⁴ 1.52x10⁶ 7.37x10⁶ 2.05x10⁷ 8.9x10⁷ 5.37x10⁸ 2.24x10⁹ 6.25x10⁹

$D_F = 0.3 \text{ rad/da}$ $\sum f(1)$ 78.5x10⁵ 1.96x10⁷ 4.07x10⁷ 1.46x10⁸ 3.4x10⁸ 5.6x10⁸ 1.34x10⁹ 4.8x10⁹

$\lambda =$ <10.4 μ 175 330 500 880 1700 2900 4200

$V =$ 4.71(3) 2.3(7) 1.5(8) 5.2(8) 3(9) 2(10) 1(11) 5(11)

3.0 $\sum f(1)$ 78.5x10⁵ 1.96x10⁷ 4.07x10⁷ 1.46x10⁸ 3.4x10⁸ 5.6x10⁸ 1.34x10⁹ 4.8x10⁹

λ <3.3 μ 63 126 197 355 740 1230 1800

V 1.5(2) 1.03(6) 8.5(6) 3.35(7) 1.9(8) 1.75(9) 9(9) 2.4(10)

30. $\sum f(1)$ 78.5x10⁵ 1.96x10⁷ 4.07x10⁷ 1.46x10⁸ 3.4x10⁸ 5.6x10⁸ 1.34x10⁹ 4.8x10⁹

λ <1.04 μ 21.5 44.5 72 136 291 515 790

V 4.2(4) 3.7(5) 1.6(6) 1.08(7) 1.05(8) 5.8(8) 2.1(9)

300. $\sum f(1)$ 78.5x10⁵ 1.96x10⁷ 4.07x10⁷ 1.46x10⁸ 3.4x10⁸ 5.6x10⁸ 1.34x10⁹ 4.8x10⁹

λ 7 μ 15 24.2 48.5 110 205 310

V 1.45(3) 1.45(4) 6.8(4) 4.7(5) 5.6(6) 3.6(7) 1.25(8)

3000 $\sum f(1)$ 78.5x10⁵ 1.96x10⁷ 4.07x10⁷ 1.46x10⁸ 3.4x10⁸ 5.6x10⁸ 1.34x10⁹ 4.8x10⁹

λ 2.26 4.9 8.1 16.4 38.5 74 117

V 4.8(1) 5(2) 2.2(3) 1.85(4) 2.35(5) 1.7(6) 7(6)

The volumes of tissue receiving exposure rates within the indicated ranges are obtained by serial subtraction of the values on A27:

For an average particle in the range 0.5 to 1.0μ

the volume for $D_r \geq 0.3$ rep/da = $2.3(7)$

the volume for $D_r \geq 3.0$ rep/da = $1.03(6)$

hence, the volume for $0.3 - 3.0$ rep/da = $2.2 \times 10^7 \mu^3$

The omission of values for ranges $< 0.5\mu$ is justified as contributing to the total less than a significant amount. For evaluating a filter which cut out some ranges of particle size the dosage volumes of A26 could be used, combined with the proper particle numbers, for the desired results.

The number of alveolar retained particles for each size range for this exposure condition (1 m^3 air inhaled) is obtained using distribution percent retentions from A17. The product of the volume about an average particle and the number of particles retained gives a total volume for each size range, and these when summed give the total for the exposure. These totals from A24, A26, and A28 are presented in Table 5.

Vol. Dose-Resp

Work Sheet Distribution "C"

DOSE VOLUMES

0.3 3.0

2.2(7) 1.4(8) 4.86(8) 2.8(9) 1.82(10) 9.2(10)

3.0 30

9.9(5) 8.13(6) 3.19(7) 1.79(8) 1.64(9) 1.42(9)

30 300

4.05(4) 3.55(5) 1.54(6) 1.03(7) 9.9(7) 5.44(8)

300 3000

1.4(3) 1.4(4) 6.18(4) 4.5(5) 5.36(6) 3.43(7)

>3000

4.8(1) 5(2) 2.2(3) 1.85(4) 2.35(5) 1.7(6)

