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A Mathematical Model for Predicting the Probability of Acute Mortality in a Human Population Exposed to Accidentally Released Airborne Radionuclides

Final Report for Phase I of the Project: Early Effects of Inhaled Radionuclides

May 1980

Prepared for
the U.S. Nuclear Regulatory Commission

Pacific Northwest Laboratory
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A MATHEMATICAL MODEL FOR PREDICTING THE PROBABILITY OF ACUTE MORTALITY IN A HUMAN POPULATION EXPOSED TO ACCIDENTALLY RELEASED AIRBORNE RADIONUCLIDES

NUREG/CR--1261

TI86 002725

Final Report for Phase I of the Project:

EARLY EFFECTS OF INHALED RADIONUCLIDES

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ABSTRACT

A mathematical model was constructed for the purpose of predicting the fraction of human population which would die within 1 year of an accidental exposure to airborne radionuclides. The model is based on data from laboratory experiments with rats, dogs and baboons, and from human epidemiological data.

Doses from external, whole-body irradiation and from inhaled, alpha- and beta-emitting radionuclides are calculated for several organs. The probabilities of death from radiation pneumonitis and from bone marrow irradiation are predicted from doses accumulated within 30 days of exposure to the radioactive aerosol.

The model is compared with existing similar models under hypothetical exposure conditions. Suggestions for further experiments with inhaled radionuclides are included.

EXECUTIVE SUMMARY

A mathematical model is described for predicting early mortality (within 1 year) from inhaled radionuclides. The model is in two parts: a dosimetry model, and a preliminary dose-response model.

The dosimetry model begins with information about the release of radionuclides into the atmosphere, the atmospheric conditions, and the potential for human exposure. Doses to relevant tissues are computed by combining the partial doses from external whole-body photon irradiation, doses from internal emitters, and the dose contribution from cross-organ irradiation.

The preliminary dose-response model was derived from existing data from animal experiments. The model is based on the relationship between the dose to lung tissue that is accumulated within the first 30 days after inhalation exposure, and survival time. By using the model, we can estimate probability of death from acute pulmonary injury caused by alpha or beta radiation. For this project, acute pulmonary injury is generally defined as a histologically observed change, such as radiation pneumonitis or pulmonary fibrosis, which results in death within 1 year after inhalation of radioactive material and/or photon irradiation.

The bone (marrow) dose-response model described in WASH-1400 was adapted for modeling early mortality resulting from cross-organ and/or external photon irradiation. The probability of early mortality from bone-marrow irradiation, and the mortality probabilities from alpha and beta irradiation of the lung, are combined to produce a model of overall

probability of early mortality. Estimates of the statistical variance in the model were calculated, and standard deviations of 170% and 100% were estimated for the mortality probabilities from bone marrow and from lung irradiation, respectively.

For comparison, other lung models from the literature were applied to the scenarios used as examples for our model.

Further experimentation will be necessary to determine the correct methods of combining mortality probabilities from various types of radiation exposure. These animal experiments will include studies of the combined effects of external irradiation and exposure to inhaled, soluble or insoluble, alpha- and/or beta-emitting radionuclides.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. STATEMENT OF THE PROBLEM

The overall objective of this project is to construct predictive models for estimating the probability of acute morbidity and acute mortality* in a human population after accidental exposure to an aerosolized radionuclide or mixture of radionuclides.

This project is being conducted simultaneously with a similar project at the Inhalation Toxicology Research Institute (ITRI) at Albuquerque, New Mexico. Each project contained two phases: Phase I included the collection and analysis of existing acute mortality data from experiments in which animals were exposed to external radiation and to internal emitters. The primary goal of Phase I was to construct the best dose-morbidity and dose-mortality models possible with existing data. Research teams from each laboratory constructed dose-mortality models which are conceptually different, even though data and ideas were shared between teams. Phase II of both the PNL and ITRI projects will consist of animal experiments to provide data for testing and refinement of the Phase I mortality models. These experiments will be designed to also provide data useful for developing dose-morbidity models; data from Phase I were considered inadequate to model morbidity.

* Acute mortality was defined as death within 1 year after exposure; to be redefined if data indicated the necessity.

The initial step for both projects was a meeting between scientists from ITRI, Pacific Northwest Laboratory (PNL) and the Nuclear Regulatory Commission (NRC) to define detailed objectives and delineate the scope of research. A general outline of steps in the mathematical model to be constructed is diagrammed in Figure 1. The following guidelines regarding the general approach to be used were formulated at that meeting.

1. Source terms will be defined by the user of the model; no specific radionuclide release scenario (as in WASH 1400[1]) is to be considered. Source terms might include alpha-emitting radionuclides and beta/gamma-emitting radionuclides (individually or in mixtures), with wide ranges of particle sizes, particle-specific activities, effective half-times in the organ of interest and particle solubilities.
2. External photon whole-body radiation dose must be considered; however, neutron irradiation may be excluded.
3. Critical organs are provisionally defined as lung, bone, liver, upper respiratory tract, gastrointestinal tract (crypts) and, secondarily, kidneys and thyroid. Standard organ weights (based on body weight or Reference Man) are to be used.
4. Organ dosimetry is to be based on established methods, modified with accepted new data.
5. The mortality model is to be constructed for a population of healthy young adults.
6. The morbidity model will include such indicators as body weight loss, hematologic changes, and changes in pulmonary function parameters.

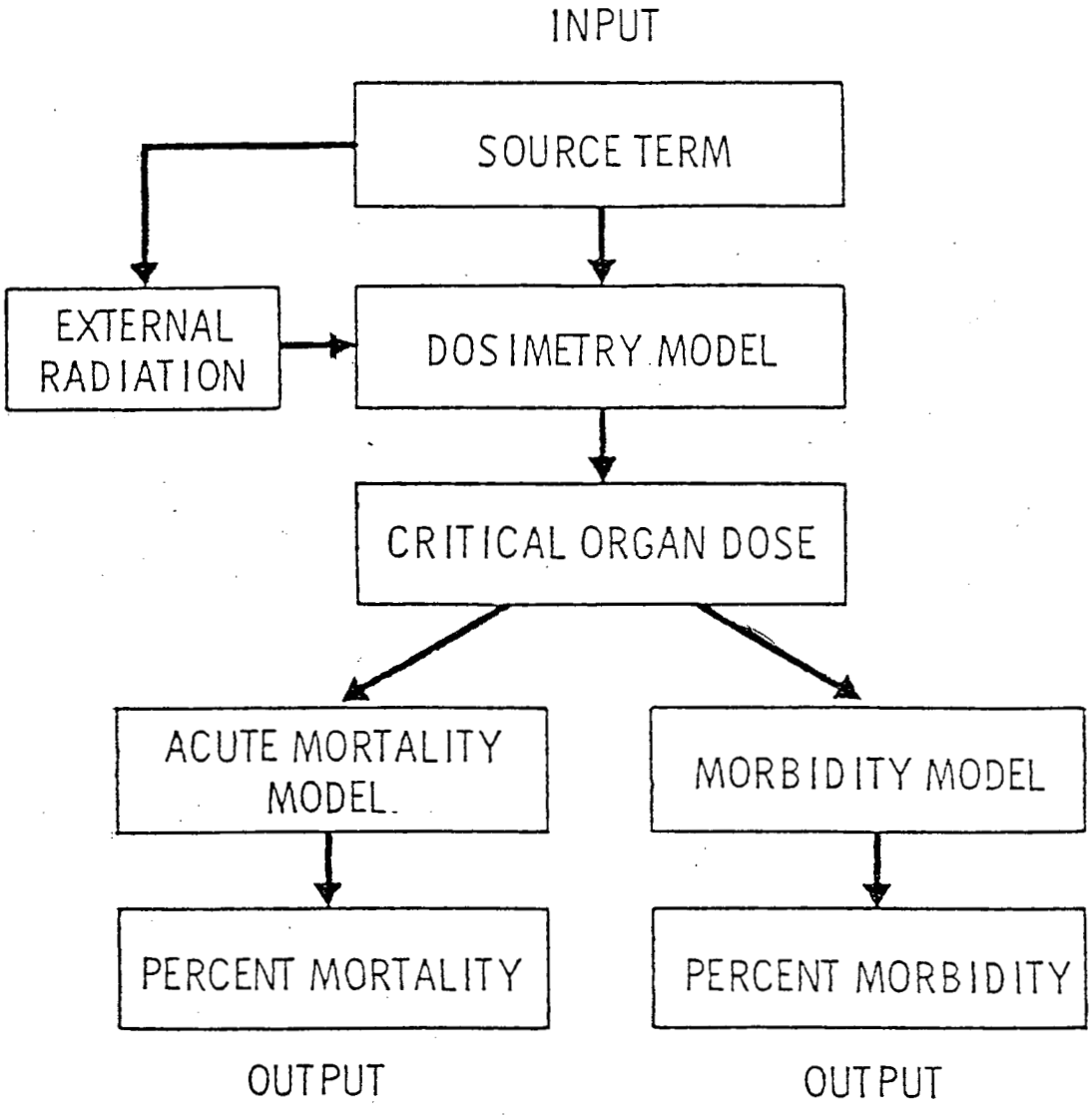

Figure 1. Generalized Mathematical Model for Predicting Acute Morbidity and Mortality from Exposure to Airborne Radionuclides.

7. Statistical variability must be considered in each step of the model and over the entire model.

Of the numerous attempts made to relate radiation dose and human mortality, one of the most widely publicized is the Reactor Safety Study (WASH 1400),[1] commonly referred to as the "Rasmussen Report." The acute mortality model in that report was designed for a specific type of accident scenario, a release of radioactive fission products from an operating nuclear power plant. Because doses from internally deposited, alpha-emitting radionuclides were small relative to those from beta-emitters, the acute mortality model for pulmonary injury was based on data from yttrium-90 and yttrium-91 in fused aluminosilicate particles (FAP).

Other lung dose/acute mortality models were constructed by Wells:[2] one for insoluble, the other for soluble materials. He correlated the effective half-life with the initial dose rate and, plotting animal data, divided the graph into three regions. They were: (1) region of probable long-term survival (0% mortality), (2) region of probable acute radiation lethality (100% mortality), and (3) region of uncertainty. The last region included the area between relatively certain death and relatively certain long-term survival. The boundaries of the region of uncertainty (0 to 100% lethality), spanned three-fold to ten-fold ranges in the initial dose rate for radionuclides with very short and long (> 100 days) effective half-lives, respectively.

A variation on Wells' insoluble radionuclide model was proposed by scientists at Science Applications, Inc.[3] (SAI), using the 365-day dose

accumulation to lung and "characteristic irradiation time" to represent the quantity of material inhaled and the dose accumulation rate, respectively. These alternative parameters, different from those used by Wells, were to allow for the inclusion of mixtures of radionuclides. In such cases, the "long-term half-life" necessary in Wells' model would be difficult to obtain. The boundaries of the region of uncertainty (0 to 100% lethality) in the SAI model span a sixfold range in the "365-day dose".

Still another model for lung dose has been proposed by Raabe and Goldman.[4] "Mean dose rate" from exposure to death is correlated with survival time; percent mortality within 365 days is related to the initial dose rate to the lung.

Three major problems are encountered in dose/acute-mortality modeling. The first problem, dose rate effect, is particularly important when total accumulated dose is used to estimate probability of mortality. Generally, widely disparate dose rates are a result of differences in the effective half-lives of the radionuclides involved.

The second problem involves the modeling of dose from mixtures of alpha-and beta/gamma-emitting radionuclides. Quality factors (Q) must be used to obtain biological equivalence for doses resulting from the two kinds of radioactive emissions. The ICRP value of Q for alphas[5] previously 10, was recently changed[6] to 20. These Q values were defined for use in radiation protection; they are not necessarily appropriate for a specific cause of mortality, such as pulmonary injury.

A third problem regards the choice of species for modeling human acute mortality. Lacking human data, it is necessary to use animal data, primarily from mice, hamsters, rats, and dogs. Unanswered questions include: (1) Are there species differences in the time course of radiation-induced pulmonary injury? (2) If so, which species most closely correlates with the human condition?

An inhalation/acute-mortality model incorporating these three problem areas has not yet been developed. The models cited[1-4] were constructed on selected single-isotope data, or were highly dependent on dose rate, which makes them less useful when mixtures of radionuclides are part of the source term.

II. GENERAL APPROACH

The overall model is comprised of two main parts: a dosimetry model to estimate doses to critical organs of humans exposed to the source-term radionuclides, and a dose-response model to predict the consequences of those doses in terms of acute lethality.

A. Dosimetry Model

The PNL dosimetry model is designed to calculate radiation doses to humans from a wide range of possible radionuclide release scenarios. Given the source term from a postulated accident, the dosimetry model will evaluate the external dose arising from exposure to a passing cloud of radionuclides, as well as the dose concurrently received from inhaled and retained radionuclides. In the latter exposure mode, special attention is given to the cross-organ contribution (radionuclides deposited in a source organ that irradiate a target organ) to the total organ dose. High- and low-LET radiation from both external and internal exposure are evaluated separately.

The Oak Ridge National Laboratory radionuclide decay data,[7] supplemented by other more recent information, are used in the PNL computational code. A detailed description of the dosimetry model, including external, internal and cross-organ doses, is contained in Chapter 3.

B. Dose-Response Model

This model allows prediction of acute mortality from radiation

doses to bone marrow and lung. One of the first steps in the construction of the dose/acute mortality model for lung was the selection of dose and mortality parameters. Initially, this was largely a trial-and-rejection process, performed with five sets of data from inhalation experiments with Beagle dogs. Data used included those from ^{91}Y, ^{90}Y, ^{90}Sr and ^{144}Ce in FAP experiments,[8] and those from $^{239}PuO_2$ experiments[9]. The process through which the lung dose-response model evolved is diagrammed in Figure 2.

Since the data collected for use in the lung mortality model were taken from several sources, and were obtained under a variety of experimental conditions, different methods were used to calculate dose (see Appendix 4), and the composite data base was not statistically balanced for all factors. (For instance, only limited species comparison was possible.) However, for the purposes of this project, the variations in the animal data base may be an asset for predicting consequences of accidental exposure, because the conditions of such exposures will vary widely.

First trials involved plotting of total lung doses against survival time (Figure 3) and initial lung dose rates against survival time (Figure 4). An early objective of these trials was to determine the relative effectiveness of alpha-emitting and beta-emitting radionuclides.

Total lung dose plotted against survival time showed poor correlation (Figure 3). Initial dose rate was related to survival time, although the data points from the ^{90}Y (FAP) experiments diverged sharply from those of the other experiments with beta emitters (Figure 4)

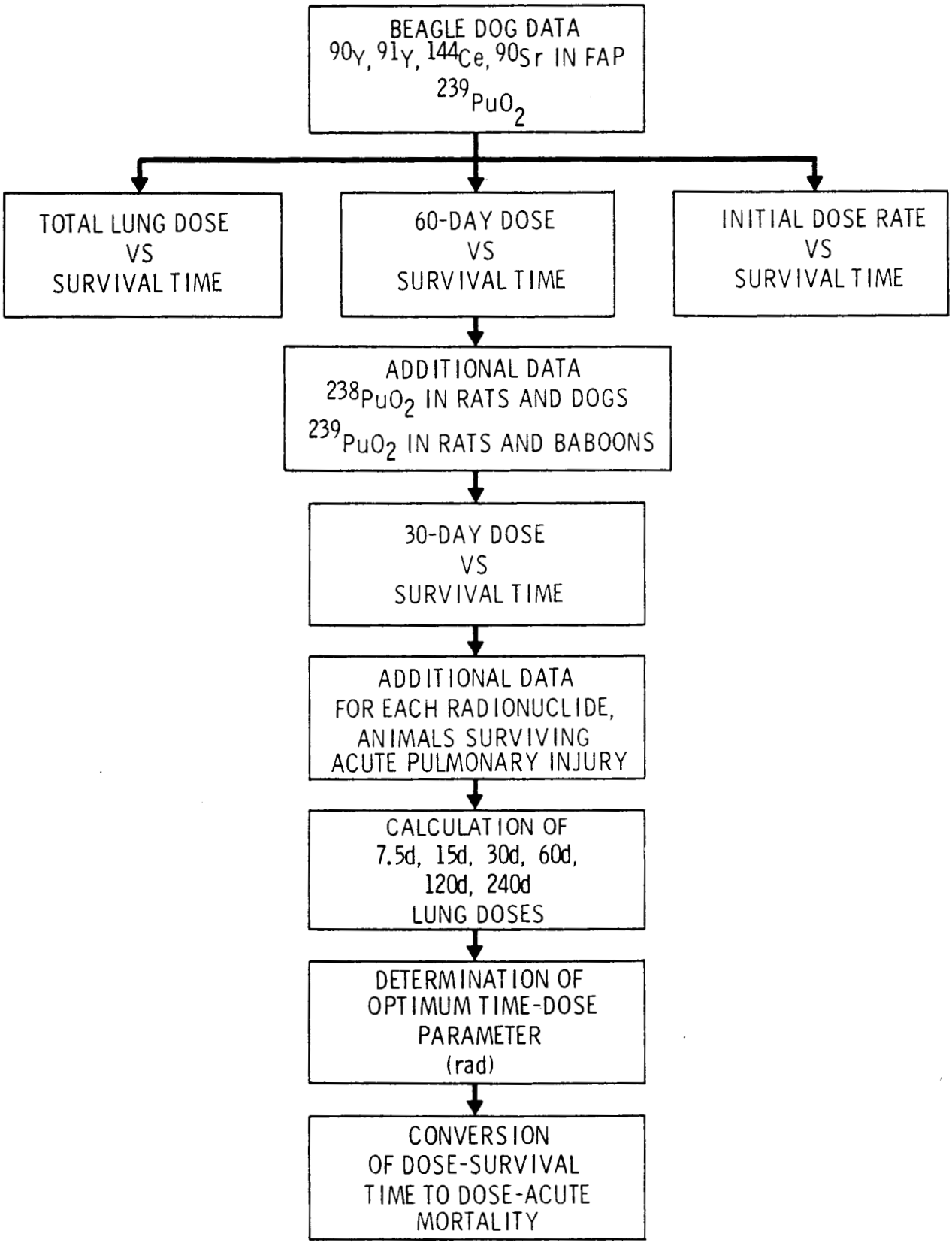

Figure 2. Developmental Sequence for Dose/Acute Mortality Model

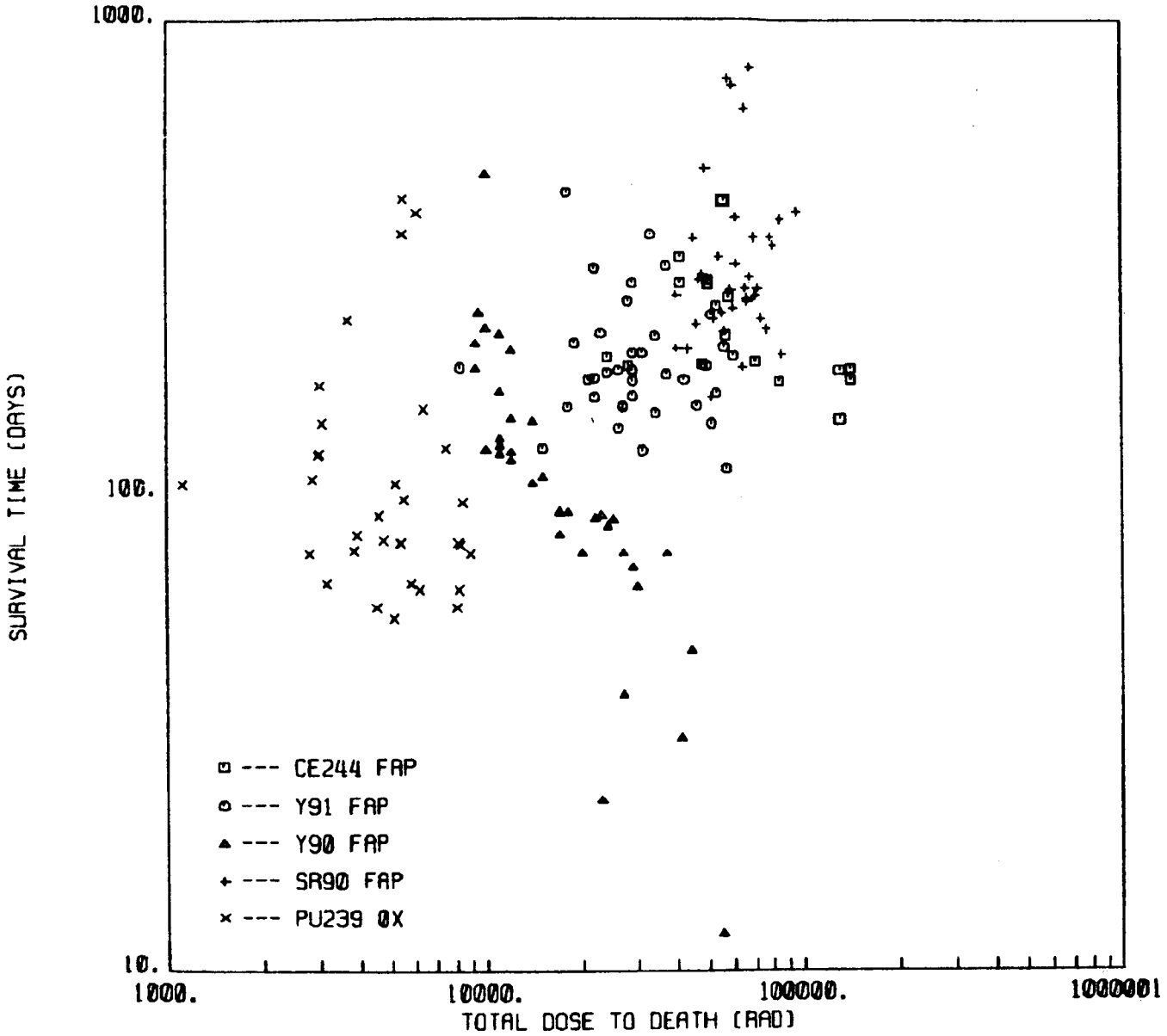

Figure 3. Relationship Between Survival Times and Total Lung Dose in Dogs Exposed to Aerosolized Radionuclides.

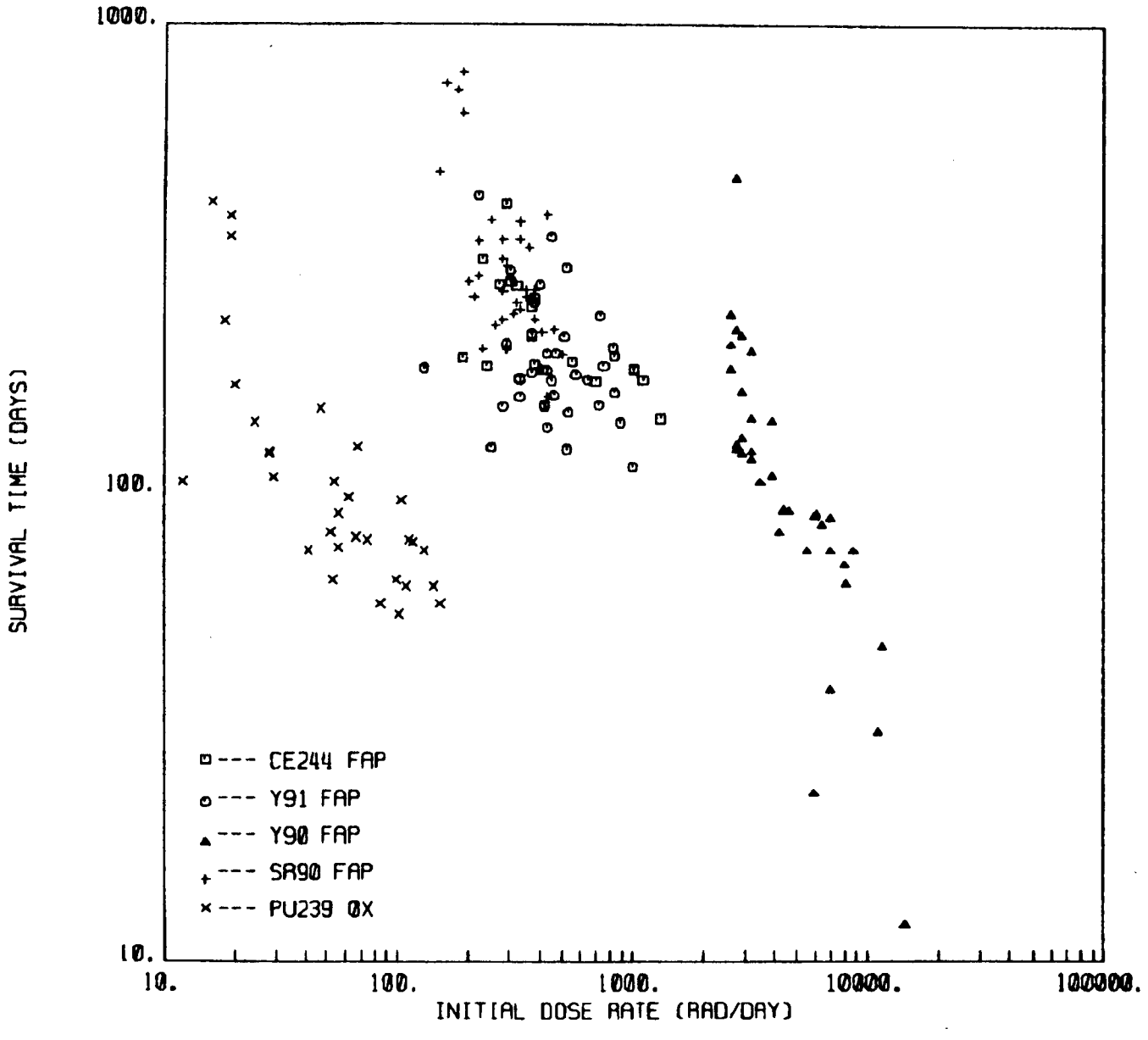

Figure 4. The Relationship of Survival Time to Pulmonary Initial Dose Rate in Dogs Exposed to Aerosolized Radionuclides.

because of the high initial dose rate associated with the short physical half-life of ^{90}Y.

