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DOSE CALCULATION MODELS FOR RE-ENTERING NUCLEAR ROCKET DEBRIS

For

Space Nuclear Propulsion Office
Atomic Energy Commission
National Aeronautics and Space Administration

By

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I. INTRODUCTION

The estimation of the biological hazards which may result from nuclear rocket engine flight failures is complicated by the more or less random nature of the deposition of engine debris into the biosphere. The debris may come to earth in an uninhabited desert or in the midst of a large city. In the first case, the probability of direct exposure of individuals to the debris will be vanishingly small whereas in the latter case the probability may be extremely high. Similarly, the probability of indirect exposure through ingestion is directly related to the likelihood of the debris falling on cultivated land.

The distribution of population over the earth's surface, the fraction of land devoted to agriculture, and those other cultural factors which affect the probability of an individual receiving a certain dose must be considered in evaluating the hazards from a malfunction of a nuclear engine; otherwise unrealistic and excessively conservative results will be obtained. The probabilistic approach to the evaluation of dose was initially treated in NUS-167;[1] much of this report is a refinement of that work.

In most cases no attempt is made to define the actual beta dose function from a source; the source composition and dimensions greatly affect the nature and amount of beta energy leaving the particle. Some beta dose functions are described in detail in NUS-217 [2]; others have been considered.

Cultural factors required for determining dose and dose probability are not given in this report. Cultural data for the band of the earth's surface between 40°N and 40°S latitude are given in NUS-230.[3]

The external dose functions and external and internal dose probability functions are derived in this report. External whole body gamma and beta dose relationships are derived for receptors who are mobile; i.e., who are not fixed in a given location for the entire exposure period. The probability of receiving at least a given external dose, the fraction of the population receiving at least a given dose and the overall population dose are also derived for

external gamma radiation exposures.

The functions for determining the probability of a receptor being struck by a particle that sticks to the skin and the number of people so affected are derived to allow estimation of the hazard from localized beta doses to the skin.

Internal dose probability functions are derived for both ingestion and inhalation. These relations consider cultural influences such as diet, agricultural production, and population density.

Functions for estimating critical organ doses resulting from plant uptake and subsequent ingestion are not derived in this report because of the variations in soil characteristics, dietary intake and cooking and eating habits that exist throughout the world. Comparisons are made, however, to fallout from nuclear weapon testing and subsequent appearance of Sr-90 and Cs-137 in food in the United States.

II. DOSE MODELS

A. External Whole Body Dose

The post operative destruction of a nuclear engine will generate a large number of reactor fragments. These will reach the earth's surface at varying times depending on such factors as altitude of destruct, shape and size of particles, velocity increment obtained from the destruct mechanism, etc. As a result of the varying re-entry times and other environmental factors associated with re-entry of these particles, a varying ground deposition pattern for each particle size will be obtained. The number density of particles deposited on the ground may assume values on the order of those shown in Table I. [1]

It can be seen in Table I that the number density of particles which are large enough to deliver significant external whole body doses (from a single particle) is only a few/km^2. This is not to imply

Table I

Typical Particle Size and Activity[1]

Diameter, μ Range	Log Mean	Volume cm^3	Activity at 1 hr, curies	Number of Particles Total	Number of Particles per km^2
< 10	3.2	1.72×10^{-11}	9.5×10^{-10}	2.7×10^{15}	5.3×10^{6}
10-50	22.4	5.96×10^{-9}	3.3×10^{-7}	7.7×10^{12}	1.7×10^{4}
50-100	70.8	1.86×10^{-7}	1.0×10^{-5}	1.8×10^{11}	830
100-200	141	1.49×10^{-6}	8.2×10^{-5}	2.9×10^{10}	240
200-400	282	1.19×10^{-5}	6.6×10^{-4}	5.1×10^{9}	95
400-800	564	9.5×10^{-5}	5.2×10^{-3}	8.0×10^{8}	52
800-1000	895	3.76×10^{-4}	2.1×10^{-2}	3.3×10^{7}	4.7
1000-1600	1270	1.09×10^{-3}	6.0×10^{-2}	1.1×10^{7}	1.9
*1/16-1/8	** .226	6.1×10^{-3}	0.34	1.3×10^{7}	6.2
1/8-1/4	.452	4.85×10^{-2}	2.7	2.7×10^{6}	4.8
1/4-1/2	.904	0.388	21	1.6×10^{5}	1.1
1/2 - 1	1.81	3.10	170	2.3×10^{3}	0.06
> 1	3.62	24.8	1360	7.4	$\sim 10^{-3}$

*inches ** cm

that the external dose from particles of smaller size (but with a considerably greater deposition density) is negligible; however, it should be evident that the models used to calculate the contributions from these two types of sources must be different. Additionally, a normal individual does not remain fixed in a given location indefinitely; consequently, the separation from the deposited source and the dose will vary, depending on the individual's activities. It is most desirable to avoid the arbitrary and incorrect assumption that the receptor remains in a fixed location for a long period of time.

1. Gamma Dose From Single Particles

If the nuclear engine re-enters intact or if the deposited debris is spread over such a large area that the spacing between particles is large then some individuals will be affected only by single particles of any size class, i.e. receptors who receive large doses will obtain most of this dose from only one particle.

If the assumption is made that only one particle of any size class will affect a receptor then it is possible to define the dose the receptor will receive if the manner in which the receptor moves with respect to the source can be described. Of course, any analytical model employed to describe the activities of a large segment of any population must be recognized as limited in precision and scope; such a model, however, is more indicative than assuming permanently fixed receptors at arbitrary distances.

For any normal individual, it can be stated that some point exists about which that individual spends more time than at any other location. In fact, for most individuals, there may be two or more such locations about which the majority of time is spent. If the activity of individuals could be defined by such centers of motion and a distribution function about those centers, then to describe the dose to that individual it would only be necessary to define the distance from the center of motion to the source.

Three distribution functions come to mind; these are (1) a constant probability out to a fixed limit (2) a linearly decreasing probability

out to a fixed distance and (3) a two dimensional Gaussian distribution. The constant probability type of distribution can be eliminated on the basis of personal experience and logic. The' linearly decreasing probability distribution might be valid for semi-invalids and infants. The two dimensional Gaussian distribution, however, allows for infrequent occurrences of very large distances and, hence, does not impose any limit on distance to which the individual may move. For the purpose of analysis of whole body external dose, the two dimensional Gaussian distribution was selected as a reasonable approximation.

It is first assumed that the individual's location with reference to a fixed center of motion (C in Figure 1) is given by the independent variables x and z both of which are Gaussian distributed with a common standard deviation.

The probability density (probability per unit area) weighted for the fraction of time, f_i, the standard deviation of motion, σ_i, applies for an individual or group of similar individuals in the activity class i is given by

$$y_i(x,z) = \frac{f_i}{2\pi\sigma_i^2} \exp -\left[\frac{x^2 + z^2}{2\sigma_i^2}\right] \qquad (I)$$

The probability that an individual is within a given area defined by the points (x_1, z_1), (x_2, z_1), (x_1, z_2) and (x_2, z_2) is given by

$$P = \int_{z_1}^{z_2} \int_{x_1}^{x_2} y(x,z)\, dx\, dz$$

To calculate the exposure it is convenient to use polar coordinates centered on a source, Q.

From Fig. 1, if a source, Q, is located a distance, s from the center of motion, C, then

$$x^2 + z^2 = r^2 + s^2 - 2\,rs\cos\theta$$

and it is noted that

$$\frac{x+s}{r} = \cos\theta \text{ and } \frac{z}{r} = \sin\theta$$

$$\text{or, } x = r\cos\theta - s \text{ and } z = r\sin\theta$$

then

$$J\left\{\frac{x,z}{r,\theta}\right\} = \begin{vmatrix} \frac{\partial x}{\partial r} & \frac{\partial x}{\partial \theta} \\ \frac{\partial z}{\partial r} & \frac{\partial z}{\partial \theta} \end{vmatrix} = (\cos\theta)(r\cos\theta) - (\sin\theta)(-r\sin\theta) = r$$

Therefore, the probability that an individual is in an area defined by θ_1, θ_2, r_1, and r_2 is given by

$$P = \int_{r_1}^{r_2}\int_{\theta_1}^{\theta_2} g(r,\theta)\, r\, d\theta\, dr$$

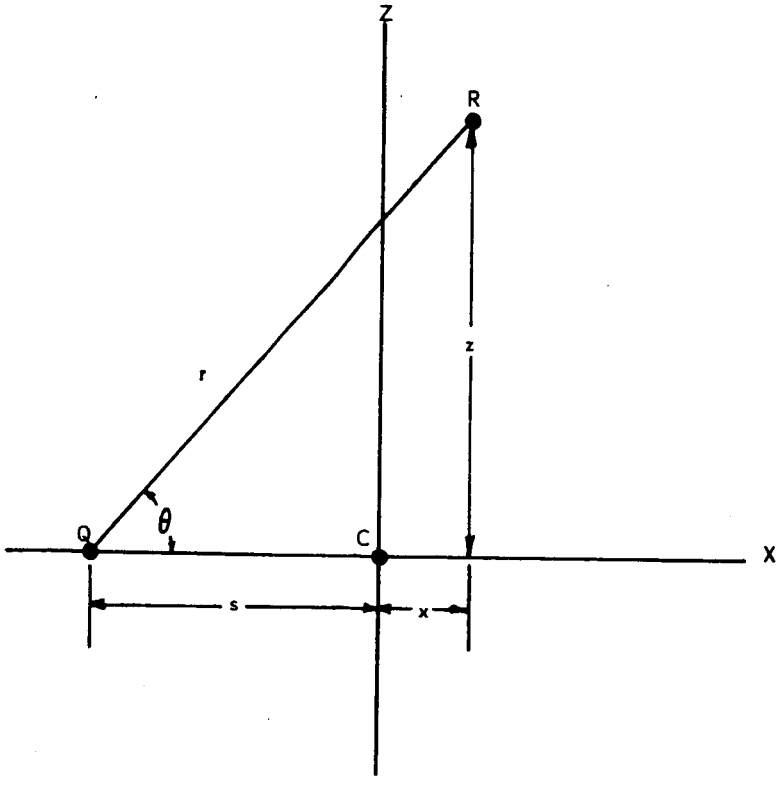
where

$$g(r,\theta) = \frac{f_i}{2\pi\sigma_i^2} \exp\left[-\frac{1}{2\sigma_i^2}(s^2 + r^2 - 2\,sr\cos\theta)\right] \qquad \text{(II)}$$

Thus the probability that an individual is found in the annular region between r_1 and r_2 is

$$P_i = \frac{f_i}{2\pi\sigma_i^2}\int_{r_1}^{r_2}\int_{0}^{2\pi} r \exp\left[-\frac{1}{2\sigma_i^2}(s^2 + r^2 - 2sr\cos\theta)\right] d\theta\, dr \qquad \text{(III)}$$