UPPER RESP NET %
NUMBERS RETAINED

ALVEOLAR NET %

NUMBERS RETAINED

23.98 4.65 4.03 6.32 8.67 3.72 1.57 1.51 0.30 0.05 <0.01

ACTIVE ALV. RETAINED

PART (PERM³-%x2x10⁶)48.0x10⁴ 9.3x10⁴ 8.06x10⁴ 1.26x10⁵ 1.73x10⁵ 7.44x10⁴ 3.14x10⁴ 3.02x10⁸ 6.0x10³ 1.0x10⁸ <25.10²

ALVEOLAR DOSE VOL'S:

0.3 TO 3.0

3.8(12) 1.05(12) 1.53(12) 8.5(12) 1.09(12) 9.2(12)

TOTAL

3.16(14)

3.0 TO 30

1.71(11) 6.05(11) 1.0(12) 5.4(12) 9.9(12) 7.82(12)

2.45(13)

30 TO 300

7.0(9) 2.64(10) 4.86(10) 3.1(11) 5.93(11) 5.44(11)

1.53(12)

300 TO 3000

2.42(8) 1.04(9) 1.94(9) 1.36(10) 3.22(10) 2.43(10)

8.33(10)

>3000

8.3(6) 3.72(7) 6.9(7) 5.6(8) 1.41(9) 1.7(9)

3.78(9)

The assumptions for Case II are here presented, principal distinction being that the amount of radioactivity instead of the number of particles is held constant.

This case is more comparable to the practical case where a measurement of submersion exposure is made (assuming contamination effects on instruments do not invalidate the results) or the gross airborne activity is measured. The question then arises as to how much difference in exposure rate will be introduced as a consequence of the size distribution of the activity bearing particles.

A submersion exposure of 100 mrep/hr is chosen to give a consequent air contamination concentration. Conversion to other submersion dose rates, or airborne activity concentrations, is linear from these given values.

Since the mass concentration is now constant, the numbers of particles will vary to the same extent (a factor of 216 between A* and C*) as the mass concentration did previously, but in an inverse manner. Whereas the mass and activity increased from A to B to C, the numbers of particles now decrease from A* to B* to C*.

WORK SHEET - EXPOSURE CALCULATIONS

ASSUMPTIONS: CASE II

AS BEFORE: 3 PARTICLE DISTRIBUTIONS: A* B* C*

(use of * to distinguish from CASE I)

WITH: ϕ , NUMBER MEDIAN DIAM. 0.3 0.3 0.3 μ

σ , STANDARD DEVIATION 2.0 2.7 3.66

AS CONSTANT:

NEW: SUBMERSION EXPOSURE (Z) TO BE 100 mreps/hr. ←

(AS BEFORE:) $Z(6E) = 0.35$ mev/disintegration

Ratio ^{active}/_{inert}, $R = 1\%$ for all sizes of particles

Density, $\rho = 2.6$ gm/cc " " " "

Specific Activity, $A = 20$ ^{curies}/_{gm} " " " "

THEREFORE VARYING

Concentration, C ^{number of} particles/liter or particles/cubic meter of air
(mass concentrations, mg/m³ also vary)

Internal Exposures:

W, Average Tissue Exposure Rates

D, Local Non Uniform Tissue Exposure Rates

CALCULATIONS:

$$Z = 10^3 f Z(6E) \text{ rep/hr} = 0.1 \quad (\text{formulae from A18 used here})$$

$$\therefore f = \frac{0.1}{10^3 \times 0.35} = 3.14 \times 10^{-4} \mu\text{C/cc (or C/m}^3\text{)} \text{ for Distributions A* B* C*}$$

$$\text{if } R = 100\% \quad f = 3.14 \times 10^{-2} \text{ C/m}^3, \text{ thus: } \left\{ \begin{array}{l} \text{or: } \frac{3.14 \times 10^{-4} \text{ C/m}^3}{\frac{0.01 \text{ active gm}}{\text{total gm}} \times 20 \frac{\text{curies}}{\text{active gm}}} \end{array} \right\}$$

$$\text{Mass Concentration} = \frac{f}{A} = \frac{3.14 \times 10^{-2}}{20 \text{ C/gm}} = 0.157 \times 10^{-2} \text{ gm/m}^3 = 1.57 \text{ mg/m}^3 \text{ for A* B* C*}$$

hence:

DISTRIBUTION	MASS CONC CASE I mg/m ³	FACTOR: (x more) ^{CASE II} / _{CASE I}	PARTICLE NUMBER CONC CASE I	PARTICLE NUMBER CONCENTRATION CASE II	DISTRIBUTION
A	0.074 ^{mg} / _{m³}	$\frac{1.57}{0.074} = 21.2$	2×10^8 ^{particles} / _{m³}	4.24×10^9 Part/m ³	4.24(6)/l. A*
B	0.69	$\frac{1.57}{0.69} = 2.274$	2×10^8 "	4.55×10^8	4.55(5)/l. B*
C	16.	$\frac{1.57}{16.} = 0.0982$ (or 10.16 times fewer)	2×10^8 "	1.96×10^7	1.96(4)/l. C*

The exposure rates calculated on A20 are recalculated on the basis of the different conditions of Case II using the same formulae as before (Pg. A18).

The gross lung average exposure is now constant and of the same order of magnitude as before, in millireps/hr, (30.2 compared with 1.45, 13.5 and 308. for A, B, and C, Case I - a range of 216 fold).

The average true upper respiratory exposure is still in reps/hour (due to the small tissue mass affected) and increases with σ but only over a range of a factor of 5.3 as compared with Case I where the range was a factor of 1130. The arithmetic average of $A^*+B^*+C^*$ now is 9.5 rep/hr compared to 52.5 rep/hr for $A+B+C$.

The average alveolar tissue exposure now decreases with σ , over a range of 16.2x from A^* to C^* , whereas it formerly increased with σ , over a range of 13.3x. As before, it is of the order of millireps/hr and the arithmetic average of $A^*+B^*+C^*$ is now 61.6 mrep/hr compared with 35.8 mrep/hr for $A+B+C$, and compared with 30.2 mrep/hr for the gross lung in Case II.

In the same manner and to the same degree, the lymph node dosage now decreases with σ (16.2x) whereas it formerly increased (13.3x). The order of magnitude is still the same and the arithmetic average of $A^*+B^*+C^*$ is now 2.8 rep/hr.

The relative increase in the numbers of particles (up to approximately 220 fold) for the distribution of small σ was sufficient to reverse the former increase with σ of the exposed tissue volumes for a given dose rate. At the highest dose rate the volume increase of C over A was 67.5 times and now the corresponding B^* volume (slightly greater than A^*) is 3.8 times as great as C^* .

At the lowest dose range the involved volumes vary somewhat less widely than before and again in the opposite direction with regard to the particle size distribution parameters. In this dose range the influence of the attenuation factor $e^{-\mu r}$ is most pronounced due to the larger radial distances. Here the overlapping influence of adjacent particles approaches the average alveolar exposure case and the volumes of the order of $10^{14} \mu^3$ correspond to a significant fraction of the lung tissue ($10^{14} \mu^3 = 100 \text{ cc}$). Some agreement is seen with the mean alveolar tissue dose above of 61.6 mrep/hr which equals 1.48 rep/da. and thus is in the 0.3 to 3 rep/da range. However, the calculation of an average tissue dose ignores the significant volumes of tens of cubic centimeters receiving exposures an order of magnitude greater, those of the order of cc receiving exposures two orders of magnitude greater, etc.

WORK SHEET - EXPOSURE CALCULATIONS [CASE II]

AVERAGE TISSUE EXPOSURE RATES

$$W = 2.29 \frac{Q}{m} \Sigma (BE) \text{ rep/hr}$$

AS BEFORE, $\Sigma (BE) = 0.35 \text{ mrad/hr}$. $\therefore W = 0.802 \frac{Q}{m} \text{ rep/hr}$ (from A18)

1 cubic meter (10^6 cc) contaminated air inhaled

$$\text{THUS TOTAL } Q \text{ in } 1 \text{ m}^3 \text{ air} = 8 \times 10^6 = 314 \mu\text{C} \text{ for } A^* B^* C^* \text{ (3.14} \times 10^4 \text{ C)}$$

UPPER RESPIRATORY CASE

DISTRIB.	RETENTION			AVER. U.R. EXPOS.		GROSS "LUNG" CASE	
	%	TOTAL	RETAINED	mass	W	mass	
	MASS	Q	Q	$\frac{Q}{m}$			
A*	18.2 %	314 μC	57.2 μC	3.54 $\mu\text{C/gm}$	2.84 rep/hr	mass = 10^3 grams	
B*	68.91	314	216.5	13.4	10.73	per HBS2 - insoluble part	
C*	96.12	314	302.	18.7	15.0	constant 0.12 retention	
						W	
						$Q = .12 \times 314 \mu\text{C}$	
						$= 37.7 \mu\text{C}$	
						$\frac{Q}{m} = 37.7 \times 10^{-3}$	
						W same for all $\rightarrow$	
							30.2 mrad/hr A*
							30.2 " B*
							30.2 " C*