The data from the Beagle experiments with beta-emitting radionuclides also included cumulative doses for various time intervals after exposure, such as 60, 120, 365 days. Preliminary plots of 60-day doses against survival times for individual dogs revealed that a large number of the data points were located about a common curve, and that the curve indicated a reasonable correlation between the parameters (Figure 5). Corresponding 60-day doses were estimated from the $^{239}PuO_2$ Beagle dog data and, when plotted against survival time, resulted in a curve which nearly parallelled that from the beta-emitters (Figure 5). Doses for animals that lived less than 60 days were calculated for the full 60-day period. Data for $^{239}PuO_2$ in baboons,[9] $^{239}PuO_2$ in rats,[10] $^{238}PuO_2$ in rats[10] and $^{238}PuO_2$ in dogs[11] were subsequently added to the alpha-emitter dose/survival-time curve, resulting in the graph shown in Figure 6. Comparison of the dose parameters of the curves from alpha- and beta-emitters indicated an effectiveness of alpha radiation approximately 20 times that of beta radiation.

Because the 60-day postexposure time period was chosen arbitrarily, studies were made to determine the optimum time period for calculating doses.

Cumulative lung doses were calculated for each animal at 7.5, 15, 30, 60, 120 and 240 days postexposure (Appendix 4). Of these time intervals, the 30-day cumulative radiation dose showed the best correlation of the dose/survival-time data, and was selected for subsequent use in modeling percent mortality in accidentally exposed populations.

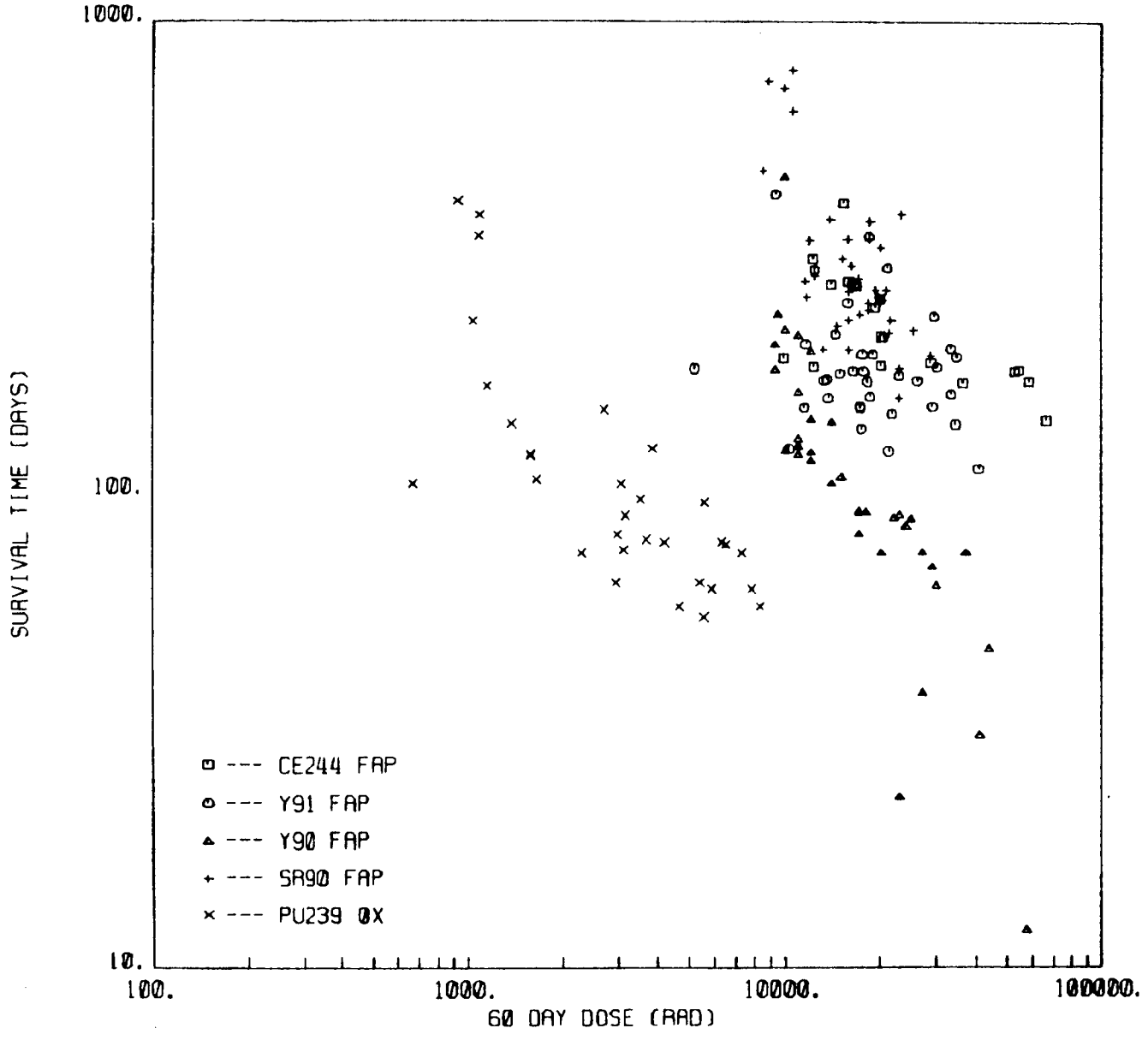

Figure 5. The Relationship Between Survival Time and Lung Dose in Dogs for 60 Days Post Exposure.

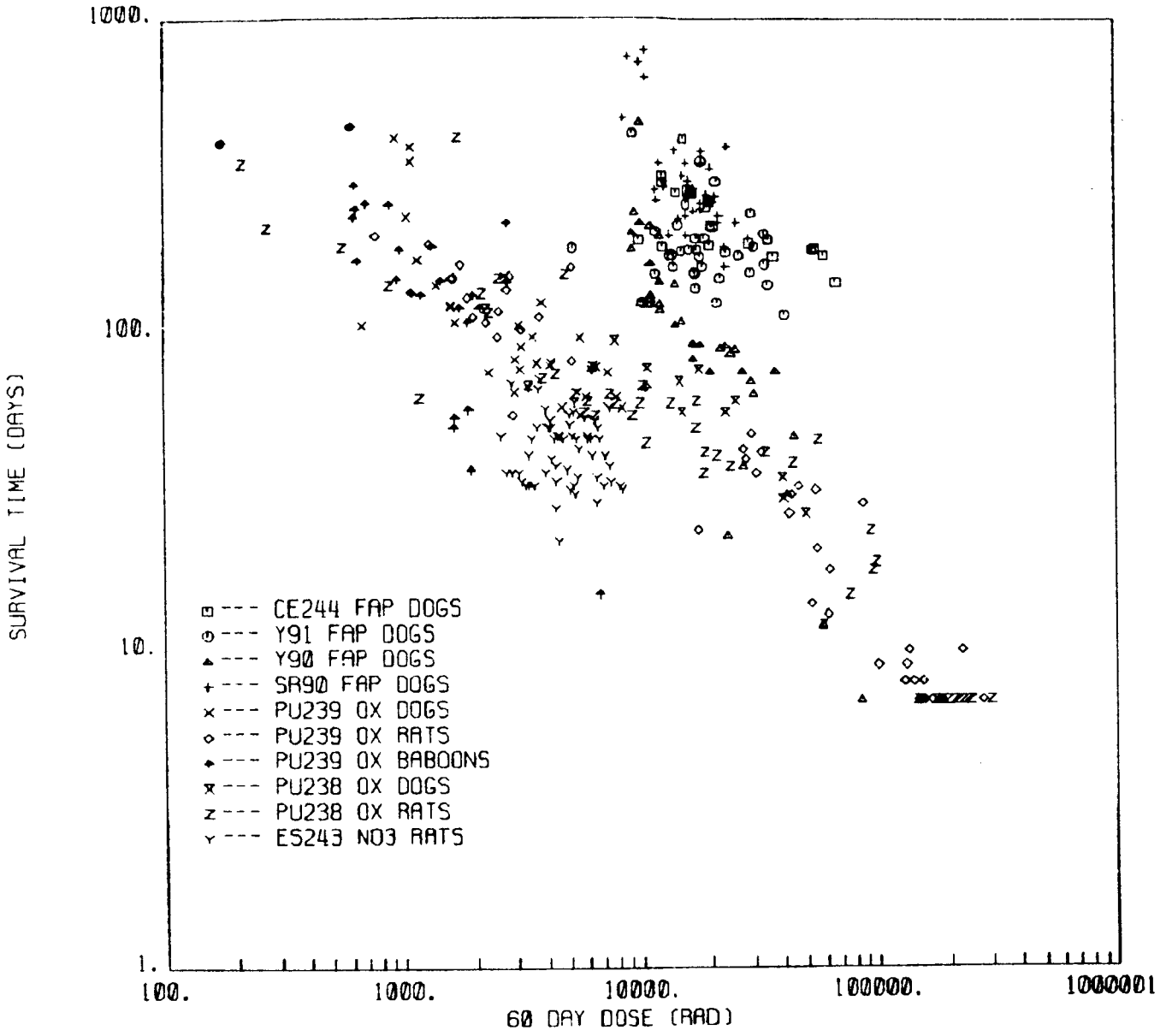

Figure 6. The Relationship Between Survival Time and 60-day Lung Dose in Dogs, Rats, and Baboons exposed to $^{239}PuO_2$ or $^{238}PuO_2$.

Because the radiation dose to bone marrow is important in some scenarios, an interim marrow-dose/early-mortality model was also developed. Data for this model are taken from the mortality predictions for whole-body irradiation in the Reactor Safety Study (WASH-1400).[1]

Section IV contains the criteria for selection of lung-dose parameters, the derivation of the lung-dose/acute-mortality model, and the bone-marrow/early-mortality model.

Although radionuclide-induced morbidity is considered to be part of the overall scope of this project, it is not treated in this report. Morbidity data from inhaled radionuclides are not available in quantity sufficient for dose-morbidity modeling.

III. DOSIMETRY MODEL

The wide variety of source terms that may be encountered requires that the dosimetry model accommodate a variety of input parameters, which are listed in Figure 7, along with the series of steps that led to the PNL dosimetry model.

Of the several ways to implement the model (depending upon the amount and kind of information the user has), the simplest is through path A (Figure 7). The information required for path A is: radionuclide identification, activity conconcentration in inhaled air, solubility classification (D, W, Y) of the radionuclide, and particle size or deposition fraction in the three lung compartments.

Path B requires the same information, as well as atmospheric dilution factor and breathing rate. This pathway is used when the amount of radioactive material available for inhalation by the individual or population is known.

Path C requires detailed information concerning the release, as well as atmospheric conditions during release.

To assist in assessing external as well as internal radiation dose, an atmospheric transport model[12] is incorporated in the code to calculate air concentrations of radionuclides at several locations downwind from a radionuclide release. A bivariate normal distribution model is employed to calculate concentrations on the centerline of the cloud. External dose, for all input paths, is determined by multiplying the activity concentration in air by a dose conversion factor. The

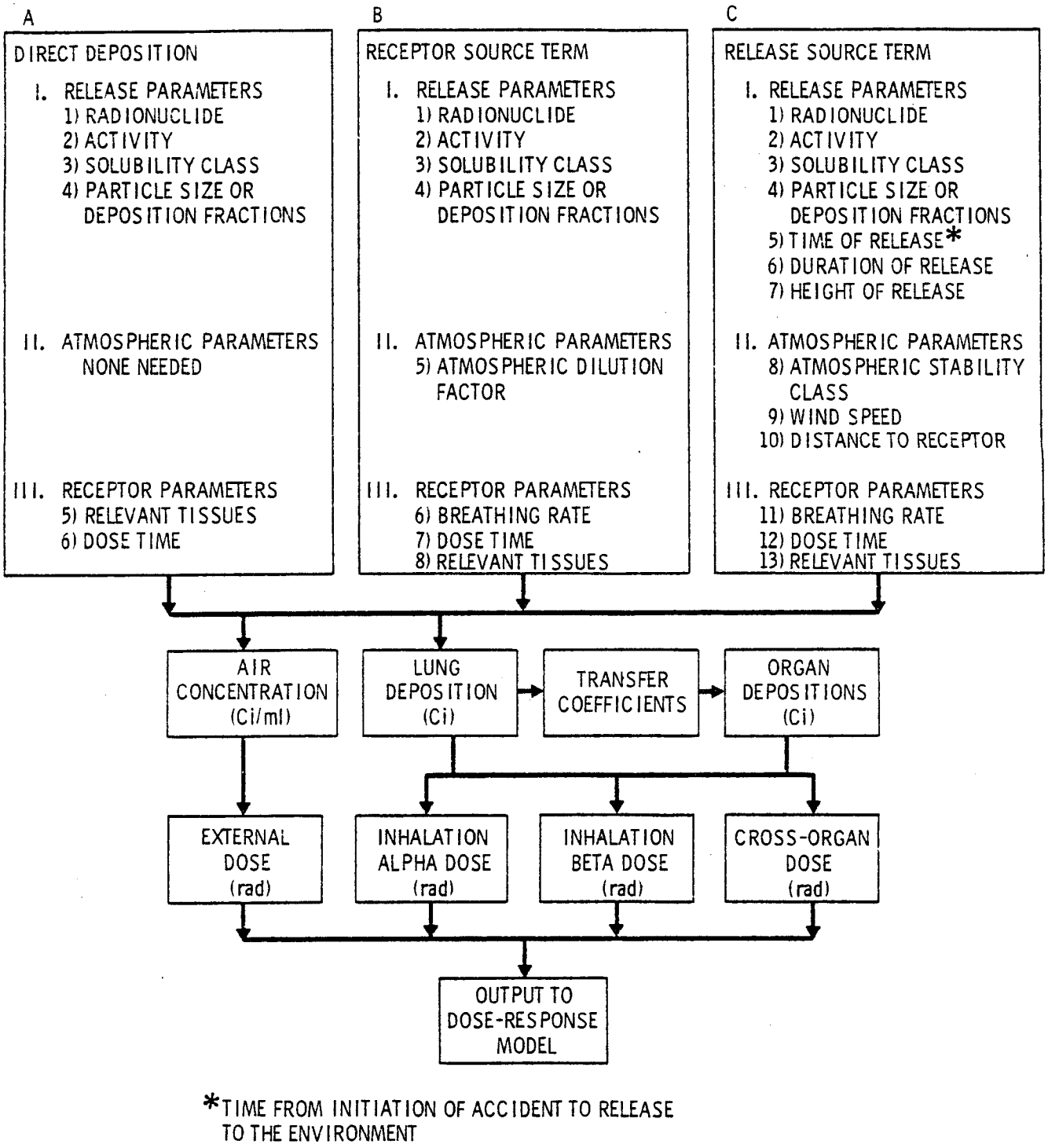

Figure 7. Sequence of Steps in the Mathematical Model for Calculating lung Doses to Humans from Hypothetical Source Terms.

standard deviations of the cloud concentration in the crosswind, laterally and vertically, are estimated by using Pasquill's curves.[13]

A PNL computer program, DACRIN[12], serves as the paradigm for the internal dose evaluation portion of the PNL dosimetry model. DACRIN calculates the radiation dose to the human respiratory tract, and other organs, resulting from the inhalation of radioactive aerosols. The ICRP Task Group on Lung Dynamics Respiratory Tract Model[14] is incorporated in DACRIN in order to calculate doses to the respiratory tract from inhaled particulate radionuclides. The transfer coefficients of ICRP-Publication 2[5] are used to evaluate deposition in organs other than lung. This older ICRP-Publication 2 model is used to calculate doses to organs other than lung, and doses to the respiratory tract from radionuclides that do not behave as particulates, such as cesium, tritium and the noble gases. Exponential clearance from organs is assumed in these models. All dose contributions from progeny radionuclides are included with the parent dose.

Part of the internal dose is the result of cross-organ irradiation of target organs by gamma and X-ray emitting radionuclides which are internally deposited in other source organs. Cross-organ doses are calculated by the methodology published in ORNL-5000,[15] which uses tabulated S-factors (rem dose equivalent to a target organ per microcurie-day residence time of a radionuclide in a source organ). Calculated residence times are used to determine the cross-organ dose and dose equivalent. Cross-organ doses were initially evaluated with lung as the source organ, and with liver and homogeneous bone as the target

organs. Preliminary calculations of cross-organ doses were made for the radionuclides, ^{134}Cs, ^{95}Zr, ^{95}Nb and ^{60}Co, for the solubility classes contained in ICRP-19.[16] The cross-organ contribution to bone and liver ranged from less than 1% to over 99% of the total organ dose. This surprisingly high contribution led to the conclusion that cross-organ dose could not be neglected. Cross-organ doses were also calculated with lung as the target organ, and liver and homogeneous bone as the source organs. The cross-organ contribution to lung ranged from 0.3% to 26% of the total lung dose. Details of the cross-organ dose calculations are contained in Appendix 1. The data indicate that cross-organ effects are of sufficient magnitude to warrant inclusion in the PNL dosimetry model.

Evaluation of the external dose component in the PNL dosimetry model is based on the method used in the Oak Ridge National Laboratory EXREM-III[17] computer code, which is used to estimate external radiation doses to populations from environmental releases. EXREM-III allows calculation of dose equivalent rate and total dose equivalent to the total body and internal organs resulting from exposure to contaminated water and air, as well as exposure to a contaminated surface. Beta, positron, electron and gamma radiations are treated. For the purpose of the PNL dosimetry model, the only external exposure mode considered is submersion in contaminated air. It is assumed that an individual is immersed in a semi-infinite hemispherical cloud of air, in which the distribution of activity is spatially uniform. Special consideration is given to nuclide chains, including branching. The output of the PNL

dosimetry model, therefore, consists of separate external and internal organ doses and dose equivalents for high- and low-LET radiations, which is the required input to the dose-response model.

Although lung doses are emphasized in this report, the dosimetry model can also be used to examine other organs relevant to early radiation effects. Sample dose calculations for several radionuclides of potential importance to the Early Effects Study are used in Section V of this report, and are included in Appendix 2. Uncertainties in the calculated doses are discussed in Section V.

IV. DOSE-RESPONSE MODEL

A. Acute Mortality from Pulmonary Injury

Various approaches may be used in building a model to predict mortality resulting from exposure to a mixture of radionuclides. One way is to construct a "realistic" or process model that mathematically mimics the process by which radiation produces the biological trauma leading to death. An example is the Marshall-Groer model[18] for the induction of bone cancer by alpha radiation. However, there are insufficient data available to build such a model for most types of radiation damage.

Our approach was to use available data to construct an empirical dose-response model that is basically a linear model. Several advantages have resulted from this choice. First, linear models are good approximations to almost any monotone relationship, hence they are good predictors over the region in which data are available. Second, the linear structure easily accommodates the inclusion of many predictor variates. The effect of such variables as initial dose rate, specific activity, solubility, etc., can be included without completely reformulating the model. A third advantage is that linear models tend to provide better predictions than other model forms when the predictor variables are measured with error. Because dose, the primary predictor, is certainly not precisely known, this is an important characteristic. The controversy over the linearity of dose-response curves extended to very low doses is not of concern in the present exercise, since we are

dealing with relatively high doses for which effects data are available without extrapolation.

1. Model Derivation. Any stimulus-response model requires a quantitative measure of the intensity of the stimulus. A model for prediction of early mortality following inhalation exposure to radionuclides requires a measure of the severity of biological insult resulting from the exposure. One such measure is radiation dose, a measure of absorbed energy. For exposures resulting from internally deposited radionuclides, energy transfer continues as long as the radionuclides are in the body of the living organism; thus, "cumulative dose to death" is sometimes used to measure stimulus intensity.

If the stimulus consists of a one-time inhalation exposure to a radionuclide mixture of fixed composition, then the initial dose rate (IDR) sufficiently quantifies the intensity of that stimulus, and a quantitative relationship can be expressed between IDR and response. However, the IDR has limited usefulness because the temporal dose distribution pattern is different for each radionuclide, depending on the biological response to the exposure.

The cumulative dose calculated at a fixed time, t, includes elements of both IDR and temporal dose distribution. The relative importance attached to the two factors is dependent on t; the cumulative dose at a short time places greater weight on the IDR than does the dose at a longer time. As an example, Table 1, below, was constructed, assuming

that exposure to two radionuclides (one with effective half-time of 10 days, and one with effective half-time of 100 days) resulted in equal potential doses (cumulative dose time to + ∞).

TABLE 1. Cumulative Doses Delivered Over Various Times by Two Radionuclides with Different Half-Lives

	Initial Dose Rate (rad/day)	Cumulative Dose (rad) Days Postexposure					
		5	10	25	100	365	1000
$T_{1/2}$ = 10 days	0.0693	0.293	0.500	0.823	0.999	1.000	1
$T_{1/2}$ = 100 days	0.0069	0.034	0.067	0.159	0.500	0.920	1
Ratio	10	8.6	7.5	5.2	2.0	1.1	1

If the cumulative 5-day dose were used as an intensity measure, then the exposure to a radionuclide with a 10-day effective half-life would be rated 8.6 times more severe than the other exposure. However, if the cumulative 100-day dose were used, the first exposure would appear to be only twice as severe as the second.

In light of the above observations, cumulative dose to time t, (D_t), for various values of t less than 1 year, was considered a predictor of survival time. A logarithmic plot of survival time versus D_t, for t values of 30 or 60 days, showed apparently linear relationships between log survival time and log D_t (Figures 8, 9). Those relationships appeared to differ between deaths caused by pulmonary injury (early) and "late" deaths; and between deaths from alpha- and those from beta-emitting isotopes.

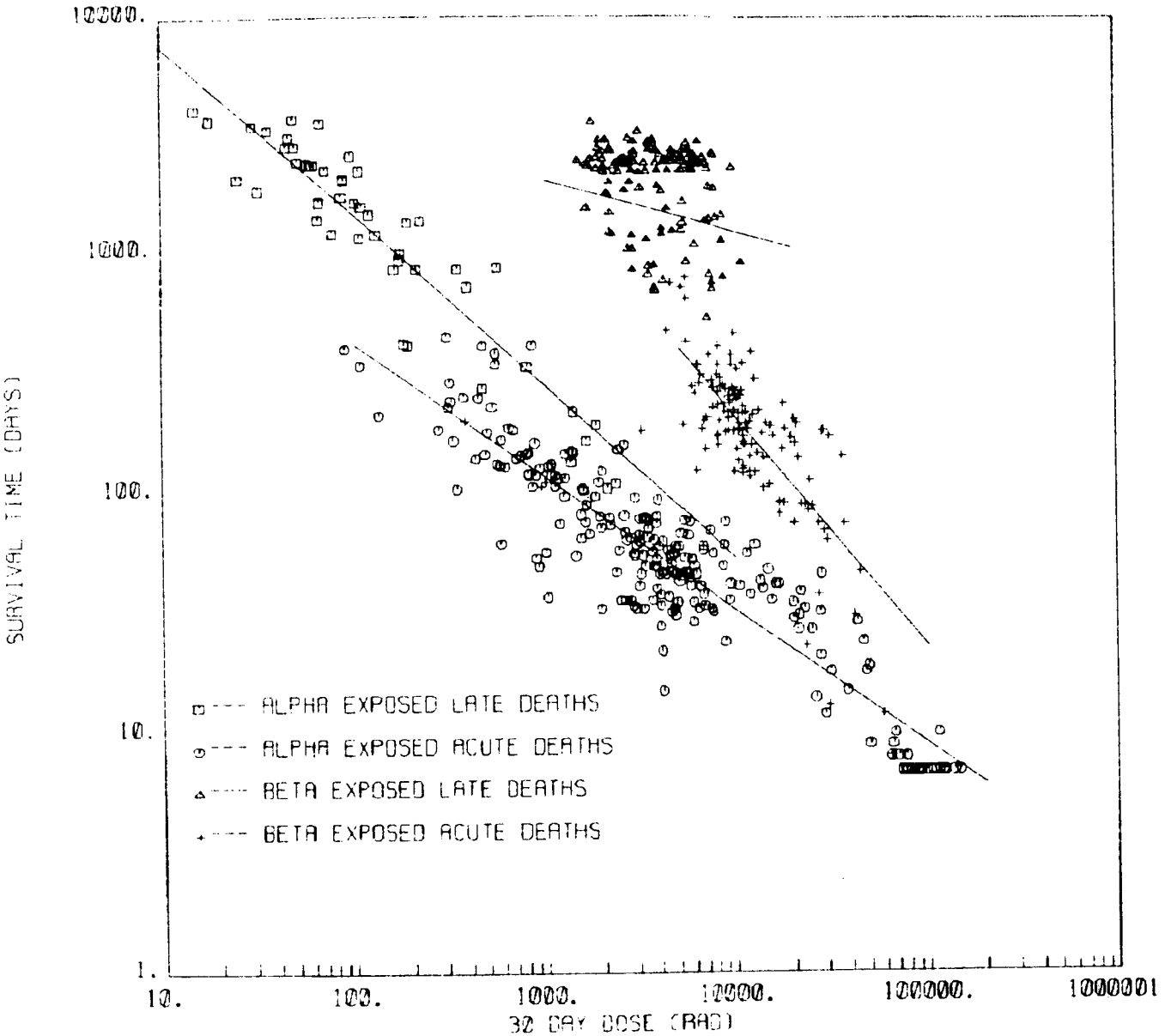

Figure 8. Relationships Between Survival Time and 30-day Lung Doses in Animals Which Died From Acute Pulmonary Injury and Animals Which Died Later From Other Causes.