FIGURE 1



MOBILE RECEPTOR GEOMETRY

The dose from an isotropic point source with buildup and attenuation included for a receptor at distance, d, from the point source is given by

$$D(d)_j = \sum_E \frac{k(E)\, Q_j(E)\, B(E)}{4\pi d^2} \exp\left(-\mu(E)d\right) \qquad \text{(IV)}$$

where: $Q_j(E)$ is the time integrated activity of energy, E, for a particle of size j; $\mu(E)$ is the energy dependent absorption coefficient: k is a dose conversion constant and B is the linear buildup factor given by

$$B = 1 + \mu(E)\, d$$

Assuming that the effective receptor height is 1 meter above the fallout plane, then

$$d^2 = r^2 + 1$$

and the dose at any distance from a source of strength, $Q_j(E)$, is given by

$$D(r)_j = \sum_E \frac{k(E)\, Q_j(E)\, \left(1 + \mu(E)\sqrt{r^2+1}\right)}{4\pi (r^2+1)} \exp\left[-u(E)\sqrt{r^2+1}\right] \qquad \text{(V)}$$

Since the receptor is not at a fixed distance from the source, equation (V) must be multiplied by the probability that the receptor will be located in a given distance interval, $r_2 - r_1$. Integrating over all values of r results in

$$D(s)_{j,i} = \frac{1}{8\pi^2} \frac{f_i}{\sigma_i^2} \sum_E k(E) Q_j(E) \int_0^{\infty} \int_0^{2\pi} \frac{1+\mu(E)\sqrt{r^2+1}}{r^2+1}$$

$$\exp\left[-\mu(E)\sqrt{r^2+1} - \frac{s^2 + r^2 - 2s\, r \cos\theta}{2\sigma_i^2}\right] r\, d\theta\, dr \qquad \text{(VI)}$$

Equation (VI) can be directly multiplied by dose reduction factors afforded by housing where applicable.

2. Individual Exposure Probability

The separation distance, s, in equation (VI) cannot be explicitly derived for any population group since the spatial distribution of the particles and people is an essentially random process.

To determine separation distance, the probability of any single individual receiving a dose not less than a certain value can be described. It is assumed that the spacing of particles is so large that persons are exposed to or affected only by a single particle. This assumption is believed reasonable since the analysis of flight hazards is primarily concerned with high dose levels. This requires the receptors to be relatively close to a particle. Furthermore, when one considers terrain effects, the shielding introduced by ground irregularities and structures should become increasingly important as the separation distance between the source and receptor increase.

For the purposes of this analysis it is assumed that the distribution of the particles is described by a Poisson distribution.

If we consider a large area in which the average deposition of particles of size class j is $\bar{m}$ particles per unit area then in a smaller area, a, the probability of finding exactly x_j particles of size class j is given by

$$P_{x_j} = \frac{(\bar{m}\, a)^{x_j}}{x_j\,!}\, e^{-\bar{m}\, a_j} \qquad \text{(VII)}$$

Now, for any receptor, the probability that one particle will be located within a distance s of the receptor

$$P_{z=1} = \frac{(\bar{m}\pi s^2)^1}{1\,!}\, e^{-\bar{m}\pi s^2} = \bar{m}\,\pi s^2\, e^{-\bar{m}\,\pi s^2} \qquad \text{(VIII)}$$

The probability that more than one particle is located within radius s of the receptor is

$$P_{z>1} = 1 - \bar{m}\pi s^2 e^{-\bar{m}\pi s^2} - e^{-m\pi s^2} \qquad \text{(IX)}$$

The value of $P_{z=1}$ (from equation VIII) increases to a maximum value at $\bar{m}\pi s^2 = 1$ and then decreases; the value of $P_{z>1}$ (from equation IX) continuously increases and approaches a value of 1 as the value of s increases. When the value of $\bar{m}\pi s^2 = 1.25$ $P_{z=1} = P_{z>1}$. Obviously then, equation VIII can be used to express the probability that the receptors dose is greater than a given value only when $m\pi s^2 < 1$. Since the single particle (for which the distance probability relationship is given by eq. VIII) can be no further from the receptor than distance s the dose to the receptor is equal to or greater than the dose at distance s.

3. Dose Distribution and Population Dose

The number of people receiving a dose equal to or exceeding a given dose can be evaluated as follows;
The number of people who are expected to be at a distance from a single particle or closer is on the average

$$z_i = \bar{n}_i \pi s^2 \qquad \text{(X)}$$

then for M particles the total number of people in the i^{th} group (over which $\bar{m}_i$ and $\bar{n}_i$ are valid) who are at a distance s or closer to any particle is

$$N_i = M_j z_i = M_j \bar{n}_i \pi s^2$$

The lowest possible dose any of these individuals may get is that dose corresponding to a separation distance s. Thus, the fraction of the total population, N_i / N_0, receiving a dose no less than

$D(s)_{j,i}$ is

$$\left[\frac{N_i}{N_0}\right]_{D \geq D(s)_{j,i}} = \frac{M_j}{N_0} \bar{n}_i \pi s^2 \qquad \text{(XII)}$$

But since

$$\frac{M_j}{N_0} = \frac{\bar{m}_j}{\bar{n}}$$

$$\left[\frac{N_i}{N_0}\right]_{D \geq D(s)_{j,i}} = \frac{\bar{n}_i \bar{m}_j \pi s^2}{n} = f_p \bar{m}_j \pi s^2 \qquad \text{(XIII)}$$

where f_p is the fraction of the population which moves about with a given value of σ_i used to calculate $D(s)_{j,i}$

The population dose from particles of size j can be defined as the summation of the dose to each individual.

$$P.E._{(j)} = \sum_s D(s)_j z(s) \qquad \text{(XIV)}$$

As before, the probable number of people in the i^{th} group in an area of radius s about a single particle is

$$z_i = \bar{n}_i \pi s^2$$

and

$$\frac{dz_i}{ds} = 2\bar{n}_i \pi s$$

But for a fixed value of dose (distance)

$$\frac{d\,(P.E.)_i}{dz_i} = D(s)_{j,i}$$

therefore

$$\frac{dz_i}{ds}\;\frac{d\,(P.E.)_{(j)}}{dz_i} = \frac{d\,(P.E.)_{(j)}}{ds} = 2\bar{n}_i\,\pi\,sD(s)_{j,i} \qquad \text{(XV)}$$

and the population exposure for a single particle of size class j and population group i becomes

$$P.E._{(j,i)} = 2\bar{n}_i\,\pi \int_0^\infty D(s)_{j,i}\,ds \qquad \text{(XVI)}$$

where $D(s)_{j,i}$ is given by Equation (VI). For the entire population group, i, and for M_j particles the total population exposure becomes

$$P.E._{(j)} = \sum_i 2\bar{n}_i\,\pi M_j \int_0^\infty s_j\,D(s)_{j,i}\,ds \qquad \text{(XVII)}$$

4. Gamma Dose From a Uniformly Contaminated Plane.

A basic assumption used in the development of the probability relationships is that no one person will receive a significant dose from more than one particle in any given size class except within the framework of several centers of motion for different diurnal periods. As the particle density becomes large, the separation distance between particles will become smaller and this assumption is no longer useful. However, the uniformly contaminated plane source may be used to represent the large number of discrete point sources as the number of particles becomes large.

The dose, D_j, from a point source at distance, r, from the base of a receptor one meter above the source plane is given by

$$D_j = \sum_{(E)} \frac{k(E)Q_j(E)}{4\pi(r^2+1)} \left[1+\mu(E)\sqrt{r^2+1} \right] e^{-\mu(E)\sqrt{r^2+1}} \quad \text{(XVIII)}$$

If G_j is the time integrated source strength per unit area then

$$Q_j(E) = G_j(E)\, dA = G_j(E)\ 2\pi r\, dr \quad \text{(XIX)}$$

then

$$D_j = \sum_{(E)} \frac{k(E)\ G(E)_j}{2} \left[\int_0^\infty \frac{re^{-\mu(E)\sqrt{r^2+1}}}{(r^2+1)}\, dr + \int_0^\infty \frac{r\mu(E)\sqrt{r^2+1}}{r^2+1}\, e^{-\mu(E)\sqrt{r^2+1}}\, dr \right] \quad \text{(XX)}$$

Performing the indicated integrations by substituting $t^2 = \mu^2(E)\ (r^2+1)$ and using the approximation that $e^{-\mu(E)} \approx 1$

$$D_j = \sum \frac{k(E)\ G(E)_j}{2} \left[1 + \int_{\mu(E)}^\infty \frac{e^{-t}}{t}\, dt \right] \quad \text{(XXI)}$$

Equation (XXI) should be used when the particle deposition or the value of σ_i is large. As an arbitrary guide to the use of equation (XXI) in place of equation (VI) the following rule is suggested:

> If more than 5% of an individual's time is spent at a distance from the center of motion that is larger than half the mean particle spacing then equation (XXI) should be used.

Simply stated equation (XXI) is used if

$$2.45\ \sigma_i \geq \sqrt{\frac{1}{\bar{m}_j\ \pi}} \quad \text{(XXII)}$$

Table II shows some values of σ_i and m_j above which the uniformly contaminated plane model should be used rather than the model developed in section A-1.

Table II

σ_i (meters)	(part/km^2)
10	532
20	133
40	33
60	15
80	8
100	5

The equations for probability, obviously, do not apply to the dose calculated from equation (XXI); however, this dose contribution must be included in the overall individual dose and population dose derived for other particles sizes.

B. External Whole Body Beta Dose

1. Beta Dose From Single Particles

The beta dose to the whole body is probably not significant from the standpoint of biological effects due to the limited beta particle range in both air and tissue. The beta decay energy is largely expended in the cornified layer of skin which has little biological significance from the standpoint for radiation damage.

The fraction of time an individual is within a distance interval $r_2 - r_1$ is given by equation III.

The beta dose is a function of decay energy, distance, and time integrated activity and can be evaluated from methods given in NUS 217[2] or other sources. If the energy dependent beta dose at distance r from the source of unit activity integrated with respect to time for particle size class j is represented by $J_j(r,e)$ then the beta dose to a mobile receptor is given by

$$D(s)_{j,i} = \sum_{E} \frac{f_i Q_j(E)}{2\pi\sigma^2} \int_0^{\infty} \int_0^{2\pi} J_j(r,E) \exp\left[-\frac{1}{2\sigma_i^2}(s^2+r^2-2sr\cos\theta\right] r\,d\theta\,dr \qquad \text{(XXIII)}$$

The separation distance, s, and exposure probabilities are defined by the equations derived in sections A-2 and A-3 of the report.

The fraction of time individuals in a population group spend inside the dwelling and structures can be obtained from NUS-230[3]. Since in all dwellings the beta particles are effectively stopped, no beta dose will be received by the occupants.