ALVEOLAR CASE

DISTRIB.	RETENTION			AVER. ALVEOLAR EXPOS.		LYMPH NODE AVER. EXPOS. CASE	
	%	TOTAL	RETAINED	mass	W	mass	
	MASS	Q	Q	$\frac{Q}{m}$			DISTRIB.
A*	43.8 %	314 μC	137.5 μC	$153 \times 10^{-3} \mu\text{C/gm}$	122.6 mrad/hr	mass = 20 gm	A*
B*	19.84	314	62.3	693×10^{-3}	55.6		B*
C*	2.7	314	8.48	9.42×10^{-3}	7.55		C*
						$Q = 9 \mu\text{C/gm}$	
						8.55 rep/hr	
						3.12	
						2.5	
						0.424	
						0.34	

LOCAL AND NON-UNIFORM EXPOSURE RATES

$$D_r = 12.43 Q \frac{e^{-\mu r}}{r^2} \text{ rep/da at } r \text{ cm from particle center (from A18)}$$

Q here is $\mu\text{C/particle}$

Since specific activity and ratio active/inert the same,
and the distributions A* B* and C* have the
same NMD and σ as A B and C

Q/particle will be the same as before and
the exposed tissue volumes will vary with the
number of particles or the mass concentration factor $\frac{\text{cases}}{\text{cases}}$

DOSE LEVELS	A	B	C	A*	B*	C*
0.3 to 3.0 nrad/da	1.56 (13)	9.49 (13)	3.16 (14)	3.29 (14)	1.94 (14)	3.11 (13)
3.0 to 30	8.51 (11)	5.72 (12)	2.45 (13)	1.79 (13)	1.31 (13)	2.41 (12)
30 to 300	3.86 (10)	3.16 (11)	1.53 (12)	8.15 (11)	7.24 (11)	1.51 (11)
300 to 3000	1.55 (9)	1.51 (10)	8.33 (10)	3.23 (10)	3.46 (10)	8.20 (9)
> 3000	5.59 (7)	6.21 (8)	3.78 (9)	1.20 (9)	1.42 (9)	3.72 (8)

A* = 21.2 x A
B* = 2.274 x B
C* = 0.0912 x C

ABOVE VALUES ARE TISSUE VOLUMES IN CUBIC MICRONS

NUMBER IN PARENTHESIS IS POWER OF 10 (1) = $\times 10$

Sampling for Radioparticulate Hazards - Appendix A

Calculations - The Influence of Particle Variables

Local and Non-Uniform Exposure Rates

Since there are excellent reasons (Supplement 2) for considering the exposure rates in the vicinity of insoluble radioactive particles as of the greatest final significance, it is important to consider the relative influence of the exposure variables.

Energy possessed by a beta particle emitted will influence its range and, in the aggregate, determine the value of μ . For betas of relatively high average energy the contribution of the $e^{-\mu r}$ term will be small for relatively small values of r , possibly out to 30 or 100 μ . This permits an approximation which simplifies some of the considerations of interest, that $D_r \doteq 12.43 Q r^{-2}$. This may be useful for considering Q small and when the radius r for a particular dose value is not great. Hence, this would be of interest in low specific activities or where only small particles are concerned. With lower energies of beta particles, the degree of localized dosage would increase and the simplifications introduced in the following section for ease of analytical consideration are not valid.