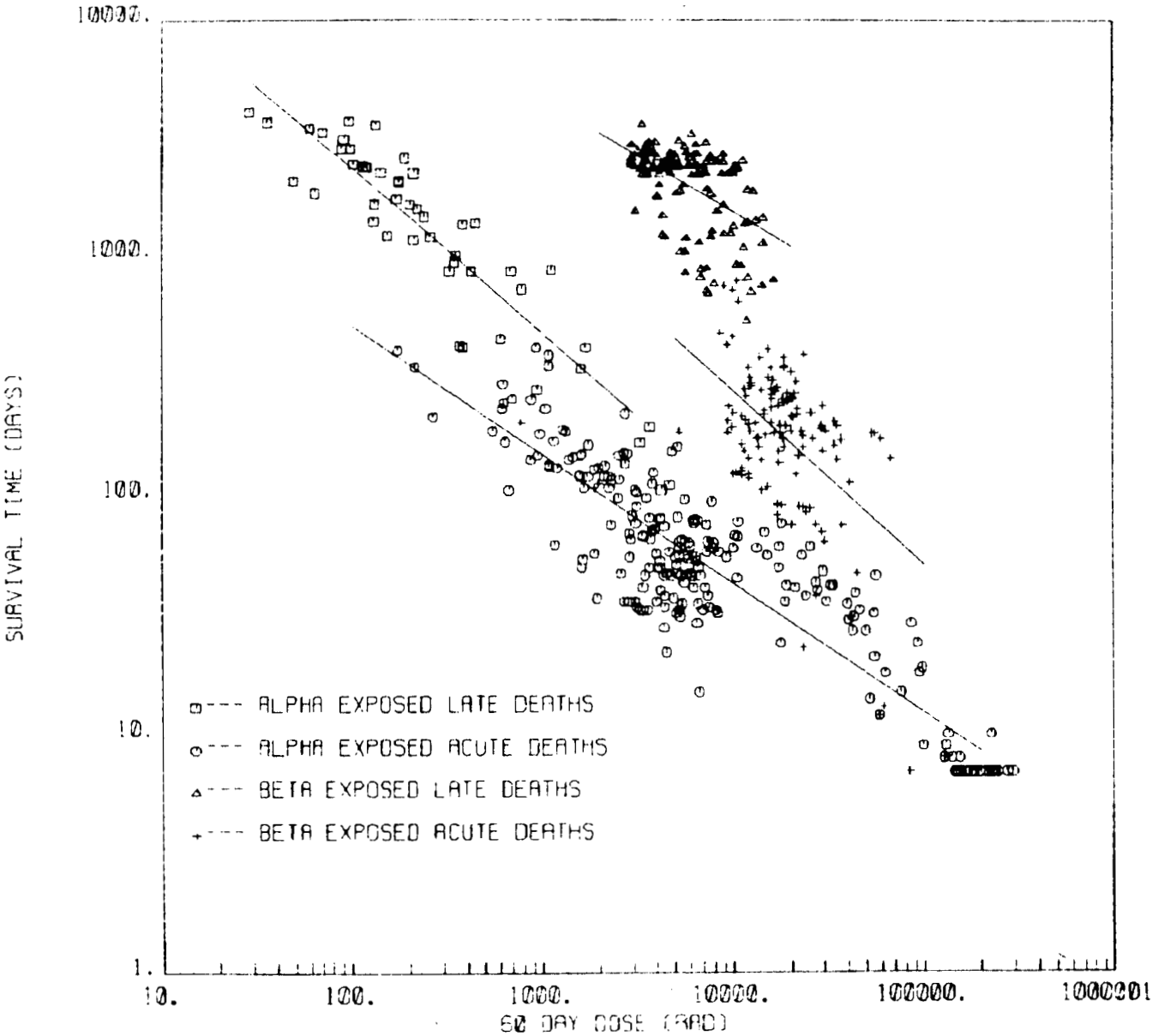

Figure 9. Relationship Between Survival Time and 60-day Lung Dose in Animals Which Died From Acute Pulmonary Injury and Animals Which Died Later From Other Causes.

In none of these cases was there a statistically significant departure from linearity.

An analysis of the residuals from the model revealed some differences remaining in the composite data set. Dogs exposed to $^{238}PuO_2$ appeared to have longer survival times than the model predicted. However, the difference between the residuals for the $^{239}PuO_2$ and $^{238}PuO_2$ rats was not significant, nor was the difference significant between the $^{239}PuO_2$ rats and the $^{238}PuO_2$ dogs. Thus, the longer survival time of the $^{238}PuO_2$ dogs can not clearly be related to a nuclide difference.

Both dogs exposed to ^{90}Y-FAP and rats exposed to $^{243}Es\ (NO_3)_3$ appeared to die earlier than predicted by the model. This may be related to the short (less than 10 days) effective half-times of these nuclides. If this were the case, then an additional adjustment to the model for IDR should account for the difference. However, when the residuals were adjusted for IDR, the ^{90}Y-FAP group moved closer to the grand mean, but the $^{243}Es(NO_3)_3$ group moved very little relative to the grand mean. Therefore, the shorter survival times for the ^{90}Y-FAP and $^{243}Es(NO_3)_3$ groups cannot be unambigously attributed to effective half-life effect.

Several regions in the response space can be defined by regions in the D_t space. For low doses there are no deaths from pulmonary injury, and for high doses all deaths are from radiation pneumonitis. In the intermediate region, there is some likelihood of long-term survival as well as some likelihood of early death. A model of the form

$$S(D_t) = S_1(D_t)\psi(D_t) + S_2(D_t)(1 - \psi(D_t)) + \varepsilon$$

would provide a concise description of the data, where

D_t = dose to day t,

$S(D_t)$ = logarithm of survival time for dose D_t,

$\psi(D_t)$ = random variable, assuming values in [0,1],

ε = random component,

$S_1(D_t)$ = logarithm of survival time where death is due to pulmonary injury,

$S_2(D_t)$ = logarithm of survival time for all other causes.

The random variable, ψ, is included to express the fact that at a dose, D_t, some subjects will die of acute pulmonary injury, while others will survive, probably to die later from a malignant tumor. Two types of models can be considered for this variable. In one case, ψ can be only 0 or 1, corresponding to the noninteracting competing-risk model. For example, an exposed animal is subject to a risk of early death or a risk of late death. If the death can be considered to have resulted from either pulmonary injury or some "other" cause, and if the biological stress that causes pulmonary injury does not influence the time of late death, then this model should apply. Conversely, if stress from pulmonary injury significantly lowers resistance to another injury, then the noninteracting, competing-risk model may not be appropriate. Such a case could be modeled by using any value in the interval [0,1] for ψ.

A schematic diagram of the model is given in Figure 10. The two conditional mean survival times S_1 and S_2 are sketched in Figure 10(a). These two curves are then combined using the weighting function sketched in Figure 10(b) to give the unconditional mean survival time curve in Figure 10(c).

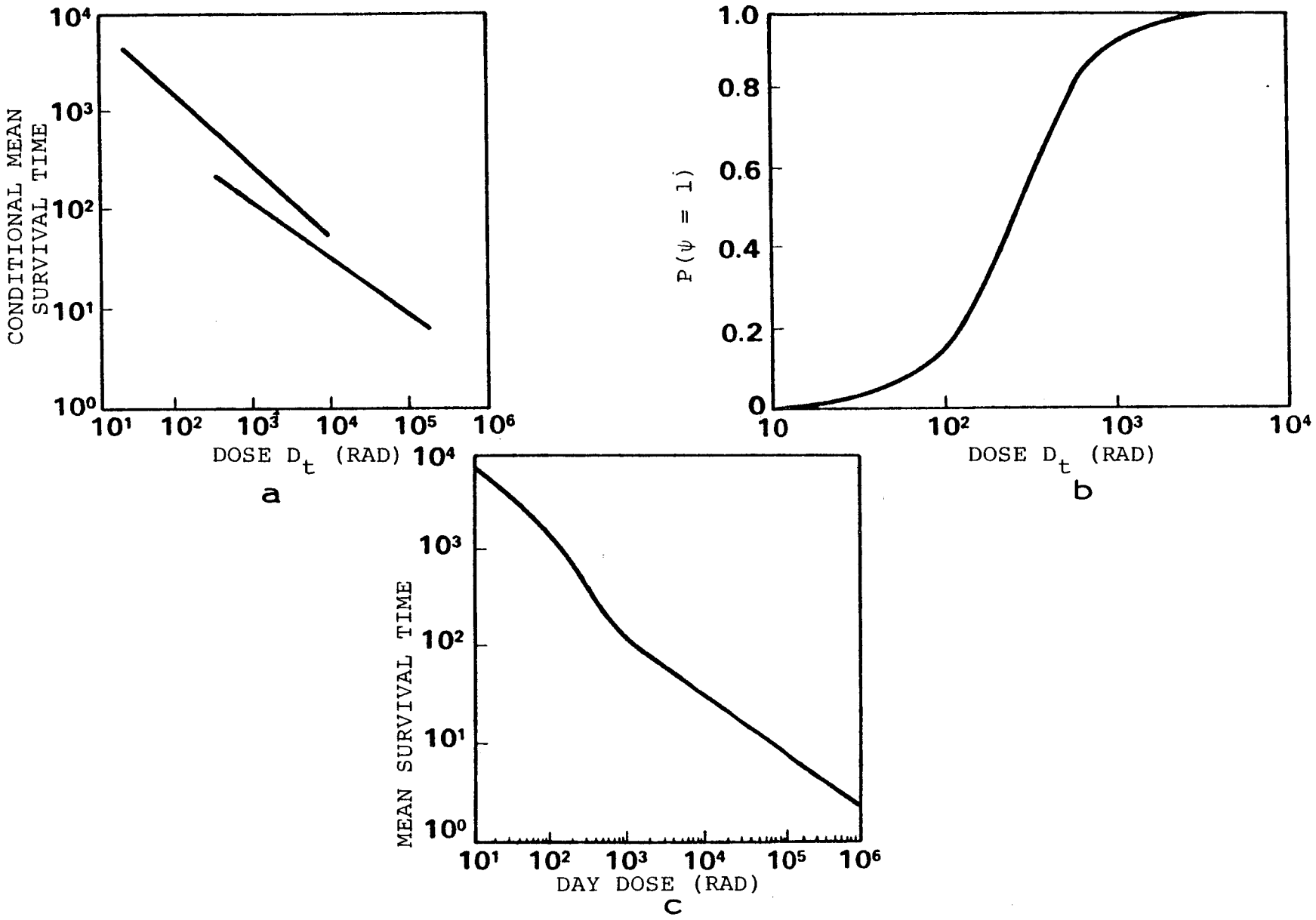

Figure 10. Schematic Dose-Response Model

An analysis of the data in Figures 8 and 9 indicated that the independent competing-risk model was probably adequate for describing the relationship between pulmonary injury and later death. Probability plots of residuals indicated that the random component, ε, had an approximately gaussian distribution. Thus, the probability density function of S_j,

$$f_j(s) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp -\left(\frac{(s_j - \mu_j)^2}{2\sigma^2}\right), \quad j = 1,2,$$

where

$\mu_1 = \mu_1(D_t)$ = average log survival time for pulmonary injury death for dose D_t, and

$\mu_2 = \mu_2(D_t)$ = average log survival time for other death for dose D_t.

Because there is a linear relationship between S_j and log D_t, the average survival times can be represented by

$$\mu_j(D_t) = a_j + b_j \log D_t, \qquad j = 1,2.$$

If Phase II experiments provide evidence that some other predictor variable has a significant influence on survival time, the model can be revised to account for that influence. For instance, if it were demonstrated that "effective half-time", $T_{1/2}$, significantly affected survival time, an extended model would be

$$\mu_j (D_t, T_{1/2}) = a_j + b_j \log D_t + c_j T_{1/2}, \; j = 1,2.$$

The conditional density of T, given that $\psi = 1$, is $f_1(s)$, the density of S_1. Similarly, given that $\psi = 0$, the density of S is $f_2(s)$. Because the joint density is the product of the marginal and conditional densities, it follows that the joint probability mass-density function of S and ψ is

$$f(S,\psi) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(\frac{(S-\mu)^2}{-2\sigma^2}\right) g(\psi),$$

where

$$\mu = \mu_1\psi + \mu_2(1 - \psi),$$

and $g(\psi)$is the marginal probability mass function of ψ. The variable, ψ, has a binominal distribution with parameter p, so that

$$g(\psi) = \begin{cases} p, & \text{if } \psi = 1 \\ 1-p, & \text{if } \psi = 0. \end{cases}$$

The marginal density of S is

$$\begin{aligned} f(s) &= f(s|\psi=1)g(1) + f(s|\psi=0)g(0) \\ &= pf_1(s) + qf_2(s), \text{ where } q = 1-p. \end{aligned}$$

The mean and variance of S are

$$E[S] = p\mu_1 + q\mu_2$$

and

$$Var(S) = \sigma^2 + pq(\mu_1 - \mu_2)^2.$$

The cumulative probability distribution of S is

$$F(s) = pF_1(s) + qF_2(s),$$

where

$$F_j(s) = \int_{\infty}^{s} f_j(\tau)d\tau, \quad j = 1,2.$$

These derivations provide a method for computing the probability of mortality as a function of time and dose. An illustration of the procedure is sketched in Figure 11. The probability density f(s) is the marginal density of S at D_t equal to 300 rad. The shaded area is the cumulative probability function of S evaluated at 365 days. It is the probability of death before 365 days given a t-day dose of 300 rad.

Although the appearance of the dose, D_t, was suppressed in these equations, the probability of mortality is dependent on D_t, both through the mean functions, $\mu_1(D_t)$ and $\mu_2(D_t)$, and the "weighting function,"

$$p(D_t) = \text{Prob}(\psi = 1 \text{ at dose } D_t).$$

The function $p(D_t)$ is the probability distribution function of the minimum t-day dose, say D_t^{min}, required to cause death from pulmonary injury. In general, the value of D_t^{min} for an individual cannot be determined; one can only determine whether or not a particular dose was <u>sufficient</u> to cause death from pulmonary injury. Hence, methods of estimation that treat D_t as if it were D_t^{min} will produce a downward-biased estimate of $p(D_t)$.

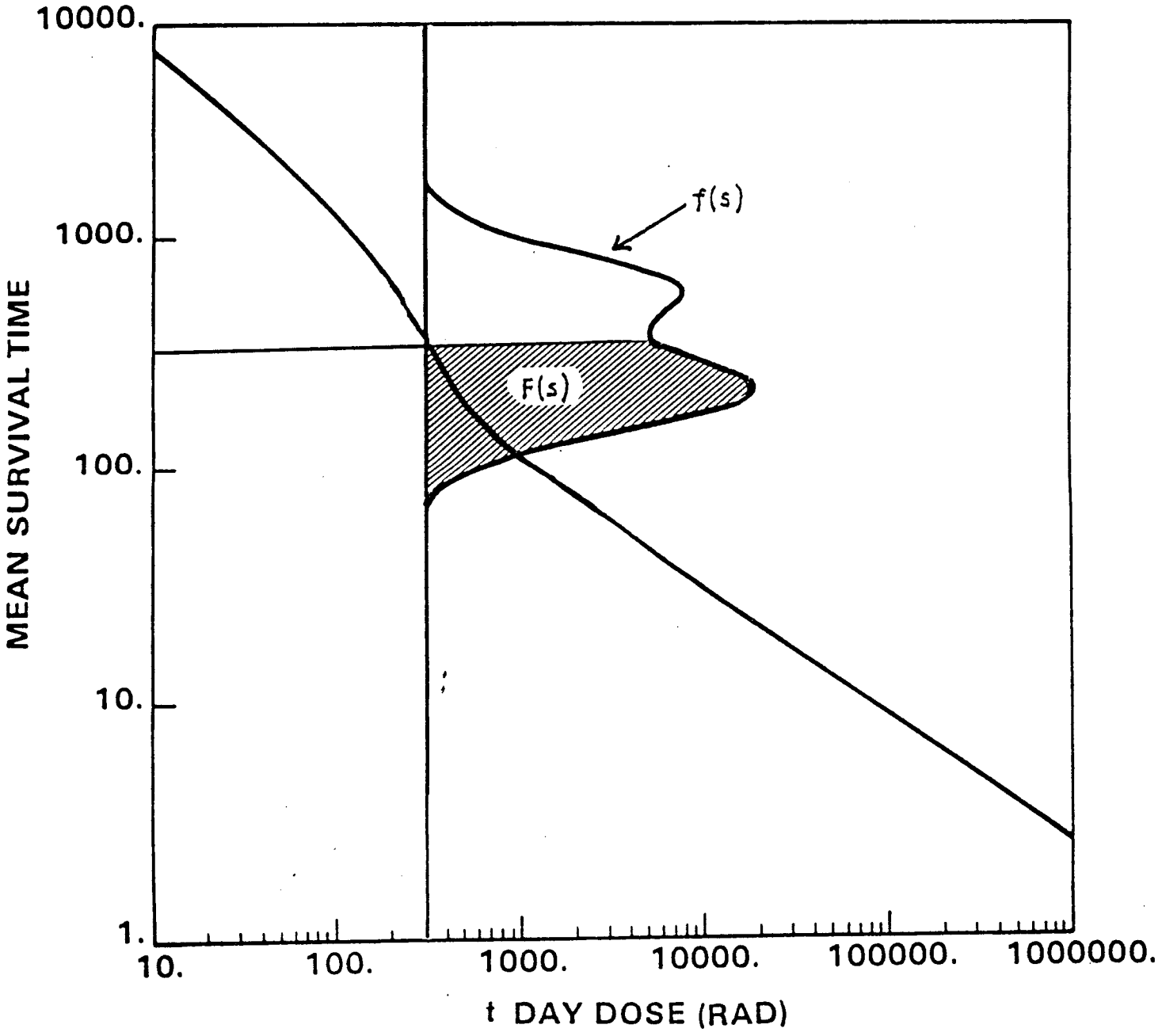

Figure 11. Illustration of Method for Computing Probability of Mortality

In contrast, a valid, nonparametric estimate can be obtained by maximum likelihood.[19] This method assumes that $p(D_t)$ is an increasing function of D_t, and produces a step function estimate of $p(D_t)$. This estimate does not require additional assumptions.

A smooth estimate of $p(D_t)$ can also be obtained by using a linear logistic model.[20] This model postulates that

$$p(D_t) = \frac{1}{1 + \exp(C_o + C_1 \log D_t)}.$$

[The designation, "linear logistic," arises from the fact that the logistic transform $\log (p(D_t) / (1-p(D_t)))$ is linear in $\log D_t$.] This particular model was selected in part because it permits extension. If Phase II research indicates that p depends on variables other than D_t, (for instance, initial dose rate or effective half-time,) these variables can easily be added to the model. If R_D is initial dose rate, a model allowing for an effect of R_D is:

$$p(D_t,R_D) = \frac{1}{1 + \exp (C_o + C_1 \log D_t + C_2 R_D)}.$$

Plots of both a nonparametric estimate and a logistic estimate of $p(D_t)$ are given in Figures 12 and 13 for alpha-emitters and beta-emitters, respectively.

2. Determination of Optimal Dose Period. If the dose computed to some fixed time is to be used as a predictor for survival time, an

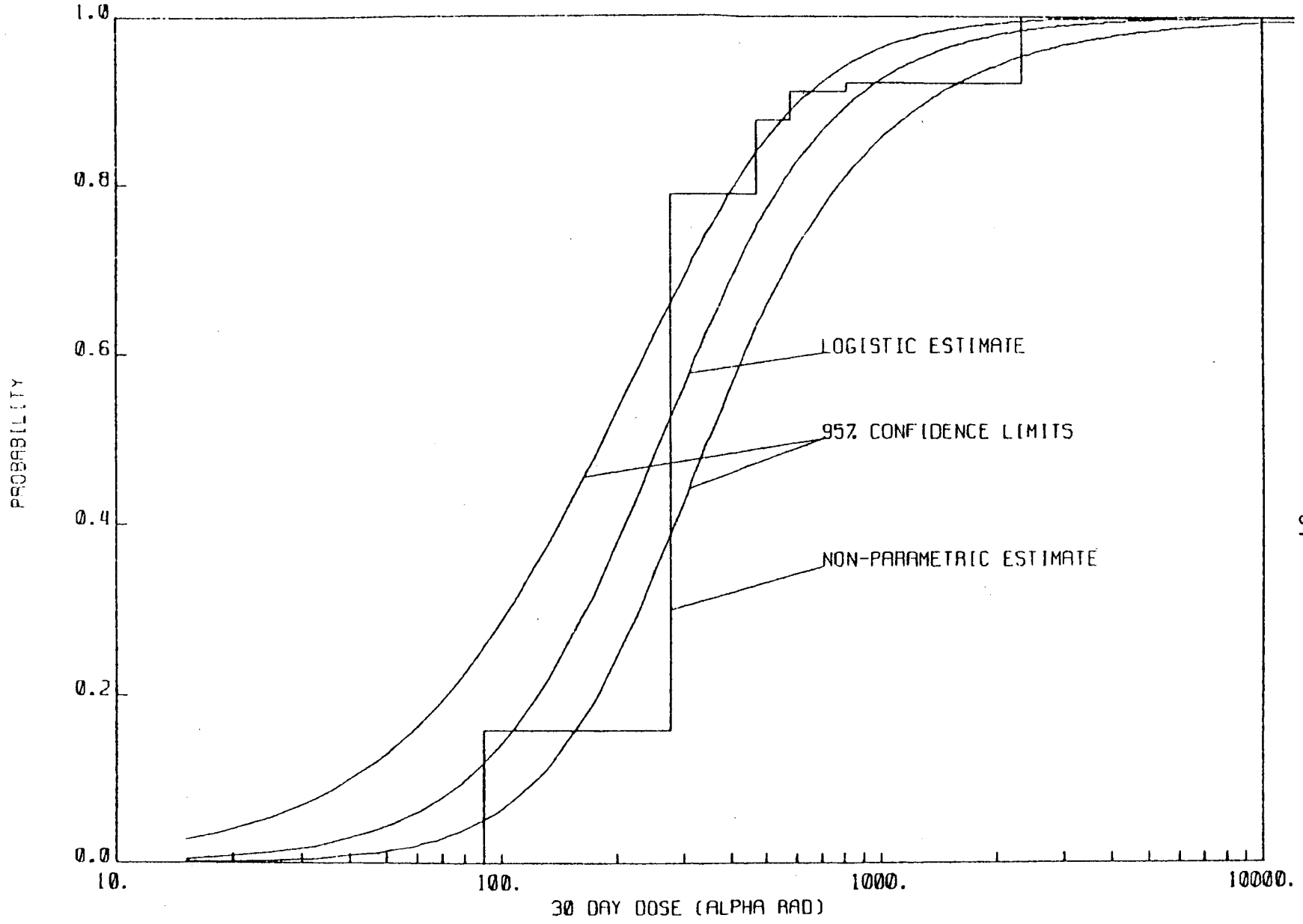

Figure 12. Probability of Death From Pulmonary Injury Caused by Alpha Radiation.

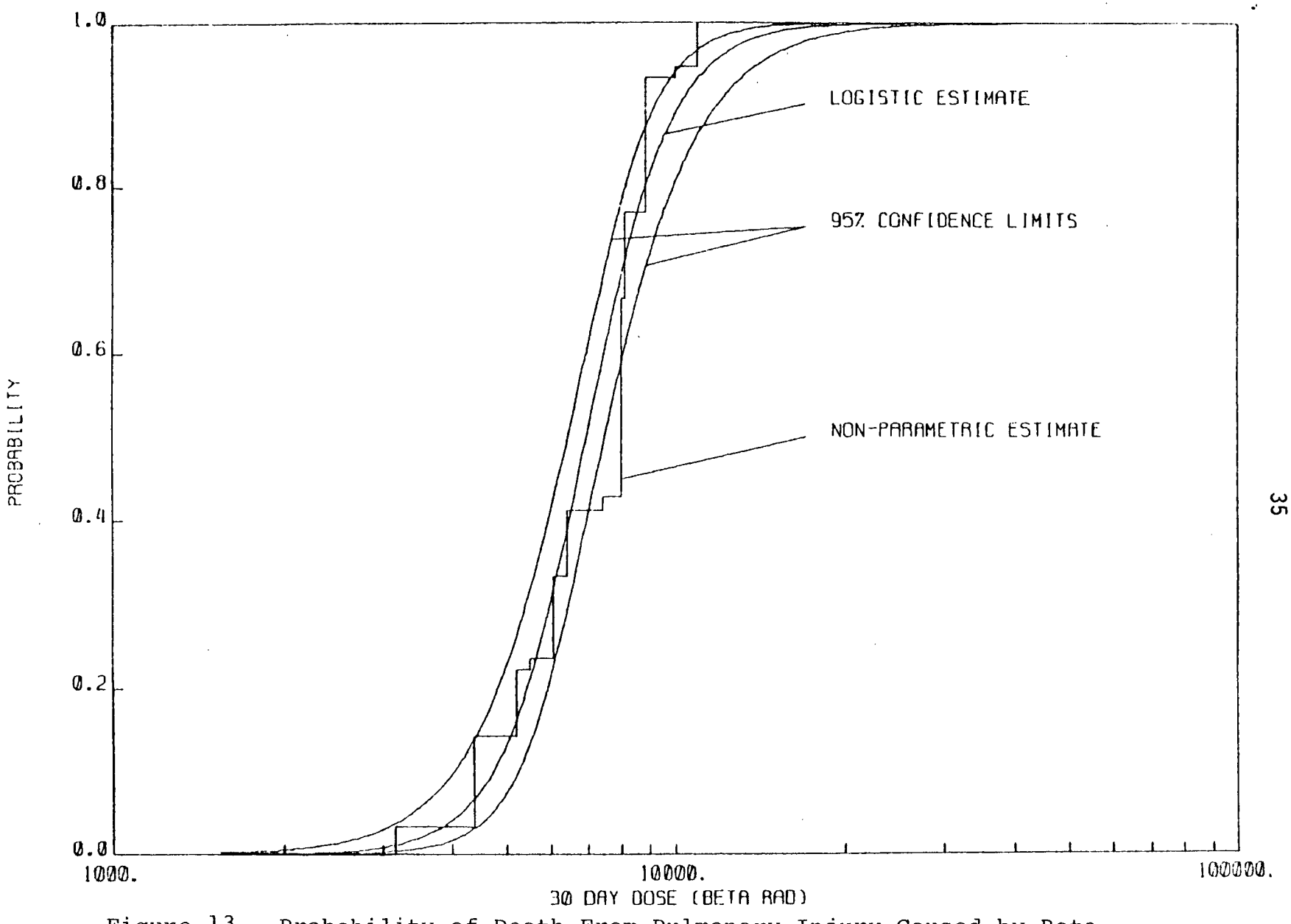

Figure 13. Probability of Death From Pulmonary Injury Caused by Beta Radiation.

"optimal" time at which to compute the dose should be selected. Unfortunately, the criteria for this selection are not clear.

Among the reasonable criteria for a good predictor are the following: (1) the residual mean square should be small, (2) the slope of the regression of log survival time on log dose should be negative: an increase in dose should lead, on the average, to a decrease in survival time and (3) the residuals should not have structure remaining. Although points (2) and (3) are qualitative criteria, they are useful in eliminating unacceptable models.

The question of selecting optimal dose period was examined by computing the dose at 7.5, 15, 30, 60, 120, or 240 days. The log survival time was regressed on the log dose for each time period. Separate slopes and intercepts were computed for each of the four groups (α, death from pulmonary injury), (α, later death from other causes), (β, death from pulmonary injury), and (β, later death from other causes).