2. Beta Dose from a Uniformly Contaminated Plane

The beta dose should be calculated using equation (XXIII) when equation (XXII) is not satisfied; i.e., when the mobile receptor model is used to calculate gamma dose. When equation (XXII) is satisfied, the following equation for beta dose applies:

$$D_{(j)} = \sum_{E} 2\pi G(E)_j \int_0^{\infty} J_j(r,E)\,dr \qquad \text{(XXIV)}$$

where $G(E)_j$ is the time integrated activity per unit area for particle size j and energy group E, and $J_j(r,E)$ is the beta dose function for particle size j, and energy E, and distance r. The basic form of equation (XXIV) is obtained from reference[5].

The limitation on the use of the mobile receptor is based on an exponential attenuation beta absorption model. If a range limited beta absorption model is used, the limitation on the use of the mobile receptor model must be revised to be consistent with the beta absorption model.

C. External Skin Contact Dose

When a shower of particles takes place one of two events may occur. The particle may land on the ground or it may interact with an individual in some manner. One way in which the particle can interact is that it may strike and stick to the receptor. Normally, beta radiation is not significant as an external source because of the limited range of betas (3-13 meters) in air; the beta radiation, however, is not negligible when the particle is in contact with or near the surface of the skin.

Obviously the probability of striking an individual is considerably lower than the probability of striking the ground. The object here is to define the probability of a particle striking and sticking to an individual,

The average number of particles striking and sticking to a person for at least time t is

$$\psi_j = \bar{m}_j \, a \Gamma_j \xi_j P_t \qquad \text{(XXV)}$$

where a is the skin area "seen" by the particle, ξ_j is the sticking probability (i.e., the number of particles sticking divided by the number striking the body); Γ_j is the impaction efficiency for a particle of size j(i.e., the fraction of particles that strike the body rather than flow around the body with air flow); and $P_t(j)$ is the probability of a particle of

size j sticking for time t. The probability of an individual being struck by M particles of size j which subsequently stick for time t or longer is

(XXVI)

$$P_{M_j,t} = \left[\frac{\psi_j}{M_j!}\right]^{M_j} \exp - \psi_j$$

USNRDL has proposed the use of a model [6] developed by A. Humphrey of the University of Pennsylvania. This model basically consists of a composite of a number of cylinders of various diameters and lengths to simulate the arms, hands, legs, trunk, and head of man. The equivalent area projected onto the ground plane as seen from a particle which is moving with a downward or terminal velocity V_T and a horizontal velocity V_W is expressed as

$$a = a_h + \frac{V_W}{V_{T(j)}} \sum_k \Gamma_k(j)\, a_k \qquad \text{(XXVII)}$$

where the subscript k refers to the various cylinders in the composite and h refers to a horizontal head surface.

The impaction efficiency $\Gamma_k(j)$ is tentatively given by NRDL as being

$$\Gamma_k(j) = \frac{300\left(\frac{\rho\gamma^2 V_W}{\Omega}\right)^3}{1 \times 10^{-7} + \left(\frac{\rho\gamma^2 V_W}{\Omega}\right)^2 + 300\left(\frac{\rho\gamma^2 V_W}{\Omega}\right)} + \frac{\gamma}{\Omega} \qquad \text{(XXVIII)}$$

where Ω is the diameter of body cylinder, k; ρ is the particle density and γ is the particle diameter.

Equation (XXVII) is from the work of Landahl and Herrmann at the University of Chicago.

Sticking probability, ξ_j, was assumed to be $\frac{50}{\gamma}$ (microns) in NUS-167[1]. This, however, was an arbitrarily assumed value only. B.R. Fish [7] at Oak Ridge has done some work with wax and plastic spheres loaded with Zn-CdS (Ag). Fish's work indicates that the surface conditions of the skin (mainly oilyness and perspiration), the weight of the particle, and the degree of activity of the individual are the most important parameters that affect sticking probability. No formal studies have been made at this time; however, experiments are planned to obtain data on sticking probability. Fish, also has obtained some data on the sticking time on the skin[7]. This work indicates an exponential decrease of the number of particles remaining with time. Thus, the probability, P_t, of a particle sticking for time t is

$$P_t(j) = \exp\left[-\frac{t}{\Lambda_j}\right]$$

where Λ_j represents a mean life of the particles sticking on the skin and can be obtained from ORNL-TM-1053[6].

The work by Fish and others will be followed since the sticking probability and sticking time are probably the most important parameters in this evaluation.

Various fractions of the body will be covered with clothing depending upon the culture of the population and the geographical location. To compensate for this a factor $f_{\mu(k)}$ is introduced. This factor is defined as the fraction of the body area, k, covered by clothing with an absorber of weight μ. Equation (XXV) becomes, then

$$\psi_j = f_o \left[\bar{m}_j \xi_j \left(a_h + \frac{V_W}{V_{T(j)}} \sum_k f_{\mu,(k)} a_k \Gamma_k(j)\right)\right] P_{t(j)} \qquad \text{(XXIX)}$$

The beta dose per particle is a function of particle size, activity and the weight of absorber, μ, between the skin and the particle, and the sticking time t thus

$$D_j = G\ (Q_j,\ \mu,\ t) \qquad \text{(XXXI)}$$

The dose function can be obtained from NUS-217[2], or other sources.

D. Internal Dose

1. Lung Dose

Table I indicates that particle number densities on the ground area quite high for the size particles that lie in the inhalable range. Particles up to about 100 μ can be inhaled; however, the upper size limit for unit density particles reaching the lung is about 10 μ. The larger 100 μ particles will require in excess of 20 hours to reach the ground; particles 10μ and less will require a significantly longer time to re-enter. Thus, even if the probabilities for inhaling respirable size material is high the decay of activity before reaching the ground will be significant and severe lung doses should not occur. The larger size particles which are inhalable but do not reach the lung are subsequently swallowed and irradiate the G.I. tract. These particles, which require a much shorter time to reach the ground, can deliver significant doses to the body.

Figure 2 shows a compartmentalized model of the respiratory system showing the various routes of inhaled particles. Particles retained in the nasal passages and upper respiratory system are assumed to be swallowed because of the ciliary action of the epithelium in these regions.

Pattle[8] measured the penetration of the particles in the nasal and mouth cavity by drawing laden air through the nose and out the mouth.

From the data obtained, he found that the following relationship represented a reasonable fit

$$P_n(j) = 0.95 \left[1-0.218 \ln \frac{\gamma_j^2 W}{20.2}\right] \qquad \text{(XXXII)}$$

where γ= particle diameter in microns

W = air flow in liters/min

For the standard man the breathing rate is 20.8 l/min[10] during the working part of the day; thus, equation (XXXII) reduces to

$$P_n(j) = 0.95 \left[1-0.436 \ln (1.015\ \rho^{1/2}\ \gamma_j)\right] \qquad \text{(XXXIII)}$$

The density term in inserted to correct from unit density to the actual particle density as suggested by the work of Landahl.[9] Figure 3 is a curve of equation (XXXIII).

Landahl[9] calculated the retention of particles in various parts of the respiratory system. Since the work of Pattle was available, Landahl's calculation for retention in the mouth-nose region was not used. However, since no experimental data exists for retention in other parts of the human respiratory system other than the mouth region it is necessary to rely on calculated values such as Landahl's

FIGURE 2
SCHEMATIC REPRESENTATION OF
THE RESPIRATORY SYSTEM

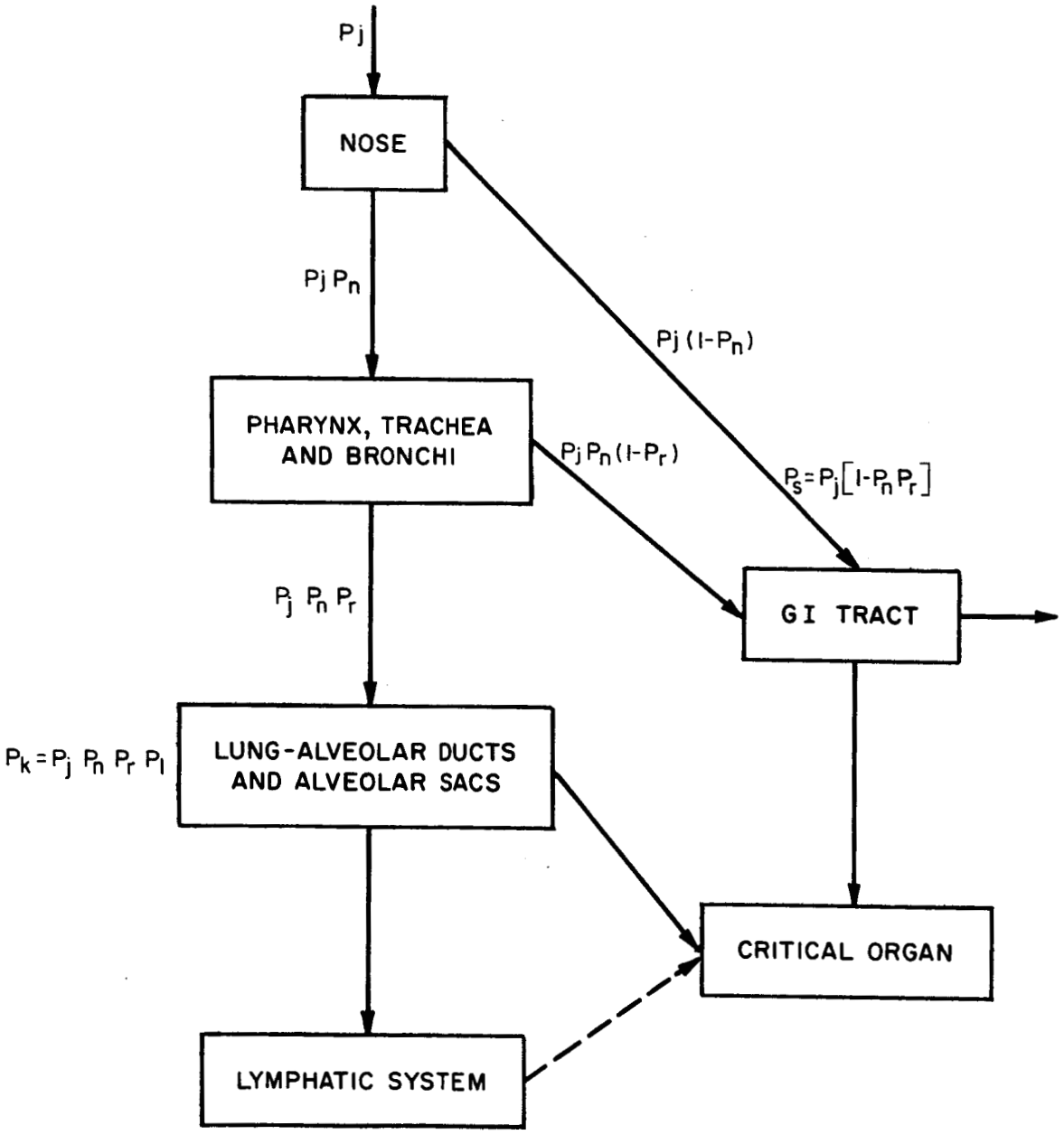
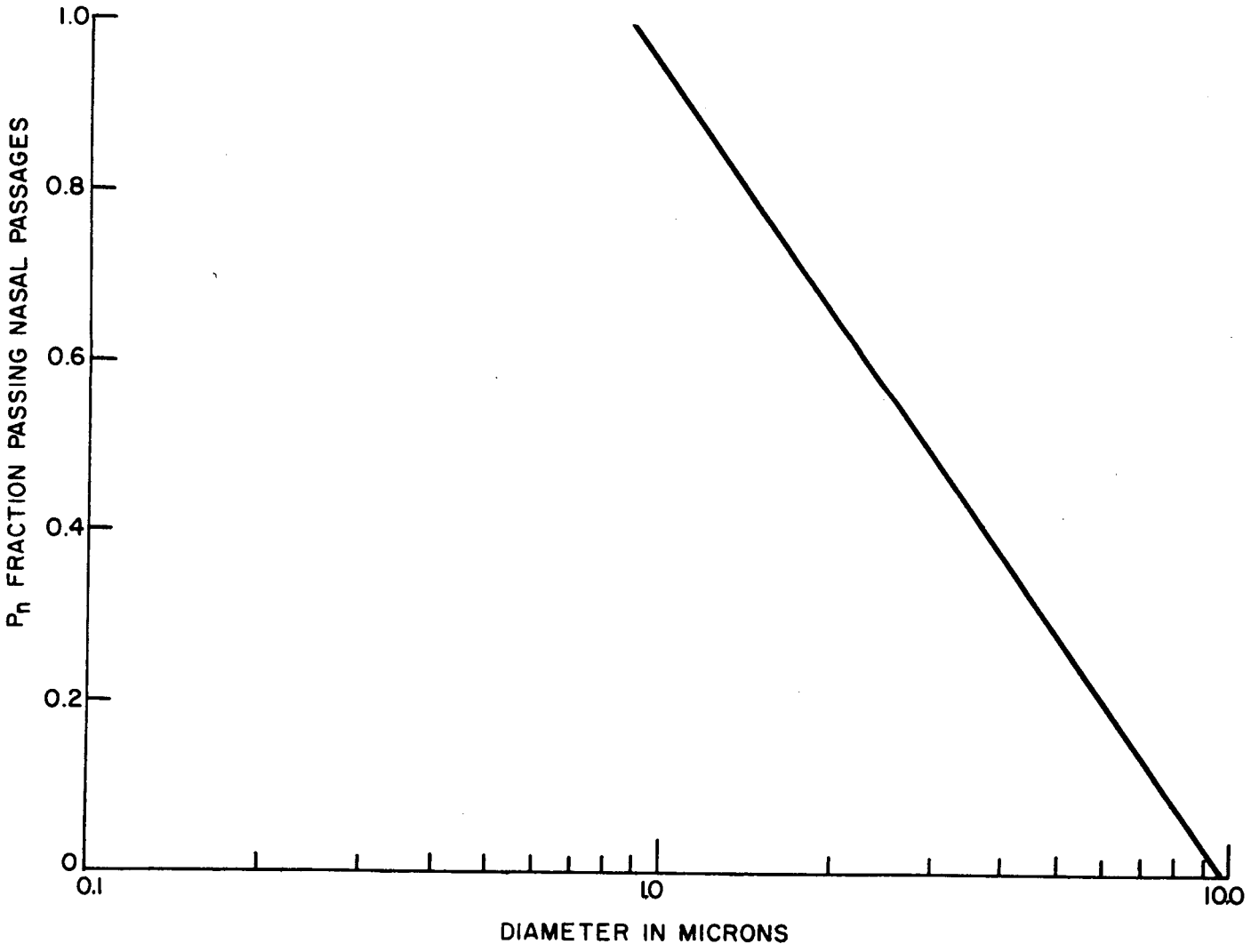