Volumes affected by radiation to the exposure level of particular dose rates may be approximated for the general case:

Given a selected dose rate, K rep/da, since $D_r \propto \frac{Q}{r^2}$

$$r_k^2 = \frac{hQ}{K}, \quad r_k = \sqrt{h} \left(\frac{Q}{K} \right)^{\frac{1}{2}}$$

$$V_k = p r_k^3 = s \left(\frac{Q}{K} \right)^{1.5}$$

where:

$Q = \mu c/\text{particle}$

$g, h, p, s = \text{constants}$

$r_k, V_k = \text{radius and volume within which } D_r \geq K.$

For a dose rate of MK rep/da;

$$r_{mk} = r_k \cdot M^{-\frac{1}{2}} \quad \text{and} \quad V_{mk} = V_k \cdot M^{-1.5}$$

Sampling for Radioparticulate Hazards - Appendix A

Thus for ΔV such that $K \leq D_r \leq MK$

$$\Delta V = V_k (1 - M^{-1.5}) = s \left(\frac{Q}{K} \right)^{1.5} (1 - M^{-1.5})$$

where: $M = 10$, $\Delta V = 0.97 V_k$ and $V_{10k} = 0.0316 V_k$

since: $Q = \frac{\pi}{6} \phi^3 \rho A \times 10^{-12}$ for any particle

$$\Delta V \propto K^{-1.5} \phi^{4.5} \rho^{1.5} A^{1.5} \text{ per particle.}$$

The total volume exposed by the retained fraction η of the particles (α of which are active) of concentration C in the breathed air T is;

$$\sum_j \Delta V = \sum_j \{ n_j \times g (K^{-1.5} \phi_j^{4.5} \rho^{1.5} A^{1.5}) \}$$

where: n_j = number of exposure foci particles of size

$$\phi_j, \text{ and } \sum_j n_j = \eta_j C_j T \alpha$$

$$\text{So that: } \sum_j \Delta V = \sum_j (\eta_j C_j \alpha T) \cdot g \cdot (K^{-1.5} \phi_j^{4.5} \rho^{1.5} A^{1.5}).$$

For alveolar deposition the efficiency η is a function of particle size ϕ which slowly increases to about 1μ then decreases with every increasing rapidity.

The concentration of numbers of particles present will also be a function of particle size ϕ . For $\phi_j >$ the NMD (0.3μ for these distributions), this function C_j will decrease with a rapidity related to the σ of the particle size distribution (the smaller σ is, the more sharp the decrease). These tend to offset the above 4.5 power exponent of the ϕ_j factor, independent of variation in the specific activity, etc., for a particular exposure and dose rate. The airborne concentration C is restricted by the requirement of Case II for the same total active mass, $\propto \sum C_j \phi_j^3$, for the three distributions. Thus, the resultant lesser volume fluxion is primarily due to the influence of the factor $\eta(\phi)$, $\phi^{1.5}$, and $C_j(\sigma)$.

Sampling for Radioparticulate Hazards - Appendix A

Specific Activity will be related to the contaminant particle's origin. Its increase will produce a resultant change in exposed tissue volume as indicated (proportional to the 1.5 power) for homogeneously active particles. In the practical case it might be expected that the specific activity would not be constant. Absorption or contamination of the surface of carrier particles would introduce one manner of activity variation, with particle size.

Active to Inert ratios would not be the same for all particle sizes unless the only airborne material was of contaminated origin. The manner in which R was a function of particle size would depend on the natural background dust distribution and other factors such as the mode of dispersal of active contaminant, etc. In comparing cases, the variation with R would be linear.

Times of exposure would determine the total volume of air breathed (with proper allowance for the degree of physical exertion of the exposed personnel). This would correspondingly determine the total activity contributing to an internal exposure, subject to concentration and retention variation.

Decay rates of activity will introduce time again as a variable and operate to reduce the specific activity and consequently the volume receiving a chosen dose rate. The effects of decay on total exposure are evident and would be considered in conjunction with biological elimination rates.

Concentrations will change with both location and time, usually by the loss of larger particles which settle faster so that a shift to smaller median sizes is expected. A second way in which time variation of concentrations arises is thru the meteorological factors of dilution.

The calculation of the lung tissue volumes receiving various levels of total exposure from inhaled airborne activity at a site downwind from an atomic bomb detonation would present a problem of considerable interest. This would require the consideration of independent and concurrent time variations of activity and concentration as well as the probable independent additional variations of R and A with particle size. Due to the soft components of the total betas, a combined analytical and graphical approach would probably be required since the range-energy also would vary with time. This could be worked out for several cases of interest perhaps by the Monte Carlo method or with the aid of one of

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the computing machines. At present, the incomplete data on biological effect does not readily permit a full evaluation of such total exposures and the accompanying exposure rate values.

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