The 7.5-, 15-, 120- and 240-day doses were eliminated as candidates for the optimal predictor variable because in each regression at least one of the four groups was estimated to have a positive slope. There was little difference among the models based on 30- or 60-day dose. The residuals from both models had an approximately gaussian distribution, with no evident structure remaining. Each model gave nearly the same prediction of survival time. The 30-day dose model resulted in a smaller residual mean square. The 60-day model had slopes for all four groups that were more nearly parallel. (Parallel slopes could be regarded as a strong indication that an "identical action" model applies,

which would simplify the calculation of combined radiation effects.) However, in both models, the slopes were still significantly different at the 0.05 level.

The 30-day dose was tentatively selected as the optimal dose parameter because of the smaller residual mean square, which permits narrower confidence bands for estimated survival time and probability of mortality.

3. Prediction of Effect of Combined Types of Radiation. Several forms of combined toxic action can be characterized, and Phase II experiments can be designed to distinguish between classes. One form of combined toxicity results when the several types of radiation have "identical action"; i.e., affect the same organ systems in the same way. The difference in effect, therefore, is only in degree. In this case, the dose response curves for the several types will be separated by a constant distance on the log dose scale. Thus, in effect, only a single dose-response function is needed. The response to a combination is obtained by applying scaling factors to the various doses, adding them to obtain a "total equivalent dose", and using the common dose-response function.

A second form of combined toxicity results in a "competing risk" model. This model applies generally when different types of radiation affect organ systems differently and the risks are "competing" to cause the death of the organism. In the special case of independent competing risks, the mortality response to the combined radiation effects is

computed by adding hazard functions, or by multiplying probabilities of surviving the individual risks (see Appendix 3).

The identical-action model and the independent, competing-risk model represent two extremes. Intermediate stages can be modeled either by allowing interaction among the competing risks, or by assuming that the several types of radiation have an "identical-action" component and a "competing-risk" component. At present the data set does not appear to support the hypothesis of identical action since the log survival time versus log 30-day dose curves for alpha- and beta-emitters are not separated by a constant factor. Provisionally, the independent, competing-risk model has been adopted as a predictor of the effects of combined types of radiation.

4. Parameter Estimates and Model Summary. The dose-survival model parameters were estimated using a standard least-squares regression. (Table 2). All parameter estimates are significantly different from zero at the 0.05 level.

The parameters of the logistic pulmonary injury probability model were estimated using maximum likelihood (Table 3).

The overall pulmonary dose-response model is applied to a particular scenario by specifying $D_{30}(\alpha)$, the 30-day alpha dose; $D_{30}(\beta)$, the 30-day beta dose; and ST, the survival time at which the mortality probability is to be computed. The logistic model provides estimates of p_α and p_β, respectively:

TABLE 2. Linear Regression of Log(ST) on Log(D_{30})

	Alpha-emitters		Beta-emitters	
	Coef.	Std Error	Coef.	Std Error
PI* Slope	-0.556	0.016	-0.967	0.071
PI Intercept	3.733	0.060	6.191	0.292
NPI** Slope	-0.716	0.047	-0.216	0.108
NPI Intercept	4.595	0.012	3.952	0.391
Standard Error of Estimate	0.1680		0.1950	

* PI = Pulmonary Injury
** NPI = Nonpulmonary Injury

TABLE 3. Maximum-Likelihood Estimates of Logistic Parameters

Model: $p(D_{30}) = 1/(1 + \exp(C_o + C_1 \log D_{30}))$

	Alpha-emitters		Beta-emitters	
	Parameter	Std. Error	Parameter	Std. Error
C_o	10.366	1.608	50.500	6.627
C_1	-4.288	0.614	-13.148	1.722

$$p_\alpha = 1/(1 + \exp(10.37 - 4.29 \log D_{30}(\alpha)))$$
$$p_\beta = 1/(1 + \exp(50.50 - 13.148 \log D_{30}(\beta))).$$

The dose/survival-time model provides estimates of the mean log survival times and standard deviation:

$$\mu_1(\alpha) = 3.73 - 0.55 \log D_{30}(\alpha),$$
$$\mu_2(\alpha) = 4.60 - 0.72 \log D_{30}(\alpha),$$
$$\sigma(\alpha) = 0.1680;$$

and

$$\mu_1(\beta) = 6.19 - 0.97 \log D_{30}(\beta)$$
$$\mu_2(\beta) = 3.95 - 0.22 \log D_{30}(\beta)$$
$$\sigma(\beta) = 0.1905.$$

Standardized normal variates are obtained from

$$s = \log ST$$
$$z_1(\alpha) = \frac{s - \mu_1(\alpha)}{\sigma(\alpha)},$$
$$z_2(\alpha) = \frac{s - \mu_2(\alpha)}{\sigma(\alpha)},$$

and

$$z_1(\beta) = \frac{s - \mu_1(\beta)}{\sigma(\beta)},$$

$$z_2(\beta) = \frac{s - \mu_2(\beta)}{\sigma(\beta)}.$$

Probabilities $P_1(\alpha)$, $P_2(\alpha)$, $P_1(\beta)$, and $P_2(\beta)$ that correspond to the standardized normal variates given above can be obtained from a table of the standard normal (gaussian) probability distribution. The probability of mortality from alpha exposure is given by (Figure 14)

$$P(\alpha) = p_\alpha \, P_1(\alpha) + (1-p_\alpha) \, P_2(\alpha),$$

and from beta exposure by (Figure 15)

$$P(\beta) = p_\beta \, P_1(\beta) + (1-p_\beta) \, P_2(\beta).$$

Using the independent, competing-risk model, the combined probability of mortality is

$$P = 1-(1-P(\alpha)) \, (1-P(\beta)).$$

B. Bone-Marrow Dose/Mortality Model

Several exposure scenarios would provide sufficient dose to bone (red) marrow to cause early mortality or morbidity. In some situations, such as reactor accidents, damage to bone marrow is considered the

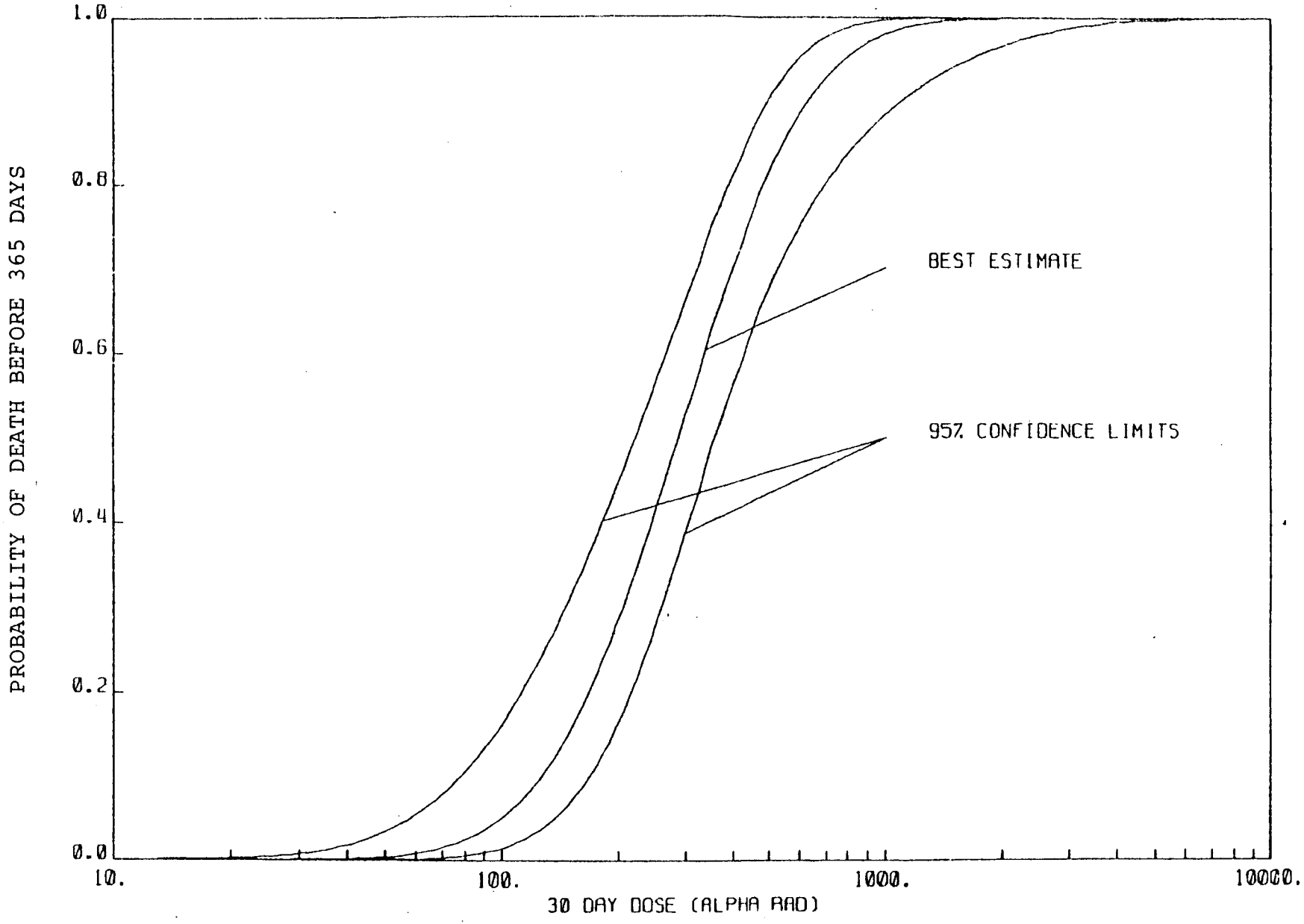

Figure 14. Mortality at 365 Days Caused by Inhaled Alpha Emitting Radionuclides.

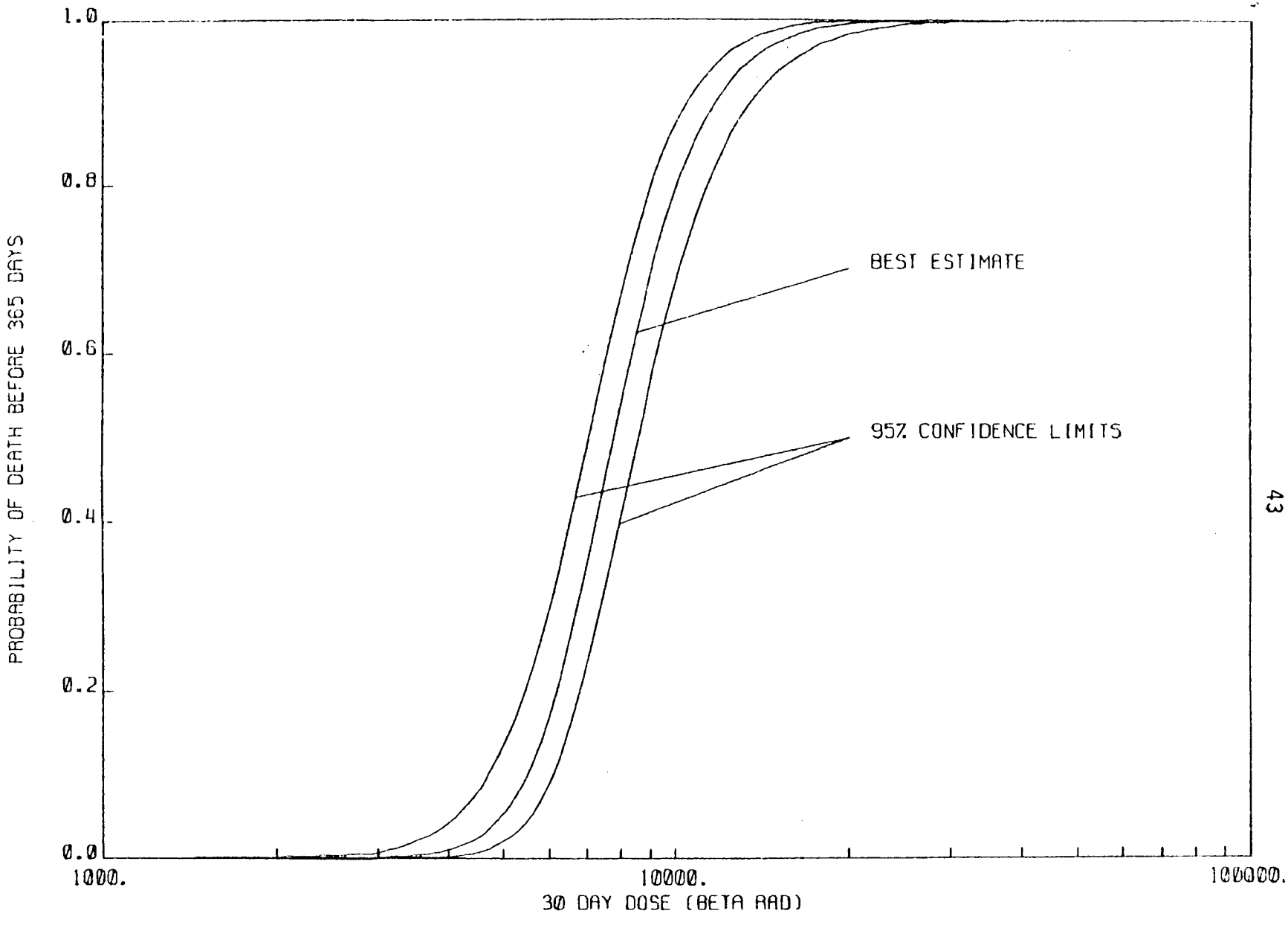

Figure 15. Mortality at 365 Days Caused by Inhaled Beta Emitting Radionuclides.

primary cause of mortality.[1] It is important, therefore, to develop a model that is predictive of early mortality from bone-marrow destruction with associated pancytopenia.

We agree with the Reactor Safety Study[1] that damage to bone marrow is the primary cause of death from large radiation doses to the whole body. As a consequence, mortality predictions based on whole-body irradiation represent the upper limit of estimates of death from bone-marrow irradiation. We further concur, at this stage of our data investigation, that the estimated whole-body dose-response curve for minimal treatment (curve A of Figure VI 9-1[1]) is appropriate for estimating percent mortality in 365 days. This curve (reproduced in Figure 16) is the best estimate established by consensus that the $LD_{50/60}$ is 340 rad if only minimal medical treatment is available. On the assumption that the $LD_{50/60}$ dose is not less than the $LD_{50/365}$ dose (and may possibly be greater), the minimal treatment curve, based on 60-day dose, is considered to apply to human populations receiving minimal-to-supportive treatment following irradiation.

There is some evidence from animal data that certain damaged organ systems cause delayed death when exposed to doses lower than those causing early death. For example, the $LD_{50/10}$ to the large bowel of dogs is 3.5 mCi/kg (^{106}Ru - ^{106}Rh) administered in food, whereas an $LD_{50/180}$ is 2.75 - 3.0 mCi/kg.[21] By analogy, a smaller whole-body dose than 340 rad might delay death up to 365 days. In any event, we conclude that the $LD_{50/60}$ minimal-treatment curve results in conservative

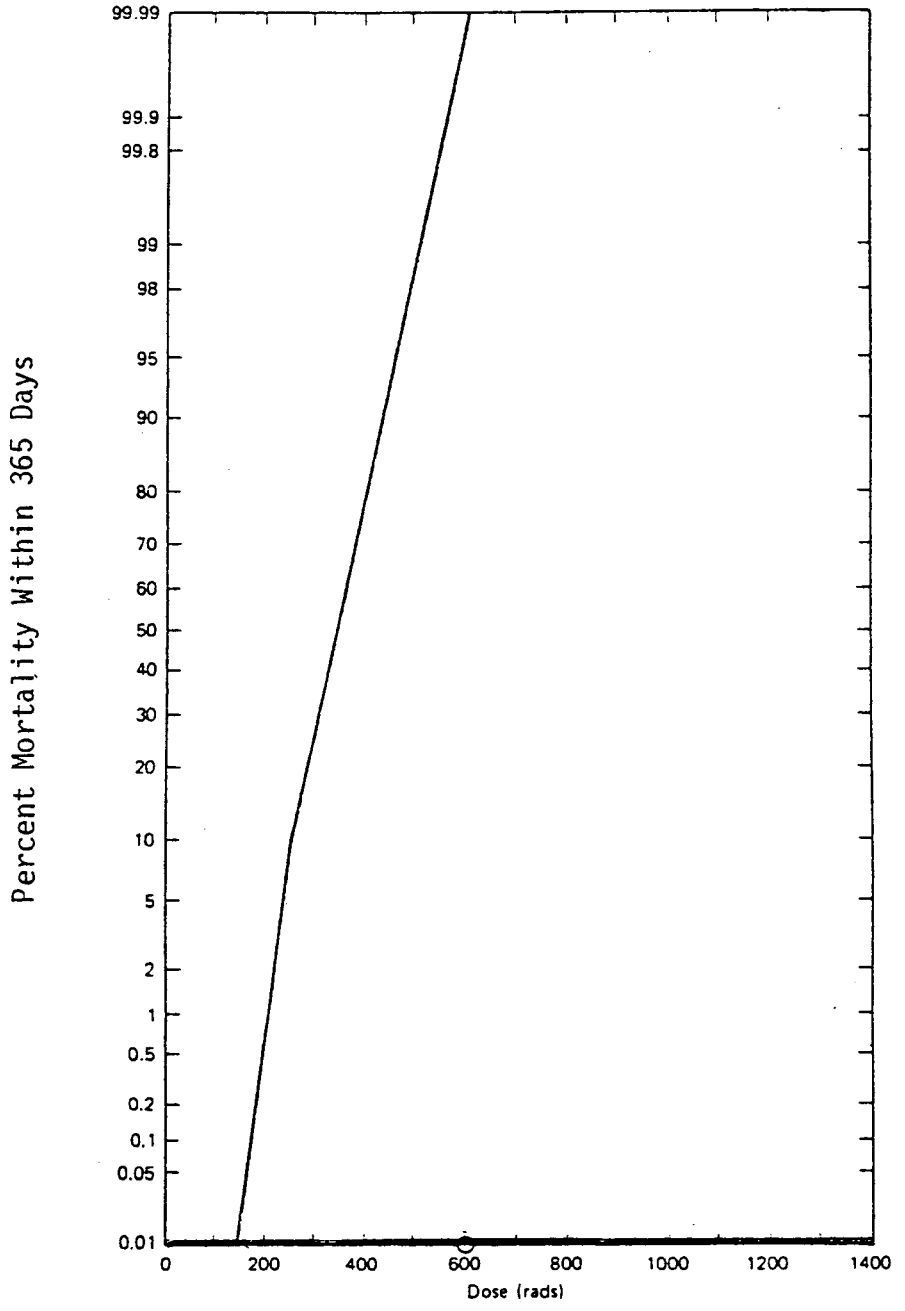

Figure 16. Bone-Marrow Dose/Mortality Model

mortality predictions from damage to bone marrow when there is some treatment following irradiation.

Available whole-body response data pertain to acute doses from irradiations of short (<1 day) duration. Mortality resulting from bone-marrow damage, therefore, can be predicted from whole-body response data for acute doses delivered to bone marrow. This would apply to doses from external radiation, such as brief exposures to ground contamination or from the passage of contaminated clouds. If an internal dose to bone marrow were delivered in a brief timespan, it is assumed to be additive to that from external radiation when estimating the combined mortality. Appendix F of the Reactor Safety Study[1] cites evidence that exposure protracted over 2 to 4 weeks is only half as effective as that delivered over a few hours. We can therefore predict mortality from slowly delivered internal doses by drawing another curve parallel to the whole-body curve but shifted to the right on the dose axis by a factor of two; or we can use the original whole-body mortality curve, and divide the 2 to 4-week cumulative dose by two. Similar appropriate dose-weighting or curve-shifting should relate to doses delivered over various other time spans.

Data obtained from ITRI experiments in dogs[22] were analyzed for mean dose to death (MDD) and mean time to death (MTD) from blood dyscrasia (Table 4). The overall MDD and MTD were 900 rad and 26.4 days, respectively (excluding the two much longer-lived animals in the ^{137}Cs experiments). Damage to bone marrow was the primary cause of death in these animals, even though other organ systems received appreciable

doses and were damaged. In these experiments, the dose rate was sufficiently low that the killing dose could not be considered as effective as that from acutely delivered external radiation. Assuming the LD_{50} ratio for man to dog is 1.4[23], we can calculate an MDD for man from an internal dose delivered to bone marrow over about a 30-day period to be: 1.4 x 900 = 1260 rad. The dose for 100% mortality, calculated from a doubled-dose shifted curve is almost exactly the same, indicating that a plausible, interim, critical bone-marrow dose for mortality modeling can be determined by adding all doses delivered from external radiation (for exposures $\leq$1-day duration) to 1/2 the 30-day dose accumulated in marrow from internal emitters which deliver their dose at similar or lower rates.

TABLE 4. Mean Dose and Mean Time to Death from Hematological Dyscrasia

Isotope	MDD (rad)	MTD (days)
$^{91}YCl_3$	723	22.4
$^{90}SrCl_3$	905	27.0
$^{144}CeCl_3$	928	31.5
$^{137}CsCl$	1063 (1182)*	25.4 (37.4)*

*Two of 11 animals lived about 2-1/2 times longer, shifting the MTD value but not appreciably altering the MDD value.

If the rate of dose accumulation in these experiments was relatively constant, the mean dose rate was approximately 30 rad/day. At this rate, 3-4 days would elapse before a sufficient dose would have accumulated to produce about 0.01% mortality, as predicted by the whole-body mortality curve. Thus, it appears that mortality from marrow dose rates much greater than about 30 rad/day should not be calculated by the general rule of halving internal emitter doses. Until further information is available, marrow doses from internal beta emitters delivered at rates equal to or exceeding 50 rad/day are directly added to externally acquired doses, weighting such doses equally with those from acutely delivered external radiation.

Table 5 depicts dose buildup in homogeneous human bone, corroborating the relatively slow buildup for ^{90}Sr, ^{91}Y and ^{144}Ce (+daughters) observed in the animal experiments. The table indicates that the dose buildup for ^{90}Y is substantially faster than for the other radionuclides examined. Also included in Table 5 is the rate of dose buildup in bone for the PWR-2 reactor accident scenario described in Section V. In this case, since early dose rates exceed 50 rad/day, doses to bone from internal emitters are given equivalent weight with those delivered to the whole body from external radiation, and mortality prediction is 100% because of the extremely high doses to bone.

The internal emitter dose calculational code (DACRIN) was designed to calculate dose to homogeneous bone rather than to bone marrow. We assume for most practical cases that the difference between dose to marrow and dose to homogeneous bone would not significantly influence

the percent mortality due to blood dyscrasia. However, caution is in order when modeling very weak beta emitters or alpha emitters. In any event, death from hematological dyscrasia following inhalation or ingestion of alpha emitters would be a very rare event.

TABLE 5. Bone Dose to Man from Internal Emitters

	^{90}Sr	^{90}Y		^{91}Y		^{144}Ce		PWR-2 Accident		
Day	% Dose	Rad*	% Dose	Rad*	% Dose	Rad*	% Dose	Rad*	% Dose	Rad
1	2.4	29	17	200	3.6	43	3.2	38	7.7	230
2	5.5	66	35	420	7.2	86	6.5	78	16	470
3	8.8	110	49	590	11	130	9.8	120	23	680
4	12	140	61	730	14	170	13	160	29	860
5	16	190	70	840	18	220	16	190	34	1000
6	19	230	77	920	21	250	20	240	39	1200
7	22	260	82	980	25	300	23	280	43	1300
14	46	550	97	1200	49	590	46	550	64	1900
21	69	830	100	1200	72	860	69	830	80	2400
28	93	1100	100	1200	94	1100	93	1100	95	2800
30	100	1200	100	1200	100	1200	100	1200	100	3000

* Assuming 30-day dose to bone is 1200 rad

V. COMBINED EARLY MORTALITY MODEL

A. Introduction

The overall model for predicting early mortality (death within 365 days) from exposure to internal and/or external ionizing radiation is a combination of the models described in Sections III and IV. It should be emphasized that even though doses to man are the calculated input to the dose-response models (Section IV), the predicted consequences to man are more or less predicated on his response being identical to that of the animals whose dose-response data were used in developing the percent mortality per unit radiation exposure. Furthermore, the combined early mortality model, at this stage of development, is useful only in predicting the consequences from internal dose to bone marrow and lung. If death were partially due to internal irradiation of other organ systems, the percent mortality calculated from this model would be underestimated.

The dosimetry model of Section III can be used to determine "critical doses" pertaining to man for whole-body, lung, bone (bone marrow), etc. from both internal and external irradiation. However, at this stage, only dose to lung and bone (marrow) are utilized. These doses are entered in the dose-response model in specific fashion for conversion to percent mortality. The critical doses are defined as follows:

Lung

1) 30-day alpha internal emitter dose, and/or

2) 30-day beta-photon internal emitter dose + 30-day cross-organ dose + acutely delivered external lung dose.

Bone (bone marrow)

1) acutely delivered external bone marrow dose + 30-day internal emitter bone dose + 30-day cross-organ dose [for initial (day 1 dose rate) internal emitter dose rate $\geq$ 50 rad/day],
2) acutely delivered external bone marrow dose + 1/2(30-day internal emitter bone dose and 30-day cross-organ dose) [for initial (day 1 dose rate) internal emitter dose rate < 50 rad/day].

The combined mortality from these specific doses is calculated by the following equation:

$$\text{Percent mortality} = \left[1-\prod_{i}^{n}(1-a_i)\right] 100,$$

where a_i is the fractional mortality from bone (bone marrow) irradiation, internal lung alpha-dose and internal (+ external) lung beta, gamma-dose.

The process of calculating percent mortality for two specific radionuclide scenarios is shown in Table 6. Table 7 contains the detailed dosimetry data for a PWR-2 reactor accident. Details of the dose calculations are presented in Appendices 1 and 2.