FIGURE 3
FRACTION PASSING NASAL PASSAGES
(Unit Density Spheres)



work. Figure 4 shows the range of Landahl's calculations for retention in the upper respiratory tract for four assumed tidal volumes. The straight line was used to represent the data for particles larger than 1μ in diameter. The particles smaller than 1 μ were neglected for simplicity since the error introduced in calculating the dose to the GI tract is negligible whereas it will result in an over-estimate of the lung dose. The equation of the fit to the data above 1μ is:

$$P_r(j) = 1 - 0.33 \ln \left(\frac{\gamma \rho^{1/2}}{1.1} \right) \qquad \text{(XXXIV)}$$

where P_{r_j} = fraction of particles not retained in the upper respiratory tract.

Again the density term is inserted to correct from the unit density used by Landahl in the calculations.

Retention of particles in the alveolar ducts and sacs can also be obtained from Landahl's work. Figure 5 shows the calculated retention in alveolar ducts and sacs. The line represents a least square fit through the calculated points and is represented by

$$P_l(j) = 0.222 \ln \left(\frac{\gamma_j \rho^{1/2}}{0.14} \right) \qquad \text{(XXXV)}$$

where P_l = fraction retained in the alveolar ducts and sacs.

The average number of particles of size j reaching the lung and being retained in the alveoli then is given by the product of equations (XXXIII) to (XXXV) and the average number of particles inhaled, P_j, thus,

$$P_k = P_j P_n P_r P_l \qquad \text{(XXXVI)}$$

FIGURE 4
RETENTION IN RESPIRATORY TRACT
FROM PHARYNX TO RESP BRONCHI INC.
(Unit Density Spheres)

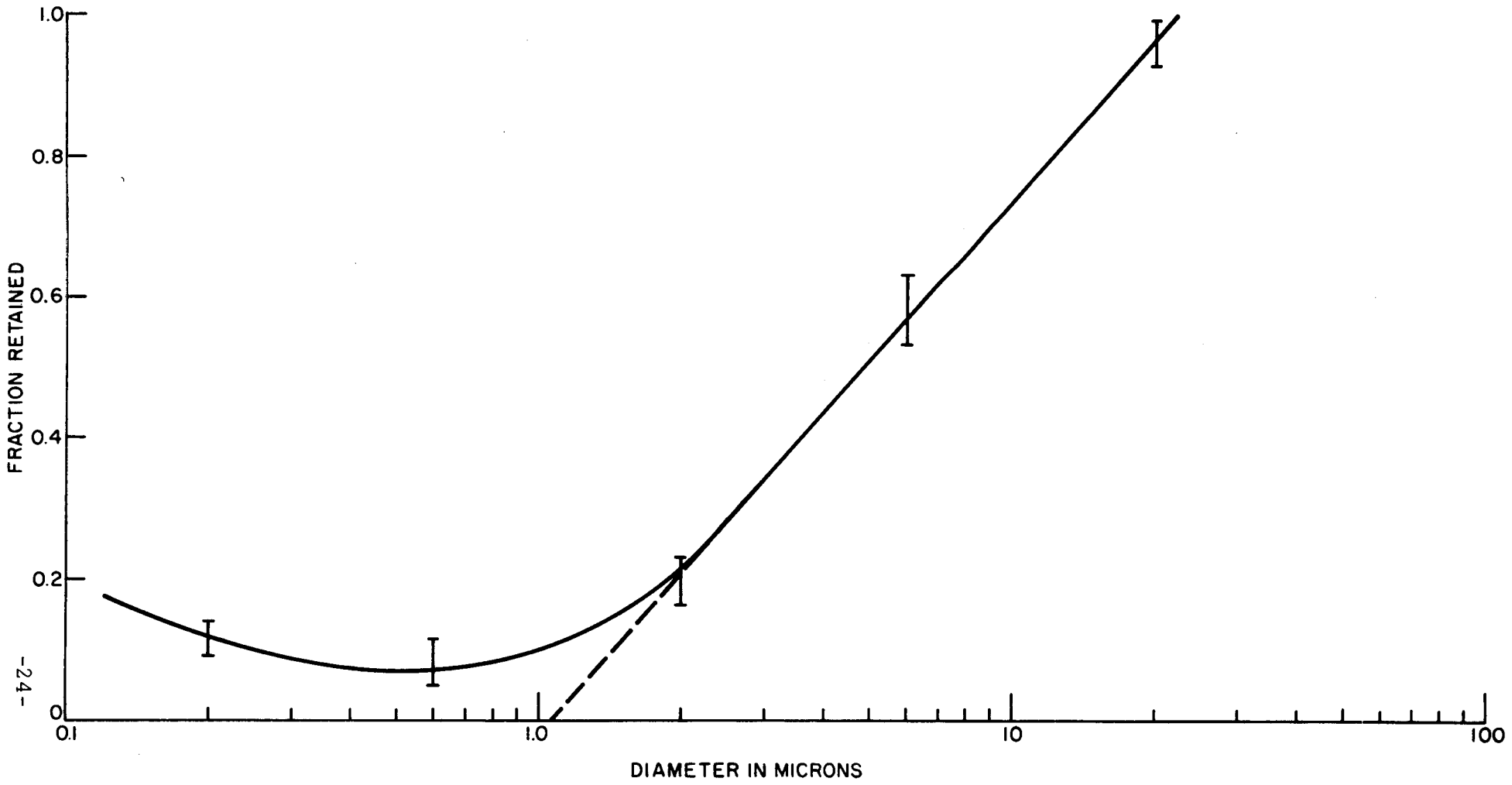
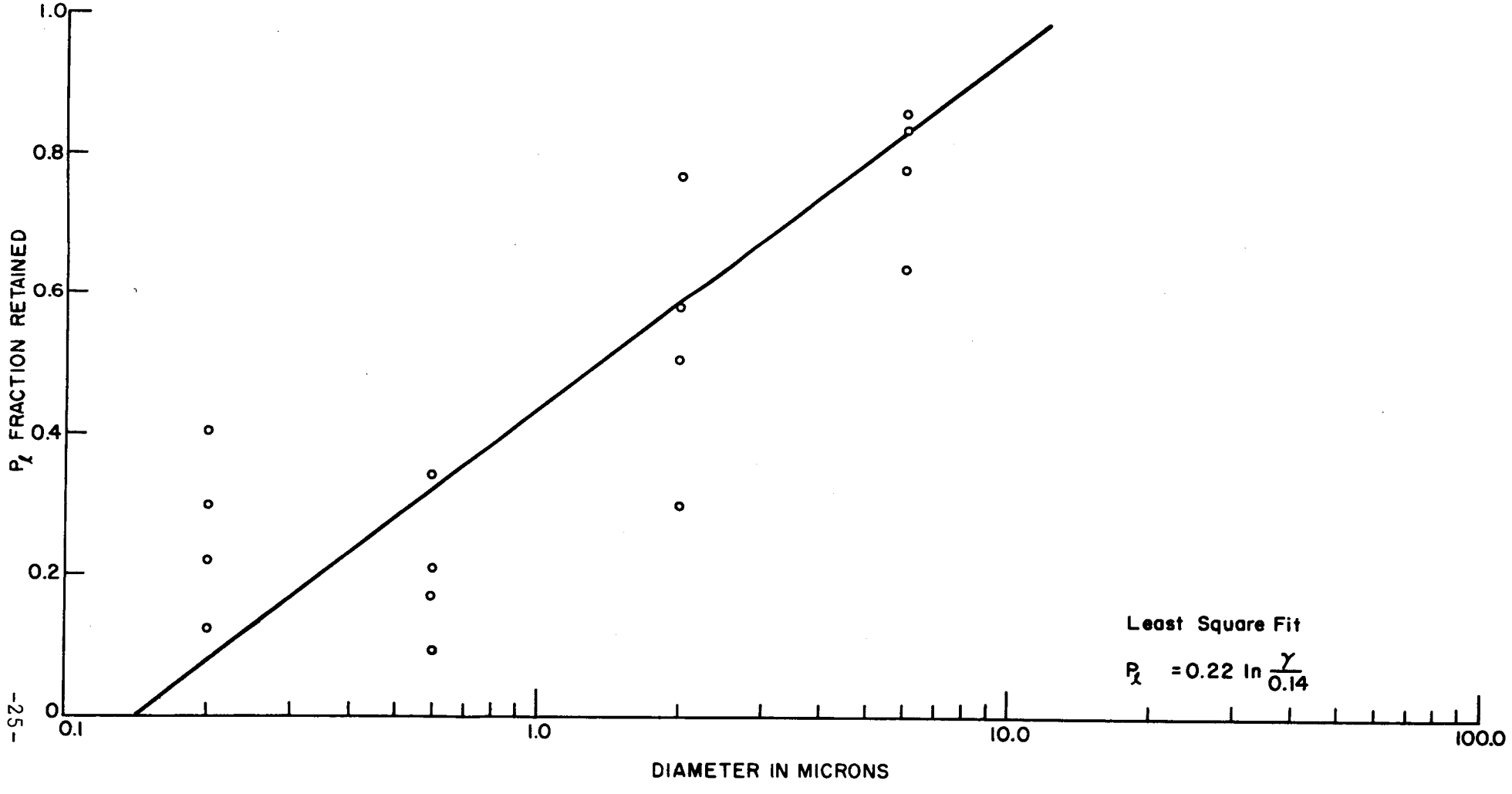