CALCULATION	ASSUMPTIONS	SCENARIO 1	SCENARIO 2
RELEASE SCENARIO	SCENARIOS 1 AND 2: RELEASE HEIGHT-25 m ATMOSPHERIC CONDITIONS- STABLE PASQUILL F WIND SPEED-2 m/sec	THIS SCENARIO IS AN IMAGINARY EXAMPLE USED TO TEST THE MORTALITY MODEL. THE RADIONUCLIDES RELEASED ARE: Zr-95 2.0 E + 6 Ci Ru-106 7.0 E + 5 Ci Pu-239 1.0 E + 4 Ci	THIS SCENARIO IS A WASH-1400 PWR-2 ACCIDENT. THE RADIONUCLIDES (TABLE 2, COL. 1) ARE RELEASED TO THE ENVIRONMENT 2.5 HRS AFTER THE ACCIDENT OCCURS. TABLE 7, COL 3 LISTS THE ACTIVITIES RELEASED.
SOURCE TERM	RECEPTOR DISTANCE DOWNWIND: SCENARIO 1-1500 m SCENARIO 2- 500 m	CONCENTRATIONS AT RECEPTOR: Zr-95 7.1 E - 8 Ci/ml Ru-106 2.5 E - 8 Ci/ml Pu-239 3.5 E - 10 Ci/ml	CONCENTRATIONS AT THE RECEPTOR APPEAR IN TABLE 7, COL. 4.
ORGAN DEPOSITION	DEPOSITION FRACTIONS: SCENARIOS 1 AND 2 $ND(D_3)$ = 0.288 $TB(D_4)$ = 0.080 $P(D_5)$ = 0.234 PARTICLE SIZE = 1.0 μm BREATHING RATE = 333 cc/sec EXPOSURE TIME = 0.5 hr	PULMONARY DEPOSITION: Zr-95 10,000 μCi Ru-106 3500 μCi Pu-239 49 μCi	LUNG DEPOSITIONS ARE LISTED IN TABLE 7, COL. 5, 6 AND 7. BONE DEPOSITION FRACTIONS APPEAR IN TABLE 7, COL. 8
30 DAY LUNG DOSE-INTERNAL	INHALATION DOSE ONLY TASK GROUP LUNG MODEL SOLUBILITY CLASS: SCENARIO 1 - ALL "Y" CLASS SCENARIO 2 - SEE TABLE 2 COLUMN 1	30 DAY LUNG DOSE: α 430 rad β-γ 8900 rad	30 DAY LUNG DOSE (TABLE 7, COL. 14): α 10 rad β-γ 7600 rad
30 DAY HOMOGENEOUS BONE DOSE-INTERNAL	ICRP II TRANSFER COEFFICIENTS: SCENARIOS 1 AND 2 - SEE TABLE 7, COLUMN 7	30 DAY HOMOGENEOUS BONE DOSE: α ~0 rad β-γ ~0 rad	30 DAY HOMOGENEOUS BONE DOSE (TABLE 7, COL. 15) α 0.07 rad β-γ 3000 rad
30 DAY CROSS ORGAN DOSE	CONTRIBUTION IS FROM γ-EMMITERS ONLY. LUNG, LIVER, BONE (RED MARROW) ARE ONLY SIGNIFICANT SOURCE TARGET ORGANS.	30 DAY CROSS-ORGAN DOSE: LUNG ~0 rad BONE MARROW ~0 rad	30 DAY CROSS-ORGAN DOSE (TABLE 7 COL. 13): LUNG ~7.8 rad BONE MARROW ~0 rad
EXTERNAL DOSE	SCENARIOS 1 AND 2: EXPOSURE TIME = 0.5 hr AIR SUBMERSION DOSE	EXTERNAL WHOLE-BODY DOSE: Zr-95 21 rad Ru-106 2 rad Pu-239 0.0 rad TOTAL 23 rad EXTERNAL LUNG DOSE = 22 rad EXTERNAL BONE MARROW DOSE = 24 rad	EXTERNAL DOSES - TABLE 7, COLUMN 9, 10, 11 AND 12 EXTERNAL WHOLE-BODY DOSE = 610 rad EXTERNAL LUNG DOSE = 570 rad EXTERNAL BONE MARROW DOSE = 640 rad
30 DAY DOSE - ACUTE (365D) MORTALITY MODEL	CRITICAL DOSE TO LUNG IS COMPOSED OF: α: 30-DAY INTERNAL DOSE β, γ: 30-DAY INTERNAL (INCLUDING CROSS-ORGAN) + EXTERNAL LUNG DOSES. CRITICAL DOSE TO BONE MARROW IS COMPOSED OF EITHER 1. E+I, IF R ≥ 50 rad/day OR 2. E+I/2, IFR < 50 rad/day WHERE E = EXTERNAL BONE MARROW DOSE I = 30-DAY INTERNAL DOSE (INCLUDING CROSS-ORGAN) R = INITIAL INTERNAL DOSE RATE	PERCENT MORTALITY AS A FUNCTION OF DOSE. CRITICAL DOSE MODE / DOSE (rad) / % MORTALITY BONE MARROW / 24 / ~0 LUNG α / 430 / 74.1 β-γ / 8900 / 68.0	PERCENT MORTALITY AS A FUNCTION OF DOSE. CRITICAL DOSE MODE / DOSE (rad) / % MORTALITY BONE MARROW / 3600 / 100 LUNG α / 10 / ~0 β-γ / 8200 / 57.5
PERCENT MORTALITY	PERCENT MORTALITY = $100\left[1-\prod_{i=1}^{n}(1-a_i)\right]$ WHERE a_i IS THE FRACTIONAL MORTALITY FROM BONE MARROW IRRADIATION, INTERNAL LUNG α AND INTERNAL PLUS EXTERNAL LUNG β-γ.	THE PERCENT MORTALITY OF PERSONNEL EXPOSED TO THE ABOVE SCENARIO WOULD BE 92.7%. (SEE SECTION V FOR TREATMENT OF ERRORS).	THE PERCENT MORTALITY OF PERSONNEL EXPOSED TO THE ABOVE SCENARIO WOULD BE 100%. (SEE SECTION V FOR TREATMENT OF ERRORS).

Table 6. Calculations of Mortality Probability from Two Hypothetical Radionuclide Release Scenarios.

				LUNG DEPOSITION (μCi)				EXTERNAL DOSE, 0.5 hr. rad exposure				30 DAY INTERNAL DOSE (rad)			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
RADIONUCLIDE	SOLUBILITY	RELEASE ACTIVITY (Ci)	CONCENTRATION AT RECEPTOR (Ci/ml)	NP-D3	TB-D4	P-D5	BONE DEPOSITION FRACTION	TOTAL BODY	LUNGS	BONE RED MARROW	BONE	LUNG CROSS ORGAN	LUNG DEPOSITED	BONE DEPOSITED	BONE CROSS-ORGAN
Co-58	Y	1.6 E + 4	4.5 E - 11	7.8	2.2	6.3	---	0.017	0.016	0.018	0.019	---	1.5	---	---
Co-60	Y	8.8 E + 3	1.6 E - 11	2.8	0.78	2.3	---	0.018	0.017	0.017	0.019	---	1.5	---	---
Kr-85	D	5.0E + 5	1.4 E - 9	13.5	3.7	11.0	---	0.0012	0.001	0.001	0.002	---	2.2	---	---
Kr-85m	D	1.5 E + 7	4.2 E - 8	7280	2020	5910	---	2.7	3.9	2.5	4.2	---	120	---	---
Kr-87	D	1.1 E + 7	3.1 E - 8	5340	1480	4340	---	10.0	9.6	10.0	11.0	---	120	---	---
*Kr-88	D	3.3 E + 7	9.3 E - 8	16, 000	4450	13, 000	---	79.0	74.6	75.1	82.5	---	1200	---	---
Rb-86	W	1.3 E + 4	3.7 E - 11	6.3	1.8	5.1	---	0.001	0.002	0.001	0.001	---	1.7	---	---
Sr-89	D	5.6 E + 6	1.6 E - 8	2720	755	2210	0.28	---	---	---	---	---	44.4	407	---
Sr-90	D	2.2 E + 5	6.2 E - 10	107	29.7	86.7	0.12	---	---	---	---	---	1.4	16.5	---
*Sr-91	D	5.5 E + 6	1.6 E - 8	2670	741	2170	0.28	5.4	5.0	5.8	6.2	0.018	41.0	17.9	---
Y-90	W	1.5 E + 4	4.2 E - 11	7.3	2.0	5.9	0.19	---	---	---	---	---	0.71	0.17	---
Y-91	W	4.8 E + 5	1.4 E - 9	233	64.7	189	0.19	0.002	0.002	0.002	0.002	---	72.0	23.4	---
*Zr-95	Y	6.0 E + 5	1.7 E - 9	291	80.9	237	0.09	0.49	0.46	0.53	0.57	0.104	106	0.30	0.009
*Zr-97	Y	5.4 E + 5	1.5 E - 9	262	72.8	213	0.09	0.75	0.70	0.77	0.79	---	14.8	0.056	0.002
Nb-95	Y	6.0 E + 5	1.7 E - 9	290	80.9	237	0.10	0.51	0.47	0.51	0.56	0.103	43.8	0.092	0.009
Mo-99	Y	3.1 E + 6	8.7 E - 9	1500	418	1220	---	5.7	0.54	0.66	0.70	0.021	83.1	---	0.01
Tc-99m	Y	2.1 E + 6	5.9 E - 9	1020	283	828	0.001	0.34	0.27	0.53	0.58	---	---	---	---
Ru-103	Y	2.2 E + 6	6.2 E - 9	1070	297	867	0.02	1.2	1.2	1.5	1.5	0.02	166	0.32	0.02
*Ru-105	Y	9.7 E + 5	2.7 E - 9	471	131	382	0.02	0.001	0.001	0.002	0.002	---	4.4	0.007	---
*Ru-106	Y	5.0 E + 5	1.4 E - 9	13.5	3.7	11.0	0.02	0.11	0.10	0.13	0.13	---	251	0.93	---
Rh-105	Y	9.3 E + 5	2.6 E - 9	451	125	367	0.02	0.085	0.076	0.12	0.13	---	0.59	0.08	---
Te-127	W	1.5 E + 6	4.2 E - 9	728	202	591	0.034	0.007	0.007	0.008	0.009	---	3.6	0.12	---
Te-127m	W	3.3 E + 5	9.3 E - 10	160	44.5	130	0.034	0.002	0.001	0.002	0.003	---	29.9	1.9	---
Te-129	W	2.1 E + 6	5.9 E - 9	1020	283	828	0.034	0.16	0.14	0.18	0.19	---	2.2	0.031	0.002
Te-129m	W	1.3 E + 6	3.7 E - 9	630	180	510	0.034	0.052	0.046	0.061	0.065	0.003	257	13.5	---
*Te-131m	W	3.7 E + 6	1.0 E - 8	1800	499	1460	0.034	6.1	5.7	6.5	7.0	0.044	2.5	98.2	0.078
*Te-132	W	3.5 E + 7	9.8 E - 8	17, 000	4720	13, 800	0.034	21.1	19.3	25.7	27.5	0.19	2394	79.8	0.16
*Sb-127	W	1.8 E + 6	5.1 E - 9	873	243	710	0.03	1.4	1.3	1.6	1.7	---	---	---	---
Sb-129	W	6.6 E + 6	1.9 E - 8	3200	890	2600	0.03	---	---	---	---	---	---	---	---
I-131	D	6.0 E + 7	1.7 E - 7	29, 100	8090	23,700	0.053	27.0	24.9	31.3	32.8	2.48	247	219	0.012
I-132	D	4.0 E + 7	1.1 E - 7	19, 400	5390	15,800	0.053	100.0	97.5	112	119.0	0.20	9.3	4.6	0.038
*I-133	D	1.1 E + 8	3.1 E - 7	53, 400	14, 800	43, 400	0.053	87.0	81.5	96.6	102.0	1.38	678	---	0.033
*I-134	D	1.9 E + 7	5.3 E - 8	9220	2560	7490	0.053	51.0	48.1	52.1	56.7	0.042	19.8	---	0.021
*I-135	D	8.1 E + 7	2.3 E - 7	39, 300	10, 900	31, 900	0.053	175.7	169.3	176.9	192.2	0.79	416	---	0.051
Xe-133	D	1.5 E + 8	4.2 E - 7	73, 000	20, 000	59,000	---	6.9	5.3	10.9	11.9	---	530	---	---
Xe-135	D	2.5 E + 7	7.0 E - 8	12, 100	3370	9860	---	7.2	6.4	9.9	10.7	---	290	---	---
Cs-134	D	3.8 E + 6	1.1 E - 8	1840	512	1500	0.03	6.7	6.3	7.3	7.7	1.6	40.7	30.4	0.003
Cs-136	D	1.5 E + 6	4.2 E - 9	728	202	591	0.03	3.6	3.4	3.8	4.1	0.45	8.5	4.4	0.002
Cs-137	D	2.4 E + 6	6.8 E - 9	1160	324	946	0.03	---	---	---	---	---	18.6	27.5	---
*Ba-140	D	9.6 E + 6	2.7 E - 8	4660	1290	3790	0.19	2.6	2.2	2.8	3.0	0.25	101	2062	---
La-140	W	6.1 E + 5	1.7 E - 9	296	82.2	241	0.1	1.8	1.7	1.8	1.9	0.042	24.3	1.4	0.021
Ce-141	Y	6.0 E + 5	1.7 E - 9	291	80.9	237	0.075	0.055	0.045	0.090	0.098	0.015	29.7	0.16	0.001
*Ce-143	Y	4.9E + 5	1.4 E - 9	238	66.1	193	0.075	0.17	0.15	0.21	0.23	0.004	12.8	0.051	0.003
*Ce-144	Y	3.4 E + 5	9.6 E - 10	165	45.8	134	0.075	0.016	0.022	0.021	0.014	0.003	157	0.90	---
Pr-143	Y	5.2 E + 5	1.5 E - 9	252	70.1	205	0.1	---	---	---	---	---	32.5	0.25	---
*Nd-147	Y	2.4 E + 5	6.8 E - 8	116	32.4	94.6	0.09	0.038	0.034	0.050	0.053	0.011	12.8	0.076	---
Np-239	Y	6.4 E + 6	1.8 E - 8	3110	863	2520	0.11	1.0	1.6	1.5	0.86	0.024	49.8	0.44	0.019
Pu-238	Y	2.3 E + 2	6.5 E - 13	0.11	0.03	0.09	0.2	---	---	---	---	---	0.85	0.004	---
Pu-239	Y	8.4 E + 1	2.4 E - 13	0.04	0.01	0.03	0.2	---	---	---	---	---	0.29	0.002	---
Pu-240	Y	8.4 E + 1	2.4 E - 13	0.04	0.01	0.03	0.2	---	---	---	---	---	0.29	0.002	---
Pu-241	Y	1.4 E + 4	3.9 E - 11	6.8	1.9	5.5	0.2	---	---	---	---	---	0.093	0.012	---
Am-241	Y	6.8 E + 0	1.9 E - 14	0.003	0.0009	0.003	0.063	---	---	---	---	---	0.025	---	---
Cm-242	Y	2.0 E + 3	5.6 E - 12	0.97	0.27	0.79	0.075	---	---	---	---	---	7.8	0.049	---
Cm-244	Y	9.2 E + 1	2.6 E - 13	0.04	0.01	0.04	0.075	---	---	---	---	---	0.36	0.0018	---
			TOTALS	288, 000	80, 000	234, 000		606	570	640	690	7.8	7650	3110	0.49

*DAUGHTERS CONSIDERED

Table 7. Calculated Organ Doses Resulting from a PWR-2 Reactor Accident

The first scenario for calculating percent mortality, contains one alpha emitter (Pu-239), one beta emitter (Ru-106), and one gamma emitter (Zr-95) which are assumed to be released from a height of 25 m into a stable atmosphere having a ground wind speed of 2 m/sec (column 3, Table 6). The quantities released were 0.01, 0.7 and 2 million Curies, respectively, and were obtained by back-calculating from the selected final lung burden. The exposed population, located 1500 m downwind from the release point, was exposed for 30 minutes to concentrations of 0.35 nCi/ml of ^{239}Pu, 25.0 nCi/m of ^{106}Ru and 71.0 nCi/ml of ^{95}Zr. The airborne concentrations, lung burdens, external doses, 30-day internal-emitter lung doses and 30-day cross-organ doses were calculated according to the methodologies of Section III, using the assumptions listed in column 2, Table 6. The external whole-body dose received by the subjects during the half-hour exposure to the radioactive cloud was 21 rad from ^{95}Zr plus 2 rad from ^{106}Ru. There is no external dose contribution from ^{239}Pu. The bone-marrow dose from external radiation was 24 rad; the 30-day lung doses from the inhaled material were 430 rad from alpha radiation and 8900 rad from beta-gamma radiation.

The percent mortality in the exposed population within the first year was calculated by applying the empirical dose-response model described in Section IV to these doses. No deaths are predicted from a bone marrow dose of only 42 rad, while 74% mortality is predicted from a 30-day lung dose of 430 rad alpha, and 68% mortality would be predicted from a 30-day lung dose of 8900 rad beta-gamma radiation. The combined percent mortality of a population exposed simultaneously to these doses

is calculated using the equation described in Part A of this section. The combined percent mortality within the first year from exposure to this scenario is calculated to be 93%.

The second scenario for calculation of percent mortality is a WASH-1400 PWR-2 accident. The radionuclides released to the environment at a height of 25 m, 2.5 hours after the accident are listed in Table 7, column 1. The solubility class for each radionuclide is given in column 2, and the total activity released to the atmosphere over a half-hour period is given in column 3. These data, along with the assumptions listed in column 2 of Table 6, were used to calculate the airborne concentration of each of the released radionuclides at the receptor, 500 m downwind (column 4, Table 7). The activity deposited in the lungs and bone during a 30-minute exposure to the center line of the radioactive cloud is given in columns 5, 6, 7, and 8 of Table 7. The rad dose from external radiation during this exposure was calculated for total body as well as for lungs only, red bone marrow only and total bone, for each of the radionuclides (column 9, 10, 11, and 12 of Table 6). The lungs received a total of 570 rad, and the red bone marrow received 640 rad during the 30-minute exposure to external radiation. The 30-day internal-emitter dose to lung and bone, and the bone cross-organ dose, are listed in columns 14, 15, and 16, of Table 7 for each of the radionuclides initially deposited in the lungs. The 30-day internal-emitter dose to lung was 10 rad alpha and 7600 rad beta-gamma. The 30-day internal emitter dose to homogeneous bone was 300 rad (column 4, Table 6).

The empirical dose-response model of Section IV predicts no deaths from the alpha dose in this PWR-2 accident. The percent mortality from the beta-gamma internal emitter lung dose is 58%. The percent mortality from the external dose and internal-emitter dose to bone marrow is 100%. The combined mortality, therefore, is also 100%.

Errors in estimated mortality for these two scenarios are discussed in the following section.

B. Estimate of Error

Mortality predictions are dependent upon a number of factors, each having a range of values with a degree of uncertainty. The uncertainty in the dose-response models for lung and bone marrow has been subjectively determined to cause a range of $\pm$100% in mortality predictions for bone marrow irradiation and $\pm$50% for lung irradiation. A range of approximately $\pm$20% of uncertainty has been cited for the $LD_{50/60}$ value for supportive treatment after whole body irradiation.[24] Although a 20% variation in LD_{50} for whole body irradiation does not quite equate to a factor of 2 error in mortality prediction (approximate error range is +60%, -70%) we considered the possibility that the $LD_{50/60}$ value is high under combined internal and external exposure modalities.

For the 30-day lung doses in Table 6, a reasonable upper limit on uncertainty of mortality prediction is $\pm$50%. However, this error increases as lung dose decreases (say at < $LD_{35/365}$ values), and decreases with lung doses above $LD_{35/365}$ values.

The dose-calculation model also has a degree of uncertainty, which may be large or small, depending upon the scenario and the population being exposed. To simplify the treatment of errors in dose calculation we have arbitrarily excluded all but adult populations, and assumed negligible errors in the physical parameters used in the dose-calculation model. We have also assumed that radionuclide concentrations to which a subject is exposed are accurately known. Known errors in the source term should be included.

Errors in dose calculation arise from inaccurately known organ burdens, breathing patterns, radionuclide solubility and particle size classification. These errors in dose are estimated below.

1. Particle Size Variation. Doses from three radionuclides, ^{90}Y, ^{91}Y and ^{239}Pu, were calculated to determine variation in 30-day dose to lung and bone from the nominally selected 1-μm particle size. Although both large and small particles may be carriers of radioactivity, we assumed that the bulk of the activity is found associated with particles ranging in size from 0.5 to 2.0 μm. For our purposes, very large particles are assumed to be removed by settling. Particle sizes will be appreciably reduced below 0.5 μm only at distances several hundred miles downwind of the exposure site. The influence on lung dose for this range is -26% to +31% for each isotope; the influence on bone dose is -38% to +52% for all three isotopes; or, excluding ^{239}Pu, -3% to +12%. We have arbitrarily selected -26% to +31% as the influence on both lung and bone dose.

2. Breathing Rate Variation. A breathing rate of 333 cm^3/sec (the value for Reference Man[25] for "light activity", and for nonoccupational activity) is usually employed for calculating dose. A rate of 500 cm^3/sec, that for heavy work, may be more appropriate to accident scenarios (fast escape from an area of contamination). Such a rate increases both lung and bone marrow dose by 50%.

3. Organ Weight Variation. Adult male and female reference lung weights are 1000 g and 800 g, respectively. These conservative values have been reduced approximately 10% from the mean lung weights tabulated in ICRP publication 23.[25] The range of weight variation in nearly bloodless lungs, also given in ICRP publication 23, is -14% to +26%. We have selected a value of $\pm$25% to represent the range of uncertainty in lung weight. This is a frequent uncertainty observed in the animal experiments. According to ICRP publication 23, the weight variation for total bone marrow may be as high as $\pm$50%, the range we have also adopted for red marrow.

4. Radionuclide Solubility Classification. Ideally, each radionuclide should have a known retention function for each organ of interest. Until such data are available, we must use the broad solubility classes. However, caution must be exercised in assigning even the broad solubility classes (D, W or Y). Misjudging the class to which an isotope is assigned might result in as much as 1700% dose variation such as found in the 30-day dose for ^{91}Y if class W were chosen rather than

class D. We subjectively assume that errors resulting from selection of D, W or Y classifications (rather than actual retention functions) range between -30% and +30%, on the average. For ^{239}Pu, for instance, a change from 500 days to 250 days in the effective half-life in the lung produces only a 2% change in dose. We recognize that the ±30% range is a subjective estimate, however, the impact on mortality of mixtures of radionuclides, such as from the exampled PWR-2 accident, may not be much different from ±30%. Radionuclides of short effective half-life are the problem and extreme caution needs to be exercised when they are included in the scenario.

5. In summary, variations used in calculating organ dose are:

Parameter	Lung	Bone Marrow
Particle size	-26 to +31%	-26 to +31%
Breathing rate	0 to +50%	0 to +50%
Organ weight	±25%	±50%
Solubility	±30%	±30%

The overall error in percent mortality is a function of the combined errors in calculation of dose and in biological variation. Although not rigorously the case, it is assumed that the individual errors are independent or uncorrelated. Under these conditions, it is possible to estimate the variance in percent mortality by summing the variances of each factor altering the mortality prediction:

$$\text{var (\% mortality)} = \text{var } (x_1) + \text{var}(x_2) + \text{---} ,$$

where $$\text{var } (x_i) \simeq \frac{(\text{range } x_i)^2}{2}.$$

The standard deviation on percent mortality, then, is

$$S = \sqrt{\text{var(\% mortality)}},$$

calculated as follows:

$$S \text{ (Bone Marrow)} = [1/2(57^2 + 50^2 + 100^2 + 60^2 + 200^2)]^{1/2} = 170\%$$

a factor of 2.7, and

$$S \text{ (Lung)} = [1/2(57^2 + 50^2 + 50^2 + 60^2 + 100^2)]^{1/2} = 100\%$$

a factor of 2.0.

The total error in mortality prediction must eventually include the errors in the source term and those resulting from extending the mortality predictions to nonadult populations. Not included in this treatment are the errors inherent in extrapolating animal data to man. The bone dose-response model is comprised of both human and animal data, the bulk of it coming from human data. The lung dose-response model contains elements of both, but the bulk of the data is from animals. As stated earlier in this section, "the consequences to man are more or less predicated on his response being identical to that of the animals whose dose-response data were used in developing the percent mortality

per unit of radiation exposure." The word "more" should be emphasized regarding the lung model. It should be noted, however, that when 30-day doses are plotted vs. survival time, and mortality predictions are derived from these data, curves were of similar slope for all species.

VI. COMPARISON TO OTHER MODELS

As noted in Section I, a number of models exist that relate radiation dose to human mortality. Of the four models mentioned (WASH 1400[1], Wells[2], SAI[3], and Raabe-Goldman[4]), only the SAI model can predict percent mortality resulting from exposure to an arbitrary mixture of radionuclides. Thus, strictly speaking, only the SAI model is comparable to the model presented in this report. However, certain elements of Scenario 1, presented in Section V, allow comparison.

The WASH 1400 model was designed exclusively for use with beta-emitters. The probability of death within 365 days is taken to be a power function of lung dose to 365 days. A curve representing the model is given in Figure VI 9-3 of the Reactor Safety Study[1]. The equation for the curve is

$$P = 2.07 \times 10^{-11} D^{2.421},$$

where P is the probability of death within 365 days, and D is the lung dose in rad.

Wells[2] related probable results of inhalation exposure to insoluable radionuclides to two parameters: $T_{1/2}$, the effective long term half-life in days; and IDR, the initial dose rate in rem/min. Possible responses were divided into three categories: long-term survival (no early mortality), early mortality (no long-term survival), and uncertain prognosis. These categories are defined as:

(1) $IDR \leq 2.0\ T_{1/2}^{-0.690}$, long-term survival is probable;

(2) $IDR \geq 8.1\ T_{1/2}^{-0.625}$, early mortality is probable;

(3) $2.0\ T_{1/2}^{-0.690} < IDR < 8.1\ T_{1/2}^{-0.625}$, prognosis uncertain.

Scientists at Science Applications Incorporated (SAI) have proposed a model for the probability of early death based on the 365-day dose, D,(rem), and a "characteristic irradiation time," m, defined as m = D/IDR, where IDR is the initial dose rate in rem/min. The model is basically a power function, relating, P, the probability of death within 1 year, to the dose, D. However, the exact form of the equation depends on m:

$$P = \begin{cases} 5.1 \times 10^{-9}\ D^{2.421}, & m \leq 20 \\ 5.4 \times 10^{-8}\ m^{-0.787}\ D^{2.421}, & 20 < m < 2 \times 10^{5} \\ 24.6\ (D/m)^{2.421}, & m \geq 2 \times 10^{5}. \end{cases}$$

Raabe and Goldman[4] proposed a model for early mortality based on the total killing dose, K. The total killing dose is said to follow a log normal distribution with a median, $\overline{K}$, and geometric standard deviation, τ_g, that are characteristic of a given radionuclide. Moreover, K is said to be independent of dose rate and survival time. A prediction

of percent mortality at some time, t, can be obtained by computing the cumulative dose to time t from a radionuclide; then using the $\bar{K}$ and τ_g for that radionuclide to compute probability of death. Estimated values of $\bar{K}$ and τ_g for $^{239}PuO_2$ are given by Raabe and Goldman as 4300 and 1.35 rad, respectively.

This example, Scenario 1, uses a release of ^{95}Zr, ^{106}Ru and ^{239}Pu. Numbers pertinent to the comparison calculations are given below:

	^{95}Zr	^{106}Ru	^{239}Pu
IDR (rad/min)	0.17	0.15	0.014
365-day dose (rad)	14,200	32,000	4080

For the models based on rem, the ^{239}Pu dose and dose rate were converted using an RBE of 10. Wells[1] model requires the use of $T_{1/2}$, the "long-term effective half-time." For the purposes of this comparison, $T_{1/2}$ was taken as the solution of

$$D = \frac{IDR \cdot T_{1/2}}{0.693}\left(1 - \exp\left(-\frac{.693(365)}{T_{1/2}}\right)\right)$$

Predicted mortalities from each model are given in Table 8.

Some of the differences in the table can be explained by differences in dose calculation methodologies. However, real differences are also present. The difference in percent mortality for the alpha- and beta-gamma-emitters in the SAI model is note worthy since the dose accumulation patterns are not greatly different. The 365-day doses (in

rem) are comparable (4.08×10^4 and 4.62×10^4, respectively) and the characteristic irradiation times differ by only a factor of 2 (2.94×10^5 and 1.45×10^5, respectively). The characteristic irradiation time may be weighted too heavily in this case.

TABLE 8. Comparison of Percent Mortality Within 365 Days, Predicted by Various Models from Example Scenario 1 (Section V)

Model	Alpha-emitters	Beta-gamma-emitters	Combined
PNL	74	68	93
WASH-1400	100	100	100
SAI	21	92	100
Raabe-Goldman	49	--	--
Wells	?*	?	?

* "?" indicates that values fell into the "region of uncertainty"

VII. FUTURE RESEARCH

During Phase I research, the need for additional animal data in various areas were identified and discussed among scientists from ITRI and PNL. The objectives of proposed Phase II animal research (Table 9) are twofold: (1) to test the respective merits of the dose/acute-mortality models designed by ITRI and PNL, and (2) to provide additional data (including morbidity) for expanding the models and refining the mortality estimates.

TABLE 9. Objectives of Proposed Phase II Animal Experiments

1. Characterization of acute (early) responses of selected species to inhaled single radionuclides.
2. Determination of methods for summing effects of inhaled beta-emitting radionuclides and of whole-body photon irradiation from external sources.
3. Determination of methods for summing effects of inhaled alpha-emitting radionuclides and of whole-body photon irradiation from external sources.
4. Determination of methods for summing effects of inhaled mixtures of alpha- and beta-emitting radionuclides.
5. Determination of methods for summing the effects of inhaled insoluble and soluble radionuclides.
6. Characterization of dose-rate effects from inhaled radionuclides.
7. Characterization of effect from spatial distribution of inhaled alpha-emitters in the lung.

The question of species differences in response to radiation is important for two reasons. First, the dose-response modes in this

report are based primarily on animal data (mostly from rats and dogs), although they are intended for extrapolation to human populations. Secondly, it must be established that the rat is a suitable representative of the mammalian species; Phase II experiments proposed by ITRI and PNL utilize the rat because of the large numbers of animals desired. Expense precludes the use of comparable numbers of a larger species (such as the dog), unless the necessity can be proven for purposes of extrapolation.

Species comparisons between rat and dog are incorporated into proposed ITRI and PNL experiments with both beta-emitting and alpha-emitting radionuclides. Inhalation exposure of rats to the same physiochemical forms of radionuclides previously administered to dogs will provide the basis for comparison of pulmonary responses.

The Phase II experiments with rats have been designed to provide data necessary for examining combined external and internal radiation hazards. Experiments planned by ITRI include exposure to combinations of inhaled insoluble beta emitters and external gamma radiation. Experiments planned at PNL include exposure to inhaled insoluble alpha emitters and external gamma radiation. Experimental designs are identical to allow data intercomparison and testing of the dose-response models from both laboratories. The bone-marrow dose-response model described in this report (Section IV-B) applies to acute doses of whole-body photon irradiation as well as to doses from internal bone-seeking radionuclides. An uncertainty exists, however, in the mortality predictions from that model and from the pulmonary injury model (Section IV-A),

when different exposure modalities are combined. No animal data are currently available which would totally validate the method used in this report or provide direction in development of another method.

Additional experimental data are urgently needed to model exposure to radionuclide mixtures containing alpha emitters and beta emitters. In the lung dose-response model, the probability of acute mortality from alpha emitters and the probability from beta emitters are essentially added together. Although statistically sound, there is no basis in biological data for such adding of effects. A Phase II experiment has been designed at PNL to test the additivity of effects. Rats will be exposed to an aerosol of a relatively insoluble alpha-emitting radionuclide, followed by exposure to an insoluble form of a beta-emitting radionuclide. The results of this preliminary experiment are expected to indicate whether or not a need exists for more extensive experiments with radionuclide mixtures. Such experimental mixtures might include numerous combinations of fresh or aged fission products in soluble or insoluble forms, with or without external photon whole-body irradiation.

The bone-marrow dose/acute-mortality model (Section IV-B) allows inclusion of damage to hematopoietic tissue caused by bone-seeking radionuclides. Relatively little is known, however, about multiple organ effects (such as the effect of radiation-induced bone marrow injury) on the development of radiation pneumonitis caused by an inhaled radionuclide. An experiment to demonstrate this effect could include inhalation of a relatively insoluble radionuclide simultaneously with a soluble bone-seeking radionuclide. Such an experiment, using ^{90}Sr in

rats, has been proposed by ITRI scientists. Resultant data would be valuable for refinement of both the ITRI and PNL acute-mortality models.

An experiment to characterize the dose-rate effect from inhaled radioactivity has also been designed by ITRI. Rats would be exposed to $^{90}Y/^{90}Sr$ - ^{90}Y (FAP) in mixtures containing the nuclides combined in various ratios. The rate at which the dose to lung is delivered would thus be controlled by the ratio of $^{90}Y(T_{1/2} = 64h)$ and $^{90}Sr(T_{1/2} = 28y)$ as $T_{1/2}$ in the mixture. Although the PNL lung dose-response model does not appear to be affected by dose rate, data obtained from this experiment would be useful for model testing.

The ITRI lung dose-response model appears to display a difference in exposure effects from ^{239}Pu and ^{238}Pu which is considered due to the spatial difference in distribution of dose between the two nuclides. An experiment is planned to examine this effect in rats' lungs by varying the specific activity of aerosol particles and the number of particles inhaled by each animal. Again, data from such an experiment would be useful in testing the PNL model.

We propose to remedy the present lack of specific information on acute morbidity induced by radiation from internal emitters by periodically making hematologic measurements and observing weight changes in experimental animals. We also plan (at PNL) to perform pulmonary function testing, therefore we hope to include a small number of dogs (along with the rats) in selected experiments to allow better extrapolation of pulmonary function test results to man.

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APPENDIX 1

Cross-Organ Dose Calculation

$$D_X = S(X \leftarrow Y) * DC_Y,$$

where D_X = cross-organ dose to organ X (rem),

$S(X \leftarrow Y)$ = S-factor

$$= 51.15 \; \Sigma f_i E_i \; \Phi_i \; (X \leftarrow Y) \; Q_i \; (X) \; N_i \; (X) \text{ rem}/\mu\text{Ci}\cdot\text{day}.$$

where

51.15 = (g·rad/MeV) (disintegrations/μCi-day)

f_i = intensity of decay event (number per disintegration)

E_i = average energy of decay event (MeV)

$\Phi_i(X \leftarrow Y)$ = specific absorbed fraction

= fraction of emitted energy from source organ Y absorbed in target organ X per gram of X(g-1)

$Q_i(X)$ = quality factor for decay type i

$N_i(X)$ = modifying factor for decay type i in the target organ X

DC_Y = dose commitment to organ Y (μCi-day).

$\Phi_i(X \leftarrow Y)$ are given for the following photon energies (all MeV): 0.010, 0.015, 0.020, 0.030, 0.050, 0.100, 0.200, 0.500, 1.000, 1.500, 2.000, 4.000 for various source-target combinations. Specific absorbed fractions for photons with energies not listed above were determined using the following interpolation routine:[1]

given table energies E_i and E_3 ($E_3 > E_1$) with associated specific absorbed fractions of S_1 and S_3, respectively, S_2 associated with photon energy E_2, such that $E_1 < E_2 < E_3$, is:

$$S_2 = S_1 + \frac{(S_3 - S_1)}{(E_3 - E_1)} (E_2 - E_1) .$$

Dose Commitment to Organ Y (DC_Y)

$$DC_Y = \int_o^T A_o e^{-\lambda t}$$

$$= \frac{A_o}{\lambda} (1 - e^{-\lambda T})$$

where A_o = initial deposition (μCi)

$\lambda = \frac{0.693}{T1/2\ eff}$ for the specific radionuclide in organ Y (d^{-1})

T = cutoff point of dose commitment calculation (d).

Assumptions

(1) Because gamma-emitters contribute to cross-organ dose $Q_i(X)$, $N_i(X) = 1$.

(2) Only Cs^{134}, Nb^{95}, Zr gamma emissions contribute appreciably (>5%) to the total dose from inhalation.[2]

(3) Lung is only significant source organ.

(4) Liver, bone (red marrow) are only significant target organs for early effects.

(5) In dose commitment determination, exposure evaluation is terminated at the end of one year (365 d).

Sample Calculation for S-Factor

Source Organ - Lung

Target Organ - Liver

Radionuclide - ^{134}Cs

E_i(MeV)	F_i	Q_i (rem/rad)	N_i	$\Phi_i(X \leftarrow Y)(g^{-1})$
0.011	0.0095	1	1	2.1E-7
0.127	0.013	1	1	9.4E-6
0.475	0.015	1	1	8.2E-6
0.563	0.084	1	1	8.1E-6
0.569	0.15	1	1	8.1E-6
0.604	0.98	1	1	8.1E-6
0.795	0.85	1	1	7.5E-6
0.802	0.09	1	1	1E-6
1.038	0.01	1	1	1E-6
1.167	0.02	1	1	1E-6
1.365	0.03	1	1	1E-6

For E_i = 0.475 MeV,

$$\Phi_i(X \leftarrow Y) = S_1 - \frac{(S_3-S_1)(E_2-E_1)}{E_3-E_1},$$

where $S_1 = 8.81E\text{-}6$, $E_1 = 0.200$ MeV,

$S_3 = 8.18E\text{-}6$, $E_3 = 0.500$ MeV,

$E_2 = 0.475$ MeV,

$$\Phi_i(X \leftarrow Y) = 8.81E\text{-}6 - \frac{(8.81E\text{-}6) - 8.18E\text{-}6)\ (0.485 - 0.200)}{(0.500 - 0.200)},$$

$$= 8.2E\text{-}6\ g^{-1}.$$

$$S_{^{134}Cs}(\text{liver} \leftarrow \text{lung}) = 51.15\ \Sigma\ f_i\ E_i\ \Phi_i(\text{liver} \leftarrow \text{lung}) Q_i\ N_i$$

$$= 51.15\ [0.0095(0.011)2.1E\text{-}7 + 0.013(0.0127)\ 9.4E\text{-}6$$
$$+ 0.015\ (0.475)\ 8.2E\text{-}6 + 0.084\ (0.563)\ 8.1E\text{-}6$$
$$+ 0.15\ (0.569)\ 8.1E\text{-}6 + 0.98\ (0.604)\ 8.1E\text{-}6$$
$$+ 0.85\ (0.795)\ 7.5E\text{-}6 + 0.09\ (0.802)\ 1E\text{-}6$$
$$+ 0.01\ (1.038)\ 1E\text{-}6 + 0.02\ (1.167)\ 1E\text{-}6$$
$$+ 0.03\ (1.365)\ 1E\text{-}6)]$$
$$= 5.5E\text{-}4\ \text{rem}/\mu\text{Ci}\cdot\text{day}\ .$$

This calculation is shown to demonstrate the S-factor equation. S-factors are also available in tabular form[1]. The linked S-factor value for ^{134}Cs (liver←lung) is 6.3E-4 rem/μCi·day. In subsequent calculations we use the S-factor values listed in the tables.

Cross-organ doses were calculated using ^{134}Cs, ^{95}Nb and ^{95}Zr as the nuclides of interest, lung as source organ, and liver and bone (red marrow) as target organs. Resulting cross-organ doses were compared to the doses to the target organs from inhalation to determine the importance of cross-organ dose contributions to the total dose to the target organ. Inhalation doses were obtained from the computer program DACRIN,[3] which uses the TGLM.[4] All doses were normalized relative to a 1μCi initial intake.

Sample Dose Commitment Calculation

Given ^{134}Cs, lung, T 1/2 eff = 0.5 d, 1 μCi initial activity for 1 year,

$$DC_Y = \frac{A_o}{\lambda}(1 - e^{-\lambda T})$$

$$DC_{lung} = 1\ \mu Ci\left[e^{\frac{-0.693(365)}{0.5}}{\frac{-0.693}{0.5}} - e^{\frac{-0.693(0)}{0.5}}{\frac{-0.693}{0.5}}\right]$$

$$= 0.72\ \mu Ci \cdot day.$$

A comparison of cross-organ dose and inhalation dose for selected radionuclides and organs is shown in Table A-1. It is apparent that for D-class material,[5] the cross-organ component is negligible. However, in the case of a W- or Y-class material, the cross-organ contribution is significant. In order that the computer code developed may be as flexible as possible in assessing dose from a variety of possible

accident scenarios, a routine to calculate cross-organ doses is incorporated into the computer model.

Calculations were also made to (according to Table A-1) to determine whether cross-organ dose is significant if lung is the target organ and liver or bone is the source organ. The results are displayed in Table A-2.

Predictably, as the solubility of the radionuclide progresses from D class (half-times on the order of days) to W-class (half-times on the order of weeks) to Y-class (half-times on the order of years), cross-organ dose becomes less significant if lung is the target organ and more significant if liver or bone is the target organ. These findings are reflected in the portion of the computer code charged with determination of the cross-organ dose.

Thirty-day dose calculations yielded results (in terms of cross-organ dose contribution to the total organ dose) similar to one-year dose calculations.

TABLE A-1. Inhalation and Cross-Organ Dose with Lung as the Source Organ; 1-Year Dose Accumulation.

Nuclide	Solubility Class	Target Organ	Cross-Organ Dose (rad)	Inhalation Dose (rad)	Total Dose (rad)	% of Total by Cross-Organ
^{134}Cs	D	Liver	2.4E-4	7.59E-2	761E-2	0.3
	W	Liver	2.4E-2	7.37E-2	9.77E-2	24.6
	D	Bone	3.6E-4	2.6E-2	2.6E-2	1.4
	W	Bone	3.6E-2	2.5E-2	6.1E-2	59.0
^{95}Zr	D	Liver	2.15E-4	3.96E-2	3.98E-2	0.5
	W	Liver	2.15E-2	8.07E-3	2.96E-2	72.9
	D	Bone	8.9E-5	1.13E-1	1.13E-1	0.1
	W	Bone	8.9E-3	2.31E-2	3.2E-2	27.8
^{95}N	D	Liver	2.23E-4	1.45E-2	1.47E-2	1.51
	W	Liver	2.23E-2	2.75E-3	2.51E-2	89.0
	Y	Liver	2.23E-1	1.47E-4	2.23E-1	99.9
	D	Bone	9.3E-5	2.26E-2	2.27E-2	0.4
	W	Bone	9.3E-3	7.27E-3	1.66E-2	56.1
	Y	Bone	9.3E-2	2.29E-4	9.3E-2	99.8

TABLE A-2. Inhalation and Cross-Organ Dose with Lung as Target Organ; 1-Year Dose Accumulation

Nuclide	Solubility Class	Source Organ	Cross-Organ Dose (rad)	Inhalation Dose (rad)	Total Dose (rad)	% of Total Contributed by Cross-Organ
^{134}Cs	D	Liver	3.6E-3	1.29E-2	1.7E-2	21.8
	W	Liver	3.6E-3	2.88E-1	2.9E-1	1.2
	D	Bone	1.25E-3	1.29E-2	1.41E-2	8.8
	W	Bone	1.25E-3	2.88E-1	2.89E-1	0.4
^{95}Sr	D	Liver	6.5E-4	2.8E-3	3.5E-3	18.8
	W	Liver	6.5E-4	1.4E-1	1.4E-1	0.5
	D	Bone	9.84E-4	2.8E-3	3.8E-3	26.0
	W	Bone	9.84E-4	1.4E-1	1.4E-1	0.7
^{95}Nb	D	Liver	3.1E-4	2.2E-3	2.5E-3	12.4
	W	Liver	3.1E-4	5.7E-2	5.7E-2	0.5
	Y	Liver	3.1E-4	9.0E-2	9E-2	0.3
	D	Bone	6.36E-4	2.2E-3	2.8E-3	22.4
	W	Bone	6.36E-4	5.7E-2	5.8E-2	1.1
	Y	Bone	6.36E-4	9.0E-2	9.1E-2	0.7

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APPENDIX 2

Dose Calculation for Radionuclide Release Scenarios

The following dose calculations were performed for inclusion in Section V of this report. Table A-3 lists those radionuclides from WASH-1400 which contribute 5% or more to internal dose. This list was used initially to test and evaluate the dose calculation methods. As reported in Section V, two source terms were utilized in testing the dose-response model. For the first source term, ^{95}Zr, ^{106}Ru and ^{239}Pu were chosen from the list in Table A-3 to represent both beta-gamma-and alpha-emitters. This source term was designed to test the probability model and does not reflect a realistic scenario. The second source term listed in Table A-4 from a PWR-2 release, considers all the radionuclides listed in WASH-1400. For both scenarios evaluated, the atmospheric conditions were very stable (Pasquill Class F), with a wind speed of 2 m/s. The release height, particle size, and breathing rate were 25m, 1.0μm and 333 cm^3/s, respectively. A 30 minute uptake time was assumed in both cases. Downwind distance to the receptor was 1500 m for the first scenario and 500 m for the PWR-2 scenario. In addition a 2.5 hr delay between initiation of the PWR-2 "accident" and release of activity to the environment is assumed; no such delay is included in the first scenario. The 2 scenarios are examined in greater detail in Table 6, Section V. External and internal doses were computed for both scenarios per Section III.

External Dose

The photon dose rate to the lung resulting from immersion in contaminated air was evaluated using the method contained in the ORNL EXREM-III[1] computer code. Photon depth dose-rate factors[2] (rad/yr per μCi/ml) were obtained, and a 1-μCi/ml concentration of radionuclide in air was assumed. For example, the photon depth dose-rate for ^{91}Y to the lung is 1.88 E+4 rad/yr per μCi/ml. Assuming a concentration of 1 μCi/ml of ^{91}Y, the resulting lung dose rate is

$$1.88E+4 \frac{\text{rad . ml}}{\text{yr . } \mu\text{Ci}} \times 1 \frac{\mu\text{Ci}}{\text{ml}} \times \frac{1 \text{ yr}}{8760 \text{ hr}} = 2.14 \text{ rad/hr.}$$

Whole-body and lung dose-rates for the other radionuclides evaluated are contained in Table A-3.

TABLE A-3. Lung and Whole-Body Doses from Radionuclides from WASH-1400 Which Contribute 5% or More to Internal Lung Dose

Radionuclide	Inhalation Dose, Lungs (rad)	Cross-Organ Dose, Lungs (rad)	EXTERNAL PHOTON DOSE RATE Whole-Body (rad/hr per μCi/ml)	Lung (rad/hr per μCi/ml)
Sr-89 (W)				
30 day	8.45E-2	----	----	----
60 day	1.20E-1	----	----	----
365 day	1.47E-1	----	----	----
Y-91 (Y)				
30 day	1.09E-1	2.82E-6	2.45E+0	2.14E+0
60 day	1.80E-1	4.79E-6	2.45E+0	2.14E+0
365 day	3.24E-1	9.24E-6	2.45E+0	2.14E+0
*Zr-95 (Y)				
30 day	1.05E-1	5.55E-4	7.36E+2	5.49E+2
60 day	1.76E-1	1.09E-3	7.36E+2	5.49E+2
365 day	3.34E-1	2.86E-3	7.36E+0	5.49E+2
*Ru-106 (Y)				
30 day	2.97E-1	1.09E-5	----	----
60 day	5.58E-1	1.37E-5	----	----
365 day	2.15E+0	1.46E-5	----	----
Cs-134 (D)				
30 day	6.36E-3	1.08E-3	1.58E+3	1.19E+3
60 day	7.58E-3	1.96E-3	1.58E+3	1.19E+3
365 day	1.29E-2	4.80E-3	1.58E+3	1.19E+3
*Ba-140 (W)				
30 day	1.38E-1	1.09E-3	1.97E+2	1.48E+2
60 day	1.55E-1	1.27E-3	1.97E+2	1.48E+2
365 day	3.34E-1	2.86E-3	7.36E+2	5.49E+2
*Ce-144 (Y)				
30 day	2.74E-1	5.03E-5	1.96E+1	1.23E+1
60 day	3.10E-1	9.48E-5	1.96E+1	1.23E+1
365 day	1.85E+0	3.41E-4	1.96E+1	1.23E+1

* Daughters included in inhalation and cross-organ doses

TABLE A-3. Lung and Whole-Body Doses from Radionuclides from WASH-1400 Which Contribute 5% or More to Internal Lung Dose (Continued)

Radionuclide	Inhalation Dose, Lungs (rad)	Cross-Organ Dose, Lungs (rad)	EXTERNAL PHOTON DOSE RATE Whole-Body (rad/hr per μCi/ml)	Lung (rad/hr per μCi/ml)
Pu-239 (Y)				
30 day	2.03E+0	----	5.9E-1	2.0E-2
60 day	3.91E+0	----	5.9E-1	2.0E-2
365 day	1.92E+1	----	5.9E-1	2.0E-2
Cm-242 (Y)				
30 day	2.31E+0	----	1.48E+0	3.0E-2
60 day	4.19E+0	----	1.48E+0	3.0E-2
365 day	1.26E+1	----	1.48E+0	3.0E-2

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APPENDIX 3

Mortality Functions, Hazard Functions and Competing Risks

Much of this project is concerned with the analysis of survival times; in particular, with the impact on survival time of certain biological hazards. This section is a brief explanation of concepts, methodology and terminology that are useful in the analysis.

The survival time, T, of a subject drawn from some population is a random variable. The cumulative mortality function for the population is defined as $F(t) = \text{Prob}\{T \leq t\}$. The mortality function gives the fraction of the population that is expected to die at or before age t. The survivor function or the fraction surviving beyond age t is

$$S(t) = \text{Prob}\{T > t\} = 1 - F(t).$$

Another important function is $\lambda(t)$, the age-specific mortality rate, which is also called the hazard function. For a small interval, dt,

$$\lambda(t)dt = \text{Prob}\{t < T \leq t+dt \mid t < T\},$$

which is the conditional probability of death in the time interval t to t+dt, given survival up to time t. The functions S(t) and $\lambda(t)$ are related by

$$S(t) = \exp\left(-\int_0^t \lambda(s)ds\right).$$

The concept of competing risks is often applied to the analysis of survival data. Suppose each member of a population is subject to a risk of death from several sources, and let T_i be the survival time if death is due to the i^{th} risk, say for $i = 1,2,\ldots,N$. Let $S_i(t)$ and $\lambda_i(t)$ be the survivor and hazard functions, respectively, associated with T_i. The actual survival time, T, is the shortest survival time of any risk, so that

$$T = \min(T_1, T_2, \ldots, T_N).$$

The survivor function of T can be obtained by applying the "Law of Compound Probabilities." For the case N = 2, this is

$$\text{Prob}\{T > t\} = \text{Prob}\{T_1 > t\}\ \text{Prob}\{T_2 > t | T_1 > t\},$$

where $\text{Prob}\{T_2 > t|T_1 > t\}$ is the conditional probability that T_2 is greater than t, given that T_1 is greater than t.

If the risks are additive and noninteracting (or equivalently, the survival times are stochastically independent), then

$$\text{Prob}\{T_2 < t|T_1 > t\} = \text{Prob}\{T_2 > t\}.$$

In this case, it follows that

$$S(t) = \prod_{i=1}^{N} S_i(t)$$

and

$$\lambda(t) = \sum_{i=1}^{N} \lambda_i(t).$$

APPENDIX 4

Data Basis for Dose/Acute-Mortality Model

The data used to develop the lung dose/mortality model was compiled from the annual reports of ITRI, annual reports and published documents originating at PNL, and data collected at the Institut de Protection et Sûrete´ Nucléaire.

Data on Beagle dogs exposed to ^{90}Y, ^{91}Y, ^{90}Sr or ^{144}Ce in fused-clay particles were taken from the ITRI annual report for 1977. The published data for each radionuclide included the initial dose rate and the dose to death. In some cases, intermediate values of dose and dose rate were also published. The method ITRI use to calculate dose has not been published. Therefore, intermediate doses were computed by assuming a single exponential clearance function using clearance parameters determined by the initial dose rate and the dose to death. This leads to some differences between the calculated intermediate doses and the published doses. In general, the differences are within the limit of round-off error.

The data on beagle dogs and baboons exposed to $^{239}PuO_2$ were taken from Bair, Metivier, and Park (1978)[2]. Their paper assumes a single exponential clearance model, with clearance half-time obtained by using

$$T_{1/2} = \frac{0.693}{\ell n(A/B)/t} \quad ,$$

where A = estimated initial pulmonary burden,
B = final lung burden,
t = days survival postexposure.

All parameters necessary to calculate dose to an arbitrary time are furnished in the paper. The above methodology and parametric values were used to calculate doses used in this report. Some of the baboons for which data was reported were immature at the time of exposure; some had all the plutonium deposited in a single lobe of the lung. These animals were dropped from the data set.