FIGURE 5
RETENTION IN ALVEOLAR DUCTS AND SACS
(Unit Density Spheres)



The probability then of a person having M_j particles of size j in the lung is

$$P_{I\ M_j} = \frac{[P_k]^{M_j}}{M_j!} \exp - P_k \qquad \text{(XXXVII)}$$

Figure 6 shows the combined retention in the lung as a function of size i.e., the product of equation (XXXIII) to (XXXV).

2. Gastrointestinal Tract Dose

The dose to the GI tract is derived from two sources. These are a) indirect ingestion via inhalation and b) direct ingestion via food.

The fraction inhaled and swallowed, P_s of size j particles is given by the sum of the fraction trapped in the nasal passages and in the upper respiratory system:

$$P_s(j) = P_j \left[1-P_n + P_j P_n \left[1-P_r\right]\right] \quad \text{which reduces to}$$

$$P_s(j) = P_j \left[1-P_n P_r\right] \qquad \text{(XXXVIII)}$$

Figure 7 shows the probability of swallowing particles as a function of size subsequent to inhalation.

The basic approach used in NUS-167 was to define the probability of intake via direct ingestion as

$$P_h(j) = f_r(j)\, \bar{m}_j\, Y c \qquad \text{(XXXIX)}$$

FIGURE 6
FRACTION OF INHALED PARTICLES RETAINED IN LUNG

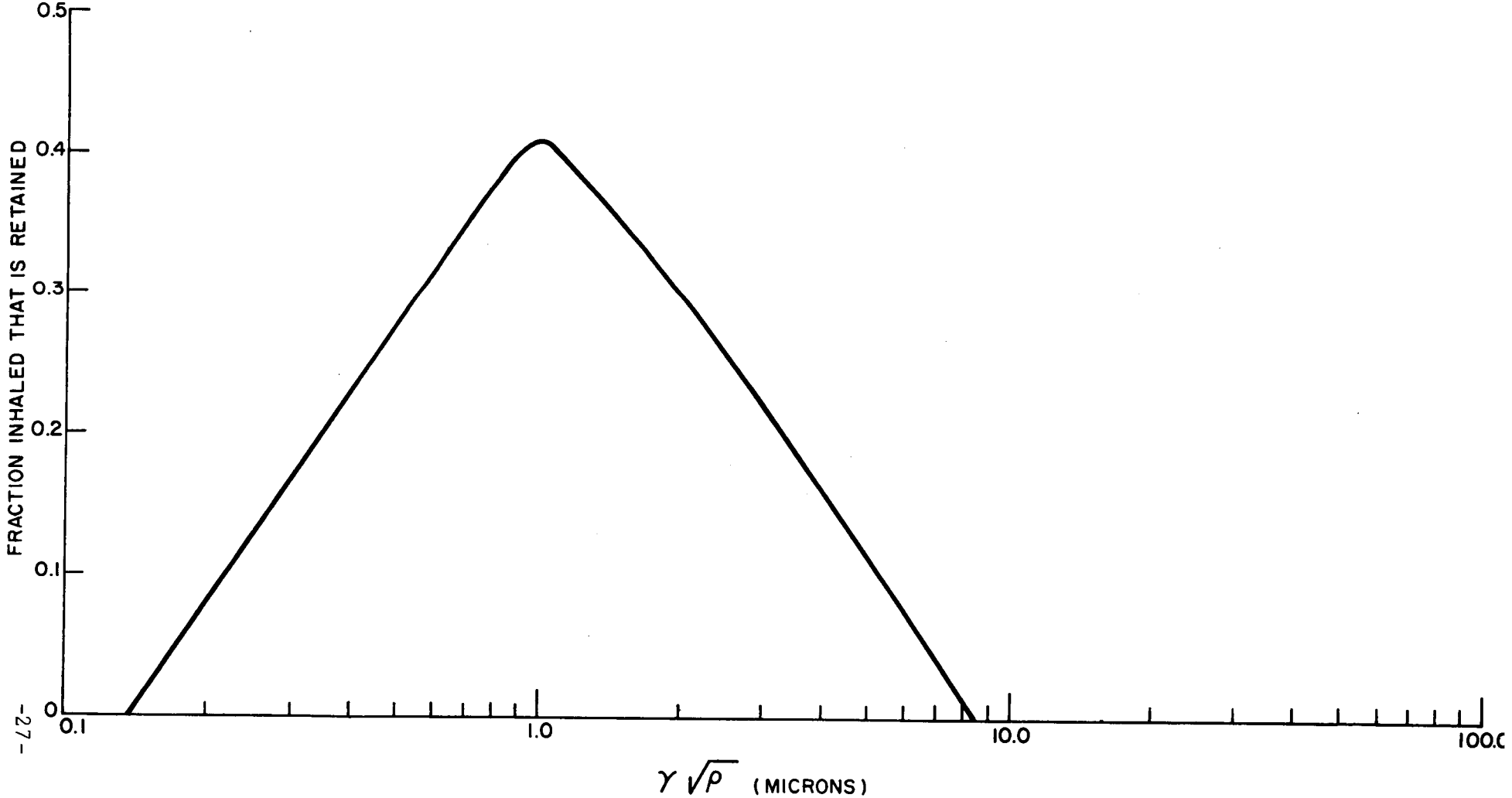
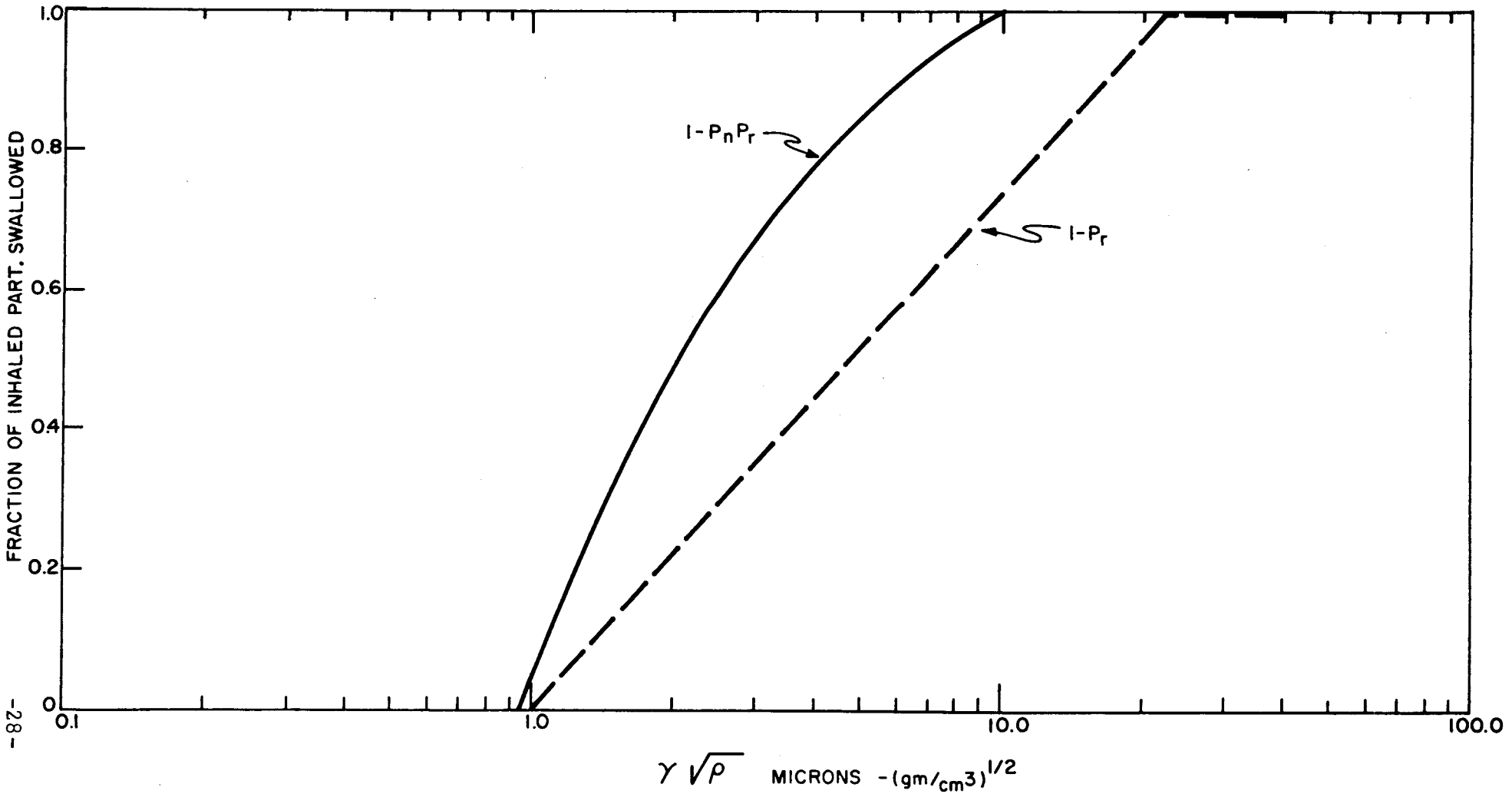


FIGURE -7

FRACTION OF INHALED PARTICLES SWALLOWED



Where $P_h(j)$ = mean number of particles of size j ingested

$f_r(j)$ = retention of foliage of particle of size j

Y_c = crop yield (area of crop/person)

The use of equation (XXXIX) was limited to leafy green vegetables which are either eaten raw or with a minimum of processing. Foods requiring processing or cooking are not amenable to analysis except by thorough study; even then processing and cooking methods would vary greatly throughout the world; the results would be almost meaningless. This is true also of the leafy green vegetables although it is believed that such crops which have a short growing period would represent the most important source of ingestable engine debris.