The data on rats exposed to einsteinium are unpublished data furnished by J. Ballou[3], PNL. Doses were computed using a two-compartment exponential clearance function with half-times of 1 and 10 days and fractions of 0.65 and 0.35, respectively. The dose calculations were based on an assumed lung weight of 2.5 grams for all rats.

The data on rats exposed to $^{238}PuO_2$ and $^{239}PuO_2$ and dogs exposed to $^{238}PuO_2$ were taken from PNL reports[4,5]. Initial pulmonary deposition and dose to death were given, although little information was available on clearance curves for these animals. Intermediate doses were calculated assuming that the dose rate was constant. Since the oxide is relatively insoluble, and the isotopes have long physical half-lives, the assumption is probably adequate for relatively short time spans.

Because the primary interest of this study is in early effects, data on animals that received "low" doses were not included. A preliminary examination of the ITRI data indicated that no animal with a 60-day dose from beta emitters less than about 3500 rad died from pulmonary injury. Accordingly, animals with a 60-day beta dose less than 3000 rad were omitted from the data set.

Early mortality from radiation exposure has not been found to be greatly dependent on species. The relationship between survival time and dose was quite similar for a rat and a dog for high doses and short survival times. However, for doses low enough that survival time approaches a significant fraction of the normal life span of a rat, the dose survival-time relationship might not be the same for a rat and a dog. The effect of species lifespan differences was adjusted for by excluding data on rats that survived more than 400 days postexposure.

1 = SURVIVAL CODE DEAD(=1) OR ALIVE(=0)
2 = TYPE OF DEATH CODE ACUTE(=1) OR NON-ACUTE(=0)
3 = EMITTER CODE BETA(=1) OR ALPHA(=0)
4 = ISOTOPE CODE
1=CEFAP
2=Y91FAP
3=Y90FAP
4=SRFAP
5=PU239OX
6=PU238OX
7=EIN243NO3
5 = SPECIES CODE
1=DOG
2=RAT
3=BABOON

Animal Dose-Response Data Used to Derive the PNL Dose/Acute Mortality Model

Table A.4.1 Alpha Emitting Nuclides

SURVIVAL TIME	INIT RATE	7.5 DOSE	15 DOSE	30 DOSE	60 DOSE	120 DOSE	240 DOSE	TOTAL DOSE	SURVIVAL CODE	ACUTE CODE	EMIT CODE	NUCLIDE CODE	SPEC CODE
4068.	0.	4.	7.	15.	29.	58.	113.	1003.	1.	0.	0.	5.	1.
3664.	1.	5.	9.	18.	36.	70.	135.	924.	1.	0.	0.	5.	1.
2050.	1.	6.	12.	25.	49.	96.	185.	978.	1.	0.	0.	5.	1.
3441.	1.	8.	15.	30.	60.	118.	229.	1687.	1.	0.	0.	5.	1.
1823.	1.	8.	16.	32.	65.	127.	247.	1312.	1.	0.	0.	5.	1.
3313.	1.	9.	18.	36.	71.	140.	269.	1578.	1.	0.	0.	5.	1.
2809.	2.	11.	23.	45.	89.	175.	338.	1981.	1.	0.	0.	5.	1.
3079.	2.	12.	23.	47.	92.	179.	341.	1697.	1.	0.	0.	5.	1.
3676.	2.	12.	25.	49.	97.	191.	367.	2250.	1.	0.	0.	5.	1.
2792.	2.	13.	25.	50.	99.	193.	368.	1913.	1.	0.	0.	5.	1.
2412.	2.	13.	26.	52.	103.	200.	380.	1716.	1.	0.	0.	5.	1.
2367.	2.	14.	29.	58.	115.	227.	444.	3060.	1.	0.	0.	5.	1.
2344.	2.	15.	30.	60.	119.	233.	446.	2217.	1.	0.	0.	5.	1.
2356.	2.	16.	31.	62.	122.	239.	460.	2455.	1.	0.	0.	5.	1.
1379.	2.	17.	33.	66.	131.	257.	495.	2048.	1.	0.	0.	5.	1.
1635.	2.	17.	33.	67.	132.	259.	498.	2234.	1.	0.	0.	5.	1.
1629.	2.	17.	34.	67.	133.	261.	507.	2495.	1.	0.	0.	5.	1.
3537.	2.	17.	34.	68.	134.	260.	493.	2350.	1.	0.	0.	5.	1.
2229.	2.	18.	36.	72.	143.	279.	533.	2606.	1.	0.	0.	5.	1.
1202.	3.	20.	39.	78.	154.	300.	571.	2002.	1.	0.	0.	5.	1.
1720.	3.	22.	44.	87.	172.	339.	656.	3256.	1.	0.	0.	5.	1.
2015.	3.	22.	45.	89.	177.	347.	669.	3449.	1.	0.	0.	5.	1.
401.	3.	23.	46.	90.	175.	330.	590.	854.	1.	1.	0.	5.	3.
2048.	3.	23.	45.	90.	178.	350.	675.	3501.	1.	0.	0.	5.	1.
2565.	3.	24.	49.	97.	190.	368.	688.	2709.	1.	0.	0.	5.	1.
1623.	3.	26.	51.	102.	202.	398.	773.	3786.	1.	0.	0.	5.	1.
1151.	4.	27.	54.	107.	212.	414.	791.	2740.	1.	0.	0.	5.	1.
343.	4.	27.	54.	107.	214.	428.	856.	1223.	1.	1.	0.	6.	2.
2211.	4.	27.	54.	107.	212.	416.	800.	4226.	1.	0.	0.	5.	1.
1549.	4.	28.	56.	111.	221.	433.	835.	3708.	1.	0.	0.	5.	1.
1446.	4.	31.	61.	122.	241.	471.	901.	3620.	1.	0.	0.	5.	1.

1184.	4.	33.	66.	131.	260.	511.	985.	3697.	1.	0.	0.	5.	1.
212.	4.	34.	67.	134.	268.	536.	1072.	947.	1.	1.	0.	6.	2.
850.	6.	41.	82.	164.	325.	636.	1222.	3556.	1.	0.	0.	5.	3.
933.	6.	44.	87.	173.	344.	677.	1312.	4287.	1.	0.	0.	5.	1.
988.	6.	45.	89.	177.	351.	688.	1322.	4298.	1.	0.	0.	5.	1.
421.	6.	46.	92.	184.	368.	736.	1472.	2582.	1.	0.	0.	6.	2.
413.	6.	48.	96.	192.	383.	766.	1532.	2636.	1.	0.	0.	6.	2.
1339.	7.	49.	97.	193.	382.	748.	1432.	5531.	1.	0.	0.	5.	1.
855.	7.	54.	107.	214.	424.	833.	1609.	4828.	1.	0.	0.	5.	1.
1357.	8.	57.	113.	225.	446.	874.	1680.	6753.	1.	0.	0.	5.	1.
185.	9.	69.	138.	276.	552.	1104.	2208.	1702.	1.	1.	0.	6.	2.
448.	10.	77.	153.	306.	607.	1197.	2327.	4138.	1.	1.	0.	5.	3.
229.	10.	78.	155.	309.	615.	1219.	2392.	2287.	1.	1.	0.	5.	3.
290.	11.	81.	161.	318.	623.	1192.	2187.	2552.	1.	1.	0.	5.	3.
243.	11.	81.	161.	320.	630.	1217.	2278.	2303.	1.	1.	0.	5.	3.
167.	11.	84.	168.	330.	638.	1198.	2119.	1588.	1.	1.	0.	5.	3.
105.	12.	88.	174.	343.	667.	1263.	2267.	1120.	1.	1.	0.	5.	1.
849.	12.	90.	178.	352.	690.	1323.	2434.	5869.	1.	0.	0.	5.	3.
252.	13.	99.	195.	376.	698.	1213.	1872.	1918.	1.	1.	0.	5.	3.
200.	13.	96.	192.	383.	766.	1532.	3064.	2553.	1.	1.	0.	5.	2.
721.	13.	99.	197.	393.	784.	1559.	3083.	8848.	1.	0.	0.	5.	3.
140.	14.	108.	217.	433.	866.	1732.	3464.	2021.	1.	1.	0.	6.	2.
250.	15.	114.	227.	448.	878.	1685.	3107.	3215.	1.	1.	0.	5.	3.
274.	16.	118.	235.	470.	940.	1880.	3760.	4293.	1.	0.	0.	5.	2.
412.	16.	119.	238.	472.	932.	1814.	3440.	5482.	1.	1.	0.	5.	1.
146.	16.	123.	244.	483.	945.	1807.	3311.	2157.	1.	1.	0.	5.	3.
180.	17.	126.	251.	496.	970.	1856.	3405.	2666.	1.	1.	0.	5.	3.
230.	18.	133.	265.	525.	1036.	2015.	3815.	3672.	1.	1.	0.	5.	1.
346.	19.	139.	277.	549.	1083.	2105.	3981.	5468.	1.	1.	0.	5.	1.
384.	19.	139.	277.	550.	1086.	2115.	4016.	6046.	1.	1.	0.	5.	1.
133.	19.	141.	281.	555.	1086.	2080.	3819.	2283.	1.	1.	0.	5.	3.
870.	19.	141.	283.	564.	1125.	2237.	4422.	15071.	1.	0.	0.	5.	3.
131.	20.	150.	296.	576.	1092.	1971.	3248.	2112.	1.	1.	0.	5.	3.
131.	20.	150.	296.	576.	1092.	1971.	3248.	2112.	1.	1.	0.	5.	3.
62.	19.	146.	291.	582.	1164.	2328.	4656.	1203.	1.	1.	0.	6.	2.
168.	20.	149.	296.	587.	1152.	2220.	4129.	3018.	1.	1.	0.	5.	1.

130.	21.	159.	316.	620.	1196.	2224.	3872.	2381.	1.	1.	0.	5.	3.
188.	21.	161.	322.	644.	1287.	2574.	5148.	4033.	1.	1.	0.	5.	2.
184.	23.	172.	343.	680.	1335.	2577.	4804.	3805.	1.	1.	0.	5.	3.
140.	24.	178.	355.	703.	1379.	2654.	4928.	3058.	1.	1.	0.	5.	1.
144.	25.	188.	375.	741.	1451.	2782.	5124.	3283.	1.	1.	0.	5.	3.
147.	27.	200.	400.	799.	1598.	3196.	6392.	3915.	1.	1.	0.	5.	2.
337.	27.	201.	402.	805.	1609.	3218.	6436.	9037.	1.	0.	0.	6.	2.
148.	27.	203.	405.	810.	1620.	3240.	6480.	3996.	1.	1.	0.	5.	2.
121.	28.	207.	411.	811.	1577.	2984.	5357.	3006.	1.	1.	0.	5.	1.
120.	28.	207.	411.	811.	1576.	2980.	5347.	2980.	1.	1.	0.	5.	1.
107.	29.	215.	428.	846.	1653.	3155.	5758.	2842.	1.	1.	0.	5.	1.
414.	28.	213.	425.	851.	1701.	3402.	6804.	11737.	1.	1.	0.	6.	2.
162.	29.	219.	437.	875.	1750.	3500.	7000.	4725.	1.	1.	0.	5.	2.
119.	30.	225.	448.	887.	1737.	3337.	6165.	3311.	1.	1.	0.	5.	3.
54.	32.	236.	462.	887.	1638.	2816.	4272.	1498.	1.	1.	0.	5.	3.
50.	35.	252.	487.	915.	1618.	2574.	3472.	1404.	1.	1.	0.	5.	3.
128.	31.	233.	466.	933.	1865.	3730.	7460.	3979.	1.	1.	0.	5.	2.
107.	32.	240.	479.	949.	1866.	3606.	6743.	3239.	1.	1.	0.	5.	3.
57.	35.	257.	508.	989.	1877.	3392.	5600.	1793.	1.	1.	0.	5.	3.
111.	33.	248.	495.	991.	1981.	3962.	7924.	3665.	1.	1.	0.	5.	2.
37.	35.	263.	519.	1014.	1932.	3518.	5890.	1236.	1.	1.	0.	5.	3.
130.	36.	264.	524.	1028.	1983.	3693.	6438.	3954.	1.	1.	0.	5.	3.
119.	36.	269.	537.	1066.	2100.	4082.	7713.	4049.	1.	1.	0.	5.	3.
132.	36.	267.	534.	1069.	2137.	4274.	8548.	4701.	1.	1.	0.	6.	2.
107.	37.	279.	559.	1117.	2234.	4468.	8936.	3984.	1.	1.	0.	5.	2.
119.	37.	280.	559.	1119.	2237.	4474.	8948.	4437.	1.	1.	0.	6.	2.
115.	38.	287.	575.	1149.	2298.	4596.	9192.	4405.	1.	1.	0.	6.	2.
75.	41.	305.	605.	1186.	2282.	4229.	7307.	2798.	1.	1.	0.	5.	1.
97.	42.	313.	626.	1251.	2502.	5004.	10008.	4045.	1.	1.	0.	5.	2.
147.	42.	316.	632.	1264.	2528.	5056.	10112.	6194.	1.	1.	0.	6.	2.
116.	42.	317.	635.	1269.	2538.	5076.	10152.	4907.	1.	1.	0.	5.	2.
135.	45.	341.	682.	1363.	2726.	5452.	10904.	6134.	1.	1.	0.	5.	2.
150.	47.	348.	693.	1372.	2690.	5171.	9573.	6339.	1.	1.	0.	5.	1.
143.	47.	348.	694.	1380.	2728.	5331.	10181.	6296.	1.	1.	0.	5.	3.
219.	48.	358.	711.	1403.	2735.	5195.	9403.	8729.	1.	1.	0.	5.	3.
149.	47.	351.	701.	1403.	2805.	5610.	11220.	6966.	1.	1.	0.	5.	2.

55.	48.	360.	720.	1439.	2878.	5756.	11512.	2638.	1.	1.	0.	5.	2.
65.	53.	393.	778.	1524.	2927.	5409.	9293.	3150.	1.	1.	0.	5.	1.
82.	52.	390.	774.	1524.	2950.	5534.	9780.	3937.	1.	1.	0.	5.	1.
105.	54.	399.	794.	1568.	3057.	5815.	10550.	5152.	1.	1.	0.	5.	1.
102.	53.	394.	788.	1576.	3152.	6304.	12608.	5358.	1.	1.	0.	5.	2.
76.	56.	413.	817.	1605.	3093.	5754.	10012.	3842.	1.	1.	0.	5.	1.
90.	56.	415.	823.	1621.	3140.	5903.	10472.	4566.	1.	1.	0.	5.	1.
165.	54.	408.	815.	1631.	3261.	6522.	13044.	8968.	1.	0.	0.	5.	2.
68.	56.	421.	843.	1685.	3370.	6740.	13480.	3819.	1.	1.	0.	6.	2.
97.	62.	463.	919.	1810.	3515.	6632.	11846.	5481.	1.	1.	0.	5.	1.
193.	61.	460.	920.	1840.	3680.	7360.	14720.	11837.	1.	0.	0.	5.	2.
112.	63.	472.	944.	1887.	3774.	7548.	15096.	7045.	1.	1.	0.	5.	2.
80.	66.	490.	969.	1899.	3649.	6747.	11610.	4739.	1.	1.	0.	5.	1.
72.	64.	484.	967.	1934.	3868.	7736.	15472.	4642.	1.	1.	0.	6.	2.
33.	74.	538.	1039.	1936.	3379.	5258.	6883.	2100.	1.	1.	0.	5.	3.
124.	67.	501.	996.	1966.	3833.	7285.	13195.	7503.	1.	1.	0.	5.	1.
105.	71.	529.	1058.	2115.	4230.	8460.	16920.	7403.	1.	0.	0.	5.	2.
79.	74.	551.	1093.	2150.	4163.	7812.	13812.	5371.	1.	1.	0.	5.	1.
79.	74.	552.	1094.	2152.	4159.	7780.	13678.	5360.	1.	1.	0.	5.	1.
74.	73.	546.	1092.	2183.	4366.	8732.	17464.	5385.	1.	1.	0.	6.	2.
110.	78.	584.	1168.	2337.	4673.	9346.	18692.	8567.	1.	0.	0.	6.	2.
47.	437.	1301.	1835.	2339.	2580.	2614.	2615.	2530.	1.	1.	0.	7.	2.
152.	80.	599.	1197.	2394.	4788.	9576.	19152.	12130.	1.	1.	0.	6.	2.
58.	84.	622.	1231.	2412.	4634.	8569.	14746.	4492.	1.	1.	0.	5.	1.
36.	456.	1360.	1917.	2444.	2696.	2732.	2732.	2542.	1.	1.	0.	7.	2.
81.	86.	642.	1283.	2567.	5133.	10266.	20532.	6930.	1.	1.	0.	5.	2.
36.	483.	1438.	2028.	2585.	2851.	2889.	2889.	2688.	1.	1.	0.	7.	2.
159.	86.	646.	1292.	2585.	5169.	10338.	20676.	13698.	1.	1.	0.	5.	2.
69.	485.	1445.	2038.	2598.	2865.	2903.	2904.	2883.	1.	1.	0.	7.	2.
64.	88.	660.	1320.	2639.	5278.	10556.	21112.	5630.	1.	1.	0.	6.	2.
36.	517.	1542.	2174.	2771.	3057.	3097.	3098.	2882.	1.	1.	0.	7.	2.
65.	98.	724.	1433.	2806.	5384.	9930.	17009.	5793.	1.	1.	0.	5.	1.
34.	533.	1589.	2241.	2857.	3151.	3193.	3193.	2938.	1.	1.	0.	7.	2.
56.	96.	723.	1446.	2892.	5783.	11566.	23132.	5397.	1.	1.	0.	6.	2.
55.	101.	751.	1484.	2901.	5545.	10150.	17151.	5121.	1.	1.	0.	5.	1.
96.	103.	765.	1509.	2940.	5585.	10103.	16713.	8410.	1.	1.	0.	5.	1.

33.	552.	1646.	2321.	2958.	3263.	3306.	3307.	3024.	1.	1.	0.	7.	2.
61.	99.	742.	1484.	2969.	5937.	11874.	23748.	6036.	1.	1.	0.	6.	2.
67.	571.	1700.	2398.	3057.	3372.	3416.	3417.	3389.	1.	1.	0.	7.	2.
41.	571.	1702.	2400.	3059.	3375.	3419.	3420.	3252.	1.	1.	0.	7.	2.
63.	108.	797.	1576.	3080.	5881.	10750.	18115.	6147.	1.	1.	0.	5.	1.
78.	103.	776.	1551.	3103.	6205.	12410.	24820.	8067.	1.	1.	0.	6.	2.
46.	582.	1735.	2447.	3119.	3440.	3486.	3486.	3365.	1.	1.	0.	7.	2.
55.	107.	801.	1603.	3206.	6411.	12822.	25644.	5877.	1.	1.	0.	6.	2.
33.	602.	1795.	2531.	3227.	3559.	3606.	3607.	3298.	1.	1.	0.	7.	2.
79.	112.	836.	1658.	3263.	6320.	11864.	20996.	8155.	1.	1.	0.	5.	1.
50.	619.	1844.	2601.	3315.	3657.	3705.	3706.	3608.	1.	1.	0.	7.	2.
78.	116.	860.	1706.	3357.	6501.	12199.	21574.	8290.	1.	1.	0.	5.	1.
66.	630.	1877.	2647.	3374.	3722.	3771.	3772.	3739.	1.	1.	0.	7.	2.
71.	640.	1906.	2688.	3427.	3780.	3830.	3830.	3807.	1.	1.	0.	7.	2.
36.	670.	1996.	2814.	3587.	3957.	4009.	4010.	3731.	1.	1.	0.	7.	2.
57.	670.	1996.	2814.	3587.	3957.	4009.	4010.	3945.	1.	1.	0.	7.	2.
64.	122.	915.	1831.	3662.	7323.	14646.	29292.	7811.	1.	1.	0.	6.	2.
50.	685.	2041.	2878.	3669.	4047.	4101.	4101.	3993.	1.	1.	0.	7.	2.
75.	129.	962.	1908.	3751.	7255.	13587.	23932.	8920.	1.	1.	0.	5.	1.
53.	704.	2097.	2958.	3770.	4159.	4214.	4215.	4124.	1.	1.	0.	7.	2.
50.	704.	2097.	2958.	3770.	4159.	4214.	4215.	4104.	1.	1.	0.	7.	2.
40.	708.	2110.	2976.	3794.	4185.	4240.	4241.	4017.	1.	1.	0.	7.	2.
80.	709.	2112.	2978.	3796.	4188.	4243.	4244.	4230.	1.	1.	0.	7.	2.
94.	0.	0.	0.	3850.	7700.	0.	0.	12000.	1.	1.	0.	6.	1.
60.	129.	967.	1934.	3869.	7737.	15474.	30948.	7737.	1.	1.	0.	6.	2.
46.	732.	2180.	3074.	3918.	4322.	4379.	4380.	4227.	1.	1.	0.	7.	2.
28.	738.	2200.	3102.	3954.	4362.	4419.	4420.	3885.	1.	1.	0.	7.	2.
34.	742.	2211.	3118.	3974.	4384.	4441.	4442.	4087.	1.	1.	0.	7.	2.
38.	743.	2214.	3123.	3980.	4391.	4448.	4449.	4180.	1.	1.	0.	7.	2.
47.	753.	2243.	3164.	4032.	4448.	4507.	4508.	4361.	1.	1.	0.	7.	2.
22.	759.	2261.	3189.	4065.	4484.	4543.	4544.	3710.	1.	1.	0.	7.	2.
63.	142.	1053.	2083.	4077.	7810.	14359.	24456.	8166.	1.	1.	0.	5.	1.
15.	170.	1204.	2277.	4084.	6660.	9308.	10779.	2277.	1.	1.	0.	5.	3.
47.	766.	2282.	3218.	4101.	4524.	4584.	4585.	4436.	1.	1.	0.	7.	2.
46.	797.	2375.	3349.	4268.	4709.	4771.	4771.	4606.	1.	1.	0.	7.	2.
58.	151.	1122.	2219.	4345.	8329.	15336.	26186.	8074.	1.	1.	0.	5.	1.

37.	827.	2464.	3475.	4429.	4886.	4950.	4951.	4630.	1.	1.	0.	7.	2.
55.	841.	2506.	3534.	4504.	4969.	5034.	5035.	4941.	1.	1.	0.	7.	2.
32.	853.	2541.	3583.	4567.	5038.	5104.	5105.	4636.	1.	1.	0.	7.	2.
51.	853.	2542.	3585.	4570.	5041.	5107.	5108.	4983.	1.	1.	0.	7.	2.
55.	153.	1149.	2298.	4596.	9192.	18384.	36768.	8426.	1.	1.	0.	6.	2.
47.	866.	2580.	3639.	4638.	5117.	5184.	5185.	5017.	1.	1.	0.	7.	2.
56.	877.	2613.	3686.	4698.	5182.	5250.	5251.	5160.	1.	1.	0.	7.	2.
33.	886.	2639.	3721.	4743.	5233.	5301.	5302.	4848.	1.	1.	0.	7.	2.
60.	891.	2655.	3745.	4773.	5265.	5334.	5336.	5265.	1.	1.	0.	7.	2.
31.	892.	2659.	3750.	4780.	5272.	5342.	5343.	4817.	1.	1.	0.	7.	2.
46.	902.	2686.	3788.	4829.	5327.	5397.	5398.	5210.	1.	1.	0.	7.	2.
46.	910.	2712.	3824.	4874.	5377.	5448.	5449.	5259.	1.	1.	0.	7.	2.
35.	916.	2730.	3850.	4907.	5413.	5484.	5485.	5076.	1.	1.	0.	7.	2.
60.	166.	1245.	2490.	4979.	9958.	19916.	39832.	9958.	1.	1.	0.	6.	2.
43.	936.	2788.	3932.	5012.	5529.	5601.	5603.	5363.	1.	1.	0.	7.	2.
68.	170.	1274.	2547.	5094.	10188.	20376.	40752.	11546.	1.	1.	0.	6.	2.
45.	174.	1302.	2605.	5209.	10418.	20836.	41672.	7814.	1.	1.	0.	6.	2.
77.	0.	0.	0.	5300.	10600.	0.	0.	13600.	1.	1.	0.	6.	1.
54.	991.	2952.	4163.	5307.	5854.	5931.	5932.	5814.	1.	1.	0.	7.	2.
47.	1007.	3000.	4230.	5392.	5948.	6026.	6027.	5832.	1.	1.	0.	7.	2.
46.	1013.	3018.	4256.	5425.	5984.	6063.	6064.	5853.	1.	1.	0.	7.	2.
67.	194.	1437.	2838.	5539.	10551.	19190.	32058.	11650.	1.	1.	0.	5.	3.
46.	1037.	3091.	4359.	5556.	6129.	6209.	6210.	5994.	1.	1.	0.	7.	2.
76.	1054.	3140.	4428.	5644.	6226.	6308.	6309.	6282.	1.	1.	0.	7.	2.
41.	1054.	3140.	4428.	5644.	6226.	6308.	6309.	5999.	1.	1.	0.	7.	2.
53.	1086.	3236.	4564.	5818.	6418.	6502.	6503.	6364.	1.	1.	0.	7.	2.
29.	1097.	3267.	4608.	5873.	6479.	6564.	6566.	5824.	1.	1.	0.	7.	2.
35.	1104.	3289.	4639.	5913.	6522.	6608.	6609.	6117.	1.	1.	0.	7.	2.
50.	1110.	3308.	4665.	5946.	6559.	6645.	6647.	6471.	1.	1.	0.	7.	2.
46.	1136.	3386.	4775.	6086.	6714.	6802.	6804.	6567.	1.	1.	0.	7.	2.
33.	1173.	3495.	4929.	6283.	6931.	7022.	7024.	6422.	1.	1.	0.	7.	2.
41.	1196.	3563.	5024.	6404.	7065.	7157.	7159.	6807.	1.	1.	0.	7.	2.
58.	1233.	3674.	5181.	6604.	7285.	7381.	7382.	7270.	1.	1.	0.	7.	2.
60.	221.	1657.	3313.	6626.	13252.	26504.	53008.	13252.	1.	1.	0.	6.	2.
38.	1240.	3696.	5212.	6643.	7328.	7424.	7426.	6976.	1.	1.	0.	7.	2.
34.	1261.	3758.	5299.	6755.	7451.	7549.	7551.	6947.	1.	1.	0.	7.	2.