Equation (XXXIX) should be modified to include a reduction factor for processing $F_p(j)$ although there appears to be little hope of obtaining satisfactory data to select a value. Rewritten, the equation becomes

$$P_h(j) = \bar{m}_j \, f_r(j) \, Y_c \, F_p(j) \qquad \text{(XL)}$$

The total dose delivered to the GI tract depends upon the location of the particle in the gut cross section. The previous treatment assumed that the particle remained adjacent to, and in contact with, the same point on the wall of the lower large intestine (LLI) for a period of 18 hours (the residence time assigned to this organ by the ICRP). Since this is obviously a possible, but most unfavorable case, the probability of such an exposure in terms of geometric considerations only was examined.

The probability that a certain dose value will be equaled or exceeded is equal to the probability of the particle lying within a distance, x of the wall corresponding to the specified dose. If

the location of small particles in the cross section of the LLI is a function of chance only, which seems reasonable, then the probability, P_p, of its lying within a distance, x, of the wall can be shown to be:

$$P_p = 1 - \frac{(R-x)^2}{R^2} \qquad \text{(XLI)}$$

where R = radius of the LLI; this relationship is shown in Figure 8 for values of $\frac{x}{R}$. The radius of the large intestine varies from about 1.25 cm in the ascending colon to 3.5 cm in the sigmoid portion of the intestine. [10] The variation of dose with distance from the wall can be calculated using the methods and relationship given in NUS-217.[2]

The transit time through the lower large intestine varies widely between individuals. Transit time studies were conducted at the Argonne Cancer Research Hospital[11]. Table III shows the results following ingestion of insoluble ceramic spheres (30 - 40 microns diameter) containing Cs^{-134}.

Table III

EXCRETION OF Cs^{134} MICROSPHERES [11]

Subject	Per cent of dose remaining on ingestion day +				
	2	4	6	8	10
1	54	< .1	< .1		
2	67	< .1	< .1		
3	69	2 .5	< .1	< .1	
4	2	0 .2	< .1	< .1	
5	8	0 .3	< .1	< .1	
6	8	< .1	< .1		
7	12	0 .1	< .1	< .1	
8	20	< .1	< .1		
9	53	2 .5	< .1	< .1	
10	9	9 .0	< .1	< .1	
11	100	83 .0	26.0	6 .0	0.2
12	94	12 .0	-	-	0.9
Average	41	9 .0	2.5	0 .6	0.2

Note: To calculate averages, < .1 = 0.1

FIGURE -8

PROBABILITY OF PARTICLE LOCATION IN INTESTINE CROSS SECTION

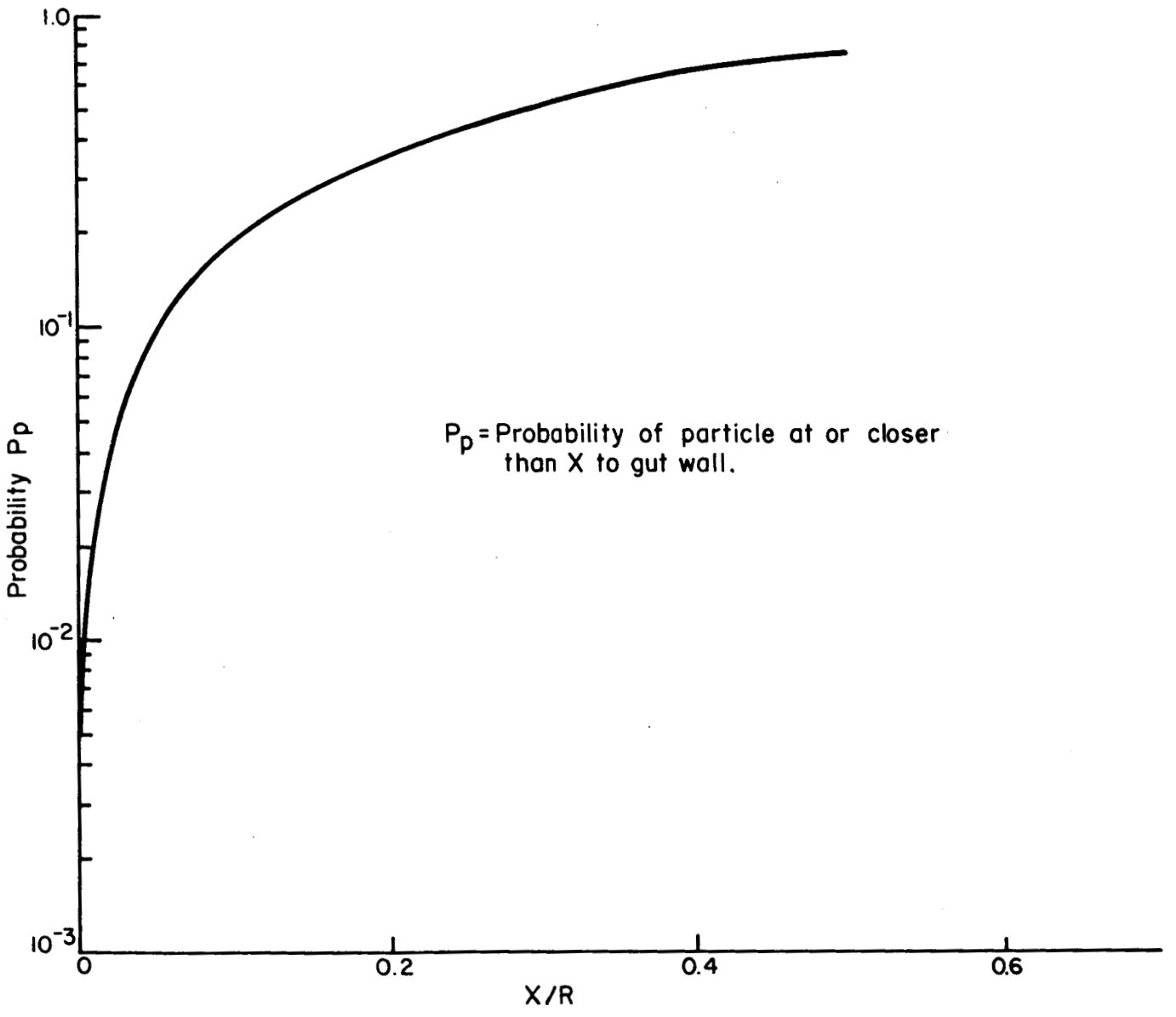


Figure 9 shows the average retention of the ingested microspheres in the GI tract as a function of time after ingestion. The data can be analytically represented by

$$P_g = e^{-\lambda t} \qquad \text{(XLII)}$$

where λ = a time constant
t = time after ingestion in days
P_g = probability that a particle is retained for at least t days in the GI tract.

The exposure time for the lower large intestine can be assumed to be a constant fraction of the total retention time in the GI tract. The ICRP[12] value for average retention time in the LLI is 18 hours; the total for the entire GI tract is 31 hours. Hence, it can be assumed that the LLI retention time is approximately 18/31 t.

However, from Table III it is seen that λ is not identical for each subject. Figure 10 shows the distribution of the value of λ for the groups of subjects. This data shows a mean value of $\lambda = 0.8$ day^{-1} and a standard deviation of 0.64 days. The data fits a Gaussian distribution well and can be represented by

$$P_\lambda = \frac{1}{0.64\sqrt{2\pi}} \int_0^\lambda \left[\exp - \frac{(0.8-\lambda)^2}{2(0.64)^2}\right] d\lambda \qquad \text{(XLIII)}$$

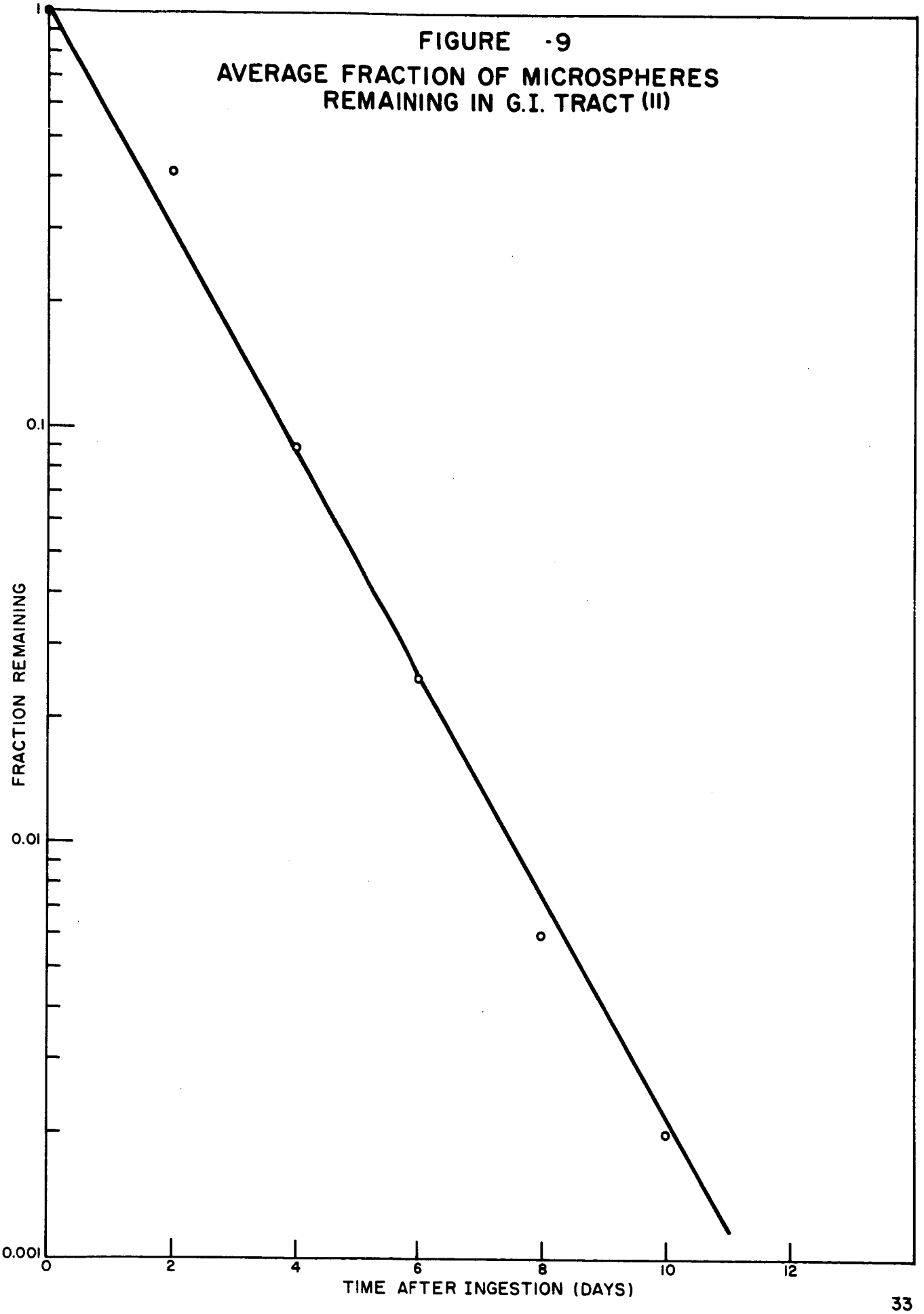
where P_λ = the probability that an individual will have a time constant value $\leq \lambda$.

The total mean number of particles of size j reaching the GI tract is

$$\psi_I(j) = P_s(j) + P_h(j) \qquad \text{(XLIV)}$$

FIGURE -9

AVERAGE FRACTION OF MICROSPHERES REMAINING IN G.I. TRACT (II)



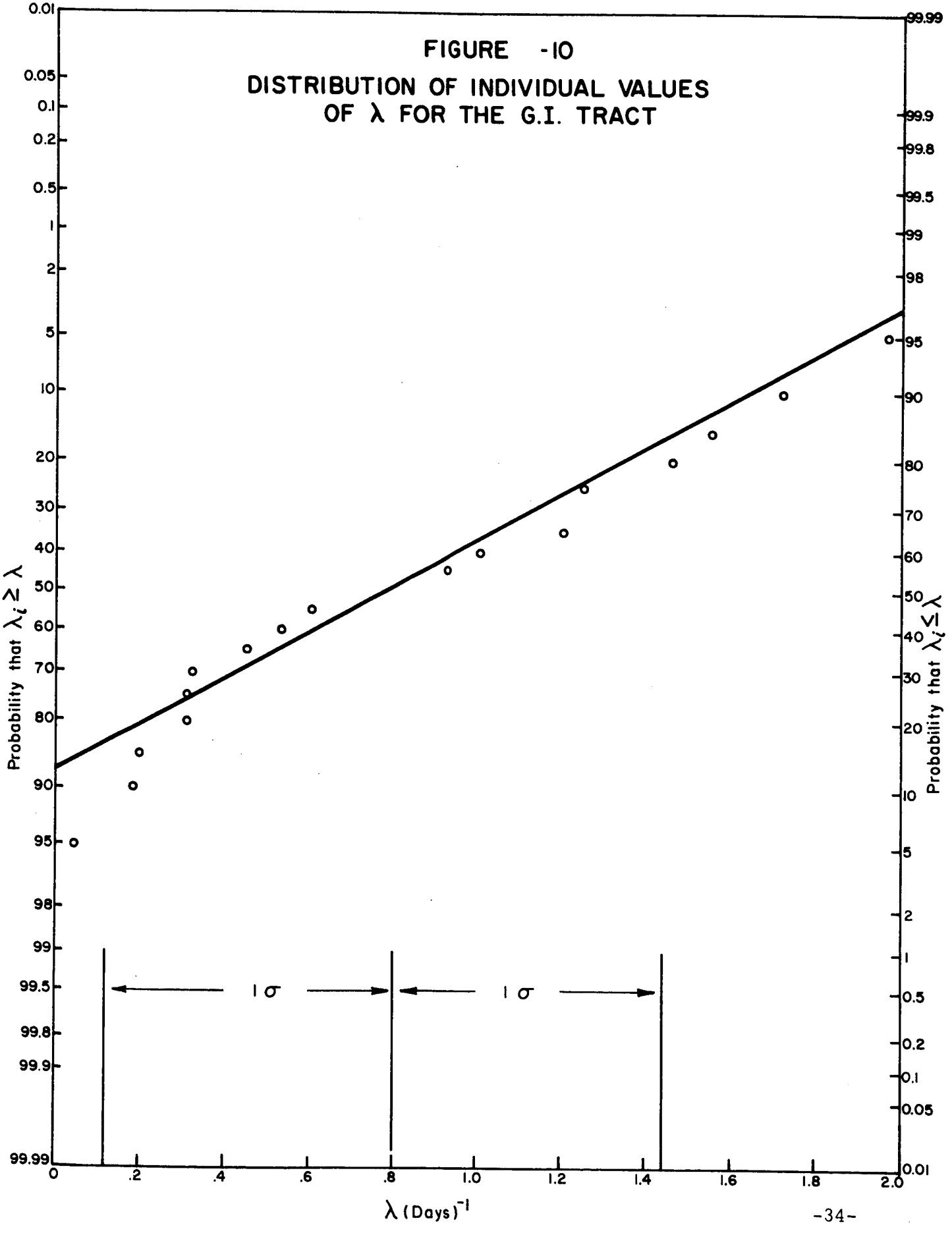


FIGURE -10
DISTRIBUTION OF INDIVIDUAL VALUES
OF λ FOR THE G.I. TRACT
Probability that $\lambda_i \geq \lambda$
Probability that $\lambda_i \leq \lambda$
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.5
99.8
99.9
99.99
1σ
1σ
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
λ (Days)$^{-1}$

The probability that M_j particles of size j will reach the GI tract of an individual and remain for time t is given by:

$$P_{g\,M_j} = \left[\frac{\psi_I(j)P_g}{Mj!}\right]^{M_j} \exp -\left[\psi_I(j)\ P_g\right] \qquad \text{(XLV)}$$

It is still considered most reasonable that the particle in lower large intestine be treated as immobile during the residence time in this section of the gut. Although there may be small scale motions during this period which could significantly reduce the gut wall dose, no experimental data is currently available to support this assumption.

3. Organ Dose from Soluble Fraction of Particles

The inhalation or ingestion of an insoluble particle will result primarily in a dose to either the lung or the GI tract. However, if a fraction of the activity in the particle is in a form that can readily dissolve in body fluids then a mechanism will exist whereby doses to other organs of the body can occur. The NURSE-1 program[13] can be adapted readily to calculate the critical organ doses; however, information on the solubility in body fluids is first required. Some re-programming effort will be required to allow running only the portions of the NURSE-1 program that are necessary to obtain organ dose for specified intakes.

4. Specific Nuclides in Food Chain

An estimate of the intake of specific nuclides in the food chain requires that the mechanism of uptake by plants, the soil characteristics, the diet of the country, and cooking and eating habits of the country be known and fully understood. Little information on any of these factors is available for most of the world and consequently, a detailed treatment of dietary intake of specific nuclides is impossible at this time.

A less specific approach that allows at least an estimate of the possible dietary intake is to relate average Sr^{90} and Cs^{137} daily intake

in the United States to the average deposition of Sr^{90} and Cs^{137} as a result of fallout from the atmospheric testing of nuclear weapons. The U.S. Public Health Service has maintained a network of monitoring stations throughout the country. These stations normally only measure air concentrations; a few stations also measure ground deposition which is analyzed for Sr^{90} and Cs^{137}.[14]

The USPHS also samples monthly and analyzes for the selected radionuclide content of 21 institutional diets. The monthly sample consists of 21 consecutive meals during that month. Figures 11 and 12 show the results of the USPHS monitoring program for Sr^{90} and Cs^{137} from the last quarter of 1962 through the second quarter of 1964.

If the cumulative monthly deposition of Sr^{90} is divided by the cumulative daily intake, the resulting ratio is found to vary between -67% and +33 % about the average value if no delay is assumed between deposition and intake. For the data shown on Figure 11,

$$\frac{\sum(\text{monthly } Sr^{90} \text{ deposition}/m^2)}{\sum[(\text{daily intake})\ (30 \text{ days})]} = 1.77 \quad \frac{\text{pc } Sr^{90}/m^2}{\text{pc intake}}$$

A similar relationship for Cs^{137} can be obtained using data from Figure 12; the ratio is found to vary between -52% and +40% about the average value if a three month delay is assumed.

$$\frac{\sum(\text{monthly } Cs^{137} \text{ deposition}/m^2)}{\sum[(\text{daily intake})\ (30 \text{ days})]} = 0.4637 \quad \frac{\text{pc } Cs^{137}/m^2}{\text{pc intake}}$$

Comparison of the delay terms for Cs^{137} and Sr^{90} would indicate that the uptake of Cs^{137} by plants is slower than for Sr^{90}. This is not consistent with the behavior of the two elements reported elsewhere[15]. The reason for this discrepancy may be that the more rapid uptake reported for cesium is due to movement through the plant via direct contamination, which does not occur with strontium. In the absence of any other data the use of the ratios developed here are recommended.

FIGURE II
Sr^{90} DEPOSITION AND AVERAGE DAILY INTAKE IN DIET

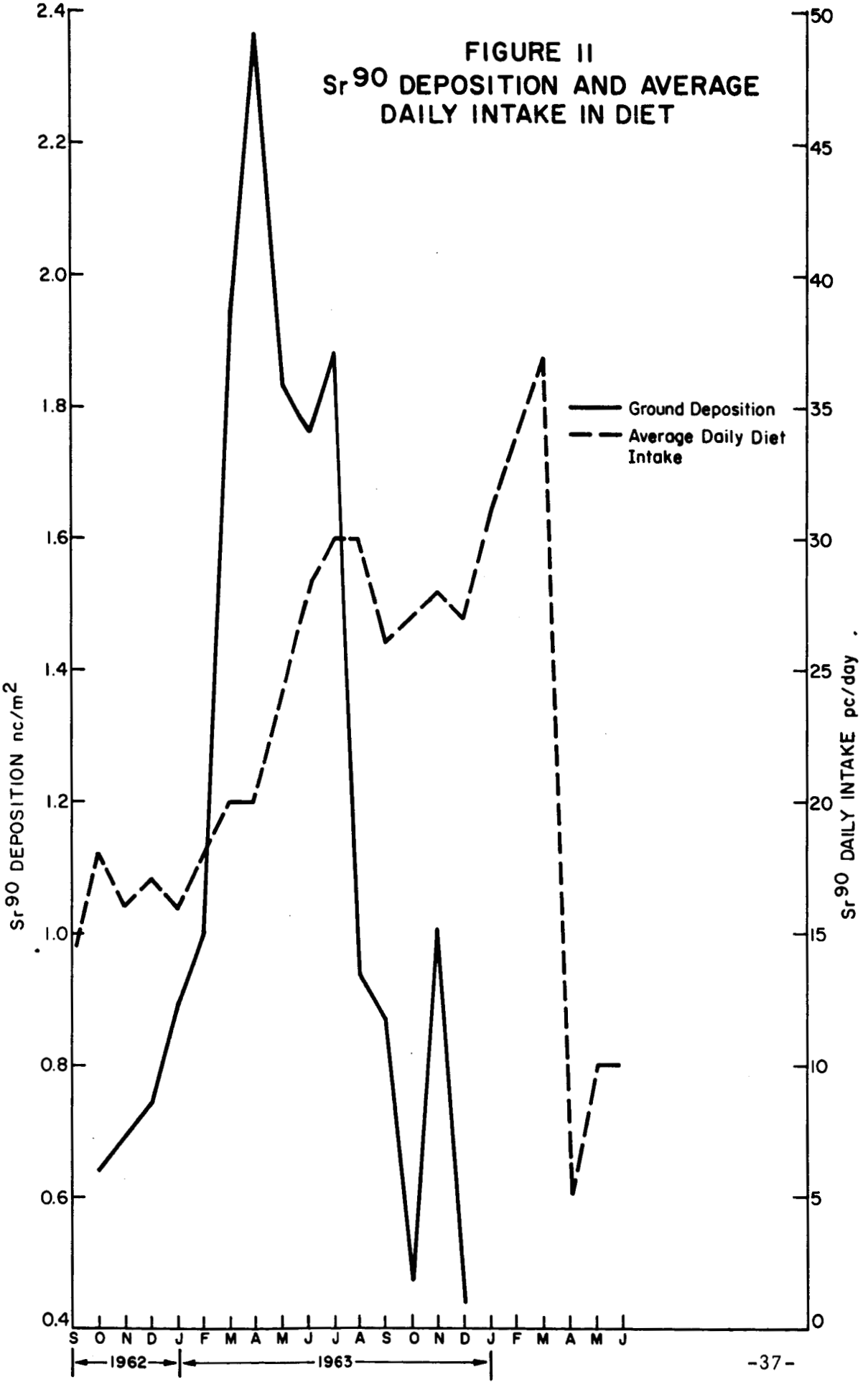
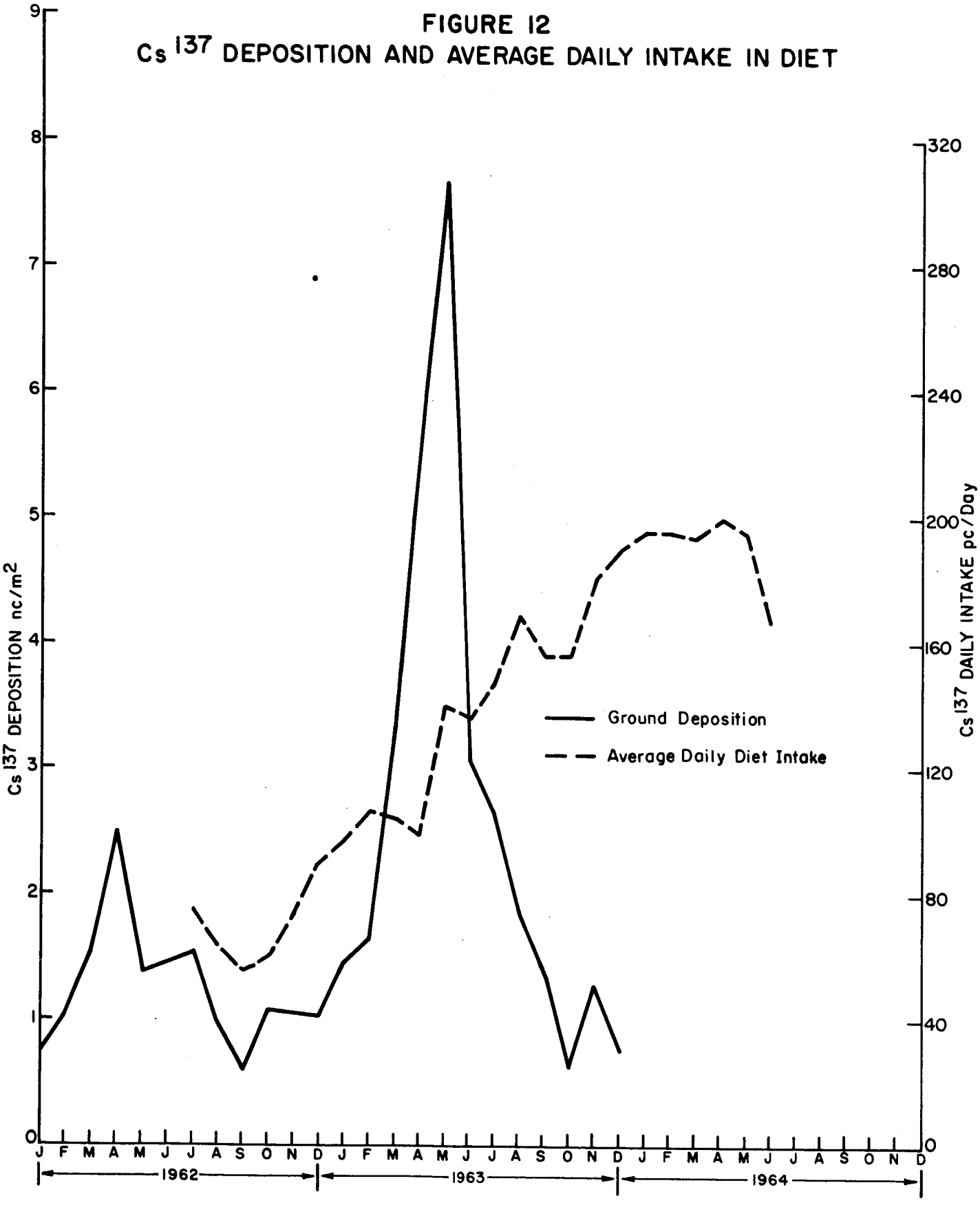


FIGURE 12
Cs 137 DEPOSITION AND AVERAGE DAILY INTAKE IN DIET



An examination of the Tri-City Diet Study indicate the major contributors to the Sr^{90} intake were milk products, fresh fruit, and bakery products; for Cs^{137} the major contributions were bread, milk, flour, and meat. With the exception of bread and flour it is anticipated that the diets of most other countries will not significantly exceed the consumption of these food products in the U.S. Thus, it is anticipated that the use of the above ratios will provide a conservative estimate of Cs^{137} and Sr^{90} dietary intake. The diet of other countries have been examined in NUS-230(3). The dietary intake of these countries can be compared to those shown in Table IV to determine the degree of conservation in the estimation of dose via uptake in the food chain of the soluble fraction of Cs^{137} and Sr^{90}.

III. CULTURAL DATA

The use of the equations for dose probability developed in section II of this report require that a number of factors which describe cultural aspects of the particular population groups. Much of the data other than population and population density and a limited amount of agricultural data do not exist in the required form. Consequently, this information must be inferred or deduced from other statistical data available for the country or surrounding countries. A detailed discussion of the method of obtaining the required cultural data is given in NUS-230(3). Listed below are those factors that must be obtained from statistical abstracts of each country.

DR = dose reduction factor afforded by housing- can be inferred only in most cases from descriptions of each country or culture.

f_c = fraction of land devoted to raising crop c - usually not available for crops of interest but an upper limit can be obtained from agricultural data.

f_i = fraction of time σ_i is valid - must be inferred.

f_p = fraction of population in $i^{\underline{th}}$ group - readily calculated from age-occupation statistics.

f_o = fraction of population outside at any time - can be inferred from estimates of f_i, σ_i, and D.R.

$\overline{n_i}$ = mean population density - usually readily calculated from age - occupation statistics.

N_o = total population - usually available.

Y_c = yield of crop c - usually not available but an upper limit can be obtained from agricultural data.

σ_i = standard deviation of motion - this figure must be inferred from cultural descriptions of each country or culture.

Table IV

AVERAGE PER PERSON DIETARY CONSUMPTION FOR NEW YORK CITY, CHICAGO, AND SAN FRANCISCO[14]

Food Category	Average U. S. consumption	
	diet (kg/yr)	Calcium (g/yr)
Bakery products	37	37.0
Whole grain products	11	10.0
Eggs	16	9.1
Fresh vegetables	43	15.0
Root vegetables	17	6.1
Milk	221	234.3
Poultry	17	9.2
Fresh fish	3	10.8
Flour	43	8.6
Macaroni	3	0.7
Rice	3	1.1
Meat	73	10.9
Shellfish	1	0.8
Dried beans	3	2.9
Fresh Fruit	68	13.6
Potatoes	45	5.8
Canned fruit	26	1.3
Fruit juices	19	1.7
Canned vegetables	20	4.2
Annual intake	674	383

NOMENCLATURE

a	=	ground area for deposition or body skin area
d	=	distance from source to receptor
D	=	dose
D.R.	=	dose reduction factor
f_i	=	fraction of total time that σ_i applies
f_o	=	fraction of population outdoors
f_p	=	fraction of total population in $i^{\underline{th}}$ group
f_r	=	foliar retention
F_p	=	fraction of particles retained after processing food
$k(E)$	=	energy dependent dose conversion constant
$\overline{m}_j$	=	mean particle density on ground of size j
M_j	=	total number of particles of size j in area under consideration
$\overline{n}_i$	=	population density for $i^{\underline{th}}$ population group
N	=	total number of people exposed
N_i	=	total number of people exposed in $i^{\underline{th}}$ group
N_o	=	total number of people in the area under consideration
$P_{g\,M_j}$	=	probability that M_j particle will be in the GI tract for at least time t^j

P_h = probability of ingesting a particle

P_j = mean number of particles of size j inhaled

P_k = fraction of inhaled particles retained in lung

P_l = fraction of particles retained in alveolar ducts and sacs.

$P_{M_j,t}$ = probability of being struck by M_j particles that stick for at least time t

P_n = fraction of particles passing nasal passages

P_r = fraction of particles passing upper respiratory system

P_s = fraction of particles swallowed

P_t = probability that sticking time is t

P_x = probability that exactly x particles will occur

P_z = probability that exactly z people will be present

P_λ = probability that an individual will have a time constant value no greater than λ

P.E. = population exposure, man-dose

Q_j = integrated activity from time of arrival for particle of size j

r = distance from source to base of the receptor

s = distance separating center of motion and the particle of size j or diameter of area, a

t = exposure time

v = distance from center of motion to receptor at any time

V_W = wind velocity

V_T = terminal velocity

x_j = number of particles of size j

y = frequency of occurrence of radius r

Y_c = crop yield (area of crop/person)

z = number of people (center of motion)

σ_i = standard deviation for individual motion

$\mu(E)$ = energy dependent absorption coefficient for air

Γ = impaction efficiency

ξ_j = sticking probability of size j particle

γ = particle diameter

Ω = diameter of body cylinder

ρ = density of particles in gm/cm^3

λ = time constant for particle passing through the GI tract

Λ_j = mean sticking time for particle size j

ψ_j = average number of particles of size j impacting and and sticking to skin for time t

$\psi_I(j)$ = mean number of particles of size j reaching the GI tract

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