70.	0.	0.	0.	7250.	14500.	0.	0.	16900.	1.	1.	0.	6.	1.
33.	1374.	4095.	5774.	7361.	8119.	8226.	8228.	7523.	1.	1.	0.	7.	2.
32.	1399.	4170.	5880.	7495.	8268.	8377.	8378.	7610.	1.	1.	0.	7.	2.
56.	0.	0.	0.	7500.	15000.	0.	0.	14000.	1.	1.	0.	6.	1.
50.	287.	2154.	4309.	8618.	17235.	34470.	68940.	14363.	1.	1.	0.	6.	2.
61.	289.	2164.	4328.	8656.	17312.	34624.	69248.	17601.	1.	1.	0.	6.	2.
24.	294.	2205.	4410.	8821.	17641.	35282.	70564.	7056.	1.	1.	0.	5.	2.
76.	0.	0.	0.	8900.	17800.	0.	0.	22500.	1.	1.	0.	6.	1.
36.	309.	2317.	4634.	9269.	18537.	37074.	74148.	11122.	1.	1.	0.	6.	2.
42.	314.	2356.	4711.	9422.	18844.	37688.	75376.	13191.	1.	1.	0.	6.	2.
41.	349.	2614.	5228.	10456.	20912.	41824.	83648.	14290.	1.	1.	0.	6.	2.
56.	0.	0.	0.	11450.	22900.	0.	0.	21300.	1.	1.	0.	6.	1.
38.	397.	2978.	5956.	11912.	23823.	47646.	95292.	15088.	1.	1.	0.	6.	2.
61.	0.	0.	0.	12600.	25200.	0.	0.	25600.	1.	1.	0.	6.	1.
43.	448.	3362.	6724.	13448.	26896.	53792.	107584.	19275.	1.	1.	0.	5.	2.
40.	459.	3443.	6887.	13773.	27546.	55092.	110184.	18364.	1.	1.	0.	5.	2.
48.	489.	3669.	7339.	14677.	29354.	58708.	117416.	23483.	1.	1.	0.	5.	2.
36.	509.	3814.	7628.	15256.	30511.	61022.	122044.	18307.	1.	1.	0.	5.	2.
42.	535.	4013.	8025.	16051.	32101.	64202.	128404.	22471.	1.	1.	0.	5.	2.
42.	554.	4156.	8311.	16622.	33244.	66488.	132976.	23271.	1.	1.	0.	6.	2.
35.	0.	0.	0.	19700.	39400.	0.	0.	23000.	1.	1.	0.	6.	1.
30.	0.	0.	0.	19850.	39700.	0.	0.	19900.	1.	1.	0.	6.	1.
27.	699.	5242.	10484.	20967.	41934.	83868.	167736.	18870.	1.	1.	0.	5.	2.
31.	710.	5323.	10646.	21293.	42585.	85170.	170340.	22002.	1.	1.	0.	5.	2.
39.	724.	5429.	10858.	21716.	43432.	86864.	173728.	28231.	1.	1.	0.	6.	2.
33.	762.	5712.	11424.	22847.	45694.	91388.	182776.	25132.	1.	1.	0.	5.	2.
27.	0.	0.	0.	24650.	49300.	0.	0.	22200.	1.	1.	0.	6.	1.
14.	862.	6462.	12924.	25848.	51695.	103390.	206780.	12062.	1.	1.	0.	5.	2.
32.	907.	6805.	13611.	27221.	54442.	108884.	217768.	29036.	1.	1.	0.	5.	2.
21.	911.	6832.	13665.	27330.	54659.	109318.	218636.	19131.	1.	1.	0.	5.	2.
46.	926.	6942.	13884.	27768.	55535.	111070.	222140.	42577.	1.	1.	0.	6.	2.
12.	965.	7239.	14478.	28955.	57910.	115820.	231640.	11582.	1.	1.	0.	6.	2.
13.	1016.	7619.	15237.	30475.	60949.	121898.	243796.	13206.	1.	1.	0.	5.	2.
18.	1034.	7754.	15508.	31017.	62033.	124066.	248132.	18610.	1.	1.	0.	5.	2.
15.	1255.	9412.	18825.	37649.	75298.	150596.	301192.	18825.	1.	1.	0.	6.	2.

29.	1422.	10664.	21329.	42657.	85314.	170628.	341256.	41235.	1.	1.	0.	5.	2.
24.	1532.	11490.	22980.	45960.	91920.	183840.	367680.	36768.	1.	1.	0.	6.	2.
18.	1570.	11777.	23555.	47109.	94218.	188436.	376872.	28265.	1.	1.	0.	6.	2.
19.	1621.	12160.	24321.	48641.	97282.	194564.	389128.	30806.	1.	1.	0.	6.	2.
9.	1651.	12381.	24763.	49526.	99051.	198102.	396204.	14858.	1.	1.	0.	5.	2.
8.	2121.	15906.	31812.	63624.	127248.	254496.	508992.	16966.	1.	1.	0.	5.	2.
8.	2145.	16087.	32173.	64347.	128694.	257388.	514776.	17159.	1.	1.	0.	5.	2.
9.	2169.	16268.	32535.	65070.	130140.	260280.	520560.	19521.	1.	1.	0.	5.	2.
10.	2229.	16719.	33439.	66878.	133755.	267510.	535020.	22293.	1.	1.	0.	5.	2.
8.	2326.	17442.	34885.	69770.	139539.	279078.	558156.	18605.	1.	1.	0.	5.	2.
7.	2413.	18097.	36194.	72387.	144774.	289548.	579096.	16890.	1.	1.	0.	6.	2.
7.	2434.	18256.	36512.	73023.	146046.	292092.	584184.	17039.	1.	1.	0.	5.	2.
7.	2494.	18708.	37415.	74831.	149661.	299322.	598644.	17460.	1.	1.	0.	5.	2.
8.	2555.	19160.	38319.	76638.	153276.	306552.	613104.	20437.	1.	1.	0.	5.	2.
7.	2567.	19250.	38500.	77000.	153999.	307998.	615996.	17967.	1.	1.	0.	5.	2.
7.	2772.	20786.	41573.	83145.	166290.	332580.	665160.	19401.	1.	1.	0.	5.	2.
7.	2911.	21831.	43662.	87324.	174648.	349296.	698592.	20376.	1.	1.	0.	6.	2.
7.	2988.	22413.	44826.	89652.	179304.	358608.	717216.	20919.	1.	1.	0.	5.	2.
7.	3013.	22597.	45194.	90388.	180776.	361552.	723104.	21091.	1.	1.	0.	6.	2.
7.	3037.	22775.	45549.	91098.	182196.	364392.	728784.	21256.	1.	1.	0.	5.	2.
7.	3243.	24321.	48641.	97282.	194564.	389128.	778256.	22699.	1.	1.	0.	6.	2.
7.	3498.	26236.	52471.	104942.	209884.	419768.	839536.	24486.	1.	1.	0.	6.	2.
7.	3600.	27002.	54003.	108006.	216012.	432024.	864048.	25201.	1.	1.	0.	6.	2.
10.	3748.	28107.	56213.	112427.	224853.	449706.	899412.	37476.	1.	1.	0.	5.	2.
7.	3779.	28342.	56684.	113368.	226736.	453472.	906944.	26453.	1.	1.	0.	6.	2.
7.	3932.	29491.	58982.	117964.	235928.	471856.	943712.	27525.	1.	1.	0.	6.	2.
7.	4060.	30449.	60897.	121794.	243588.	487176.	974352.	28419.	1.	1.	0.	6.	2.
7.	4531.	33981.	67962.	135924.	271848.	543696.	1087440.	31716.	1.	1.	0.	5.	2.
7.	4877.	36577.	73153.	146306.	292612.	585224.	1170480.	34138.	1.	1.	0.	6.	2.

PDS>

Table A.4.2 Beta Emitting Nuclides

SURVIVAL TIME	INIT RATE	7.5 DOSE	15 DOSE	30 DOSE	60 DOSE	120 DOSE	240 DOSE	TOTAL DOSE	SURVIVAL CODE	ACUTE CODE	EMIT CODE	NUCLIDE CODE	SPEC CODE
2428.	52.	388.	774.	1536.	3025.	5866.	11044.	46000.	1.	0.	1.	4.	1.
2358.	60.	442.	870.	1681.	3145.	5528.	8706.	13000.	0.	0.	1.	1.	1.
1526.	60.	442.	870.	1681.	3145.	5530.	8709.	13000.	1.	0.	1.	1.	1.
2312.	60.	446.	883.	1732.	3333.	6184.	10710.	23000.	1.	0.	1.	4.	1.
2479.	72.	513.	977.	1774.	2954.	4262.	5097.	5300.	0.	0.	1.	2.	1.
2485.	72.	514.	979.	1780.	2974.	4310.	5180.	5400.	0.	0.	1.	2.	1.
3576.	64.	473.	932.	1809.	3414.	6099.	9874.	16000.	0.	0.	1.	1.	1.
2500.	68.	501.	986.	1907.	3572.	6294.	9947.	15000.	1.	0.	1.	1.	1.
2239.	68.	501.	986.	1907.	3572.	6294.	9947.	15000.	0.	0.	1.	1.	1.
2744.	80.	569.	1080.	1952.	3224.	4591.	5418.	5600.	0.	0.	1.	2.	1.
2981.	70.	516.	1016.	1968.	3694.	6535.	10401.	16000.	0.	0.	1.	1.	1.
2669.	83.	592.	1128.	2051.	3423.	4956.	5951.	6200.	0.	0.	1.	2.	1.
2288.	74.	545.	1070.	2064.	3843.	6702.	10409.	15000.	0.	0.	1.	1.	1.
2196.	85.	605.	1149.	2077.	3436.	4904.	5800.	6000.	0.	0.	1.	2.	1.
2479.	85.	606.	1152.	2091.	3476.	5004.	5969.	6200.	0.	0.	1.	2.	1.
2981.	76.	561.	1103.	2134.	4000.	7058.	11186.	17000.	0.	0.	1.	1.	1.
1762.	77.	567.	1114.	2151.	4013.	7020.	10960.	16000.	1.	0.	1.	1.	1.
1748.	78.	576.	1133.	2194.	4121.	7300.	11640.	18000.	1.	0.	1.	1.	1.
2197.	91.	646.	1223.	2201.	3608.	5082.	5930.	6100.	0.	0.	1.	2.	1.
1973.	79.	583.	1147.	2221.	4167.	7370.	11723.	18000.	1.	0.	1.	1.	1.
2666.	91.	647.	1229.	2222.	3673.	5238.	6189.	6400.	0.	0.	1.	2.	1.
1212.	77.	573.	1137.	2239.	4343.	8175.	14542.	34000.	1.	0.	1.	4.	1.
1460.	77.	573.	1138.	2243.	4358.	8233.	14738.	37000.	1.	0.	1.	4.	1.
2749.	93.	660.	1249.	2247.	3679.	5175.	6031.	6200.	0.	0.	1.	2.	1.
1184.	78.	582.	1157.	2290.	4481.	8588.	15798.	44000.	1.	0.	1.	4.	1.
2666.	93.	664.	1265.	2301.	3846.	5579.	6711.	7000.	0.	0.	1.	2.	1.
2308.	81.	603.	1198.	2364.	4599.	8713.	15684.	43000.	1.	0.	1.	4.	1.
2371.	83.	619.	1233.	2441.	4787.	9209.	17067.	60000.	1.	0.	1.	4.	1.
2197.	100.	715.	1365.	2490.	4186.	6125.	7440.	7800.	0.	0.	1.	2.	1.
2394.	89.	657.	1295.	2514.	4741.	8461.	13668.	22000.	1.	0.	1.	1.	1.
2469.	89.	662.	1312.	2579.	4983.	9314.	16353.	38000.	1.	0.	1.	1.	1.

1820.	92.	684.	1355.	2661.	5132.	9561.	16679.	37000.	1.	0.	1.	4.	1.
2485.	110.	783.	1489.	2697.	4474.	6414.	7621.	7900.	0.	0.	1.	2.	1.
2478.	110.	784.	1493.	2710.	4514.	6512.	7789.	8100.	0.	0.	1.	2.	1.
2326.	98.	723.	1424.	2760.	5189.	9207.	14728.	23000.	1.	0.	1.	1.	1.
1030.	95.	707.	1404.	2768.	5377.	10157.	18184.	42000.	0.	0.	1.	4.	1.
2357.	100.	738.	1452.	2813.	5281.	9350.	14899.	23000.	0.	0.	1.	1.	1.
3045.	100.	738.	1454.	2820.	5309.	9443.	15171.	24000.	0.	0.	1.	1.	1.
1967.	98.	730.	1452.	2868.	5598.	10667.	19416.	57000.	1.	0.	1.	4.	1.
1024.	99.	739.	1470.	2911.	5706.	10970.	20303.	55000.	1.	0.	1.	4.	1.
842.	100.	744.	1478.	2913.	5658.	10682.	19108.	41000.	1.	0.	1.	4.	1.
2198.	120.	852.	1616.	2914.	4[illegible].	6784.	7955.	8200.	0.	0.	1.	2.	1.
1031.	100.	746.	1482.	2930.	5725.	10935.	19988.	51000.	1.	0.	1.	4.	1.
1169.	100.	746.	1484.	2935.	5744.	11006.	20240.	56000.	1.	0.	1.	4.	1.
2485.	120.	857.	1633.	2973.	4975.	7230.	8716.	9100.	0.	0.	1.	2.	1.
2407.	792.	2586.	2943.	2999.	3000.	3000.	3000.	3000.	0.	0.	1.	3.	1.
2925.	806.	2600.	2947.	2999.	3000.	3000.	3000.	3000.	0.	0.	1.	3.	1.
2576.	806.	2600.	2947.	2999.	3000.	3000.	3000.	3000.	0.	0.	1.	3.	1.
2666.	120.	859.	1641.	3002.	5065.	7458.	9122.	9600.	0.	0.	1.	2.	1.
183.	130.	924.	1752.	3159.	5199.	7368.	8649.	8300.	1.	1.	1.	2.	1.
3248.	110.	818.	1623.	3193.	6183.	11601.	20509.	50000.	1.	0.	1.	1.	1.
2177.	110.	819.	1624.	3199.	6202.	11673.	20753.	52000.	1.	0.	1.	1.	1.
1846.	130.	928.	1766.	3211.	5359.	7758.	9311.	9700.	1.	0.	1.	2.	1.
2372.	936.	2969.	3345.	3399.	3400.	3400.	3400.	3400.	0.	0.	1.	3.	1.
2101.	120.	892.	1768.	3474.	6708.	12521.	21924.	50000.	1.	0.	1.	1.	1.
1127.	120.	893.	1772.	3490.	6767.	12737.	22651.	52000.	1.	0.	1.	4.	1.
808.	120.	894.	1776.	3504.	6824.	12946.	23370.	51000.	1.	0.	1.	4.	1.
873.	120.	895.	1779.	3516.	6871.	13124.	23993.	57000.	1.	0.	1.	4.	1.
2925.	936.	3088.	3527.	3599.	3600.	3600.	3600.	3600.	0.	0.	1.	3.	1.
2703.	994.	3146.	3543.	3599.	3600.	3600.	3600.	3600.	0.	0.	1.	3.	1.
2865.	936.	3088.	3527.	3599.	3600.	3600.	3600.	3600.	0.	0.	1.	3.	1.
881.	130.	967.	1919.	3779.	7326.	13781.	24479.	52000.	1.	0.	1.	4.	1.
2999.	130.	968.	1921.	3784.	7344.	13848.	24706.	64000.	1.	0.	1.	1.	1.
715.	130.	968.	1923.	3792.	7374.	13959.	25087.	51000.	1.	0.	1.	4.	1.
2865.	994.	3266.	3725.	3799.	3800.	3800.	3800.	3800.	0.	0.	1.	3.	1.
693.	130.	970.	1930.	3820.	7486.	14377.	26559.	58000.	1.	0.	1.	4.	1.
2667.	160.	1137.	2156.	3890.	6404.	9080.	10665.	11000.	0.	0.	1.	2.	1.

2703.	1037.	3369.	3828.	3899.	3900.	3900.	3900.	3900.	0.	0.	1.	3.	1.
2372.	1037.	3369.	3828.	3899.	3900.	3900.	3900.	3900.	0.	0.	1.	3.	1.
1894.	140.	1034.	2036.	3951.	7443.	13257.	21348.	34000.	1.	0.	1.	1.	1.
2667.	160.	1142.	2175.	3956.	6608.	9577.	11511.	12000.	0.	0.	1.	2.	1.
2198.	160.	1142.	2175.	3956.	6608.	9577.	11511.	12000.	0.	0.	1.	2.	1.
2576.	1080.	3531.	4021.	4099.	4100.	4100.	4100.	4100.	0.	0.	1.	3.	1.
1184.	150.	1104.	2165.	4169.	7740.	13419.	20642.	29000.	1.	0.	1.	1.	1.
1809.	150.	1104.	2168.	4179.	7776.	13536.	20965.	30000.	1.	0.	1.	1.	1.
1252.	150.	1106.	2173.	4199.	7848.	13777.	21640.	32000.	1.	0.	1.	1.	1.
765.	150.	1107.	2180.	4226.	7947.	14108.	22591.	34000.	1.	0.	1.	1.	1.
2408.	1138.	3709.	4219.	4299.	4300.	4300.	4300.	4300.	0.	0.	1.	3.	1.
477.	150.	1118.	2222.	4387.	8556.	16281.	29555.	49000.	1.	1.	1.	4.	1.
2408.	1152.	3783.	4313.	4378.	4400.	4400.	4400.	4400.	0.	0.	1.	3.	1.
2484.	180.	1282.	2438.	4419.	7336.	10532.	12531.	13000.	0.	0.	1.	2.	1.
1522.	160.	1178.	2315.	4467.	8330.	14559.	22699.	33000.	1.	0.	1.	1.	1.
2198.	190.	1344.	2537.	4537.	7359.	10205.	11732.	12000.	0.	0.	1.	2.	1.
747.	160.	1190.	2360.	4642.	8982.	16834.	29698.	56000.	1.	1.	1.	4.	1.
2408.	1267.	4137.	4708.	4798.	4800.	4800.	4800.	4800.	0.	0.	1.	3.	1.
2577.	1267.	4137.	4708.	4798.	4800.	4800.	4800.	4800.	0.	0.	1.	3.	1.
2703.	1267.	4137.	4708.	4798.	4800.	4800.	4800.	4800.	0.	0.	1.	3.	1.
2703.	1296.	4166.	4716.	4799.	4800.	4800.	4800.	4800.	0.	0.	1.	3.	1.
1225.	170.	1256.	2476.	4811.	9089.	16273.	26438.	43000.	1.	0.	1.	1.	1.
2484.	200.	1427.	2719.	4945.	8260.	11972.	14389.	15000.	0.	0.	1.	2.	1.
2477.	200.	1432.	2736.	5003.	8442.	12430.	15203.	16000.	0.	0.	1.	2.	1.
2577.	1339.	4388.	5001.	5098.	5100.	5100.	5100.	5100.	0.	0.	1.	3.	1.
748.	180.	1337.	2650.	5202.	10028.	18658.	32477.	60000.	1.	1.	1.	4.	1.
2203.	210.	1504.	2875.	5264.	8899.	13139.	16123.	17000.	0.	0.	1.	2.	1.
1227.	190.	1399.	2746.	5294.	9852.	17155.	26583.	38000.	1.	0.	1.	1.	1.
2408.	1382.	4550.	5194.	5298.	5300.	5300.	5300.	5300.	0.	0.	1.	3.	1.
193.	190.	1400.	2751.	5312.	9918.	17375.	27197.	24000.	1.	1.	1.	1.	1.
1317.	190.	1403.	2764.	5362.	10103.	17996.	28983.	46000.	1.	0.	1.	1.	1.
2667.	220.	1568.	2982.	5408.	8988.	12927.	15410.	16000.	0.	0.	1.	2.	1.
2480.	220.	1568.	2982.	5408.	8988.	12927.	15410.	16000.	0.	0.	1.	2.	1.
1612.	220.	1568.	2982.	5408.	8988.	12927.	15410.	16000.	1.	0.	1.	2.	1.
787.	190.	1412.	2800.	5503.	10631.	19859.	34826.	68000.	1.	1.	1.	4.	1.
644.	190.	1413.	2803.	5514.	10671.	20009.	35327.	65000.	1.	1.	1.	4.	1.

426.	220.	1577.	3017.	5531.	9372.	13891.	17123.	18000.	1.	1.	1.	2.	1.
916.	200.	1475.	2899.	5606.	10492.	18463.	29117.	43000.	1.	0.	1.	1.	1.
2312.	200.	1475.	2900.	5609.	10503.	18499.	29220.	44000.	1.	0.	1.	1.	1.
2868.	1584.	4991.	5612.	5699.	5700.	5700.	5700.	5700.	0.	0.	1.	3.	1.
2868.	1584.	4991.	5612.	5699.	5700.	5700.	5700.	5700.	0.	0.	1.	3.	1.
2704.	1584.	5052.	5704.	5799.	5800.	5800.	5800.	5800.	0.	0.	1.	3.	1.
2199.	240.	1708.	3244.	5870.	9713.	13876.	16426.	17000.	0.	0.	1.	2.	1.
2204.	240.	1708.	3244.	5870.	9713.	13876.	16426.	17000.	0.	0.	1.	2.	1.
279.	200.	1493.	2972.	5887.	11555.	22264.	41386.	47000.	1.	1.	1.	4.	1.
2199.	250.	1763.	3318.	5902.	9482.	12970.	14725.	15000.	0.	0.	1.	2.	1.
2577.	1584.	5172.	5886.	5998.	6000.	6000.	6000.	6000.	0.	0.	1.	3.	1.
2409.	1584.	5172.	5886.	5998.	6000.	6000.	6000.	6000.	0.	0.	1.	3.	1.
2373.	1584.	5172.	5886.	5998.	6000.	6000.	6000.	6000.	0.	0.	1.	3.	1.
2373.	1584.	5172.	5886.	5998.	6000.	6000.	6000.	6000.	0.	0.	1.	3.	1.
2569.	1584.	5172.	5886.	5998.	6000.	6000.	6000.	6000.	0.	0.	1.	3.	1.
259.	210.	1560.	3091.	6069.	11698.	21761.	37866.	40000.	1.	1.	1.	4.	1.
2204.	250.	1781.	3385.	6134.	10177.	14600.	17358.	18000.	0.	0.	1.	2.	1.
1077.	220.	1621.	3185.	6151.	11484.	20119.	31491.	46000.	1.	0.	1.	1.	1.
124.	250.	1783.	3393.	6161.	10262.	14809.	17716.	18000.	1.	1.	1.	2.	1.
2374.	250.	1785.	3403.	6197.	10372.	15082.	18192.	19000.	1.	0.	1.	2.	1.
2577.	1728.	5433.	6105.	6199.	6200.	6200.	6200.	6200.	0.	0.	1.	3.	1.
340.	220.	1630.	3220.	6284.	11978.	21808.	36496.	45000.	1.	1.	1.	4.	1.
2336.	260.	1853.	3526.	6397.	10641.	15322.	18288.	19000.	1.	0.	1.	2.	1.
2373.	1728.	5555.	6289.	6398.	6400.	6400.	6400.	6400.	0.	0.	1.	3.	1.
286.	220.	1638.	3251.	6407.	12444.	23489.	41996.	48000.	1.	1.	1.	4.	1.
2925.	1728.	5615.	6380.	6498.	6500.	6500.	6500.	6500.	0.	0.	1.	3.	1.
311.	230.	1699.	3349.	6503.	12274.	21937.	35535.	41000.	1.	1.	1.	1.	1.
2375.	1728.	5674.	6470.	6598.	6600.	6600.	6600.	6600.	1.	0.	1.	3.	1.
185.	240.	1764.	3457.	6644.	12287.	21155.	32174.	28000.	1.	1.	1.	1.	1.
201.	230.	1715.	3412.	6749.	13206.	25293.	46478.	40000.	1.	1.	1.	4.	1.
2512.	280.	1994.	3788.	6859.	11366.	16272.	19305.	20000.	1.	0.	1.	2.	1.
152.	280.	1997.	3800.	6899.	11490.	16576.	19824.	18000.	1.	1.	1.	2.	1.
206.	290.	2061.	3910.	7055.	11623.	16495.	19393.	19000.	1.	1.	1.	2.	1.
1341.	290.	2061.	3909.	7055.	11621.	16490.	19384.	20000.	1.	0.	1.	2.	1.
2373.	1872.	6117.	6964.	7097.	7100.	7100.	7100.	7100.	0.	0.	1.	3.	1.
535.	290.	2066.	3929.	7124.	11833.	17002.	20247.	21000.	1.	0.	1.	2.	1.

2249.	2016.	6318.	7092.	7199.	7200.	7200.	7200.	7200.	1.	0.	1.	3.	1.
376.	250.	1858.	3681.	7226.	13932.	25928.	45150.	61000.	1.	1.	1.	4.	1.
1379.	300.	2134.	4051.	7320.	12088.	17218.	20319.	21000.	1.	0.	1.	2.	1.
1882.	300.	2134.	4051.	7320.	12088.	17218.	20319.	21000.	1.	0.	1.	2.	1.
810.	300.	2134.	4051.	7320.	12088.	17218.	20319.	21000.	1.	0.	1.	2.	1.
295.	300.	2141.	4077.	7414.	12377.	17926.	21528.	22000.	1.	1.	1.	2.	1.
275.	270.	1989.	3906.	7538.	14056.	24562.	38286.	41000.	1.	1.	1.	1.	1.
226.	260.	1934.	3835.	7541.	14587.	27323.	48149.	46000.	1.	1.	1.	4.	1.
704.	310.	2206.	4191.	7584.	12554.	17945.	21253.	22000.	1.	0.	1.	2.	1.
750.	270.	1993.	3924.	7606.	14302.	25391.	40651.	61000.	1.	0.	1.	1.	1.
2625.	2016.	6619.	7548.	7697.	7700.	7700.	7700.	7700.	1.	0.	1.	3.	1.
1860.	320.	2279.	4332.	7848.	13019.	18668.	22184.	23000.	1.	0.	1.	2.	1.
2569.	2100.	6884.	7769.	7898.	7900.	7900.	7900.	7900.	0.	0.	1.	3.	1.
310.	280.	2074.	4096.	7992.	15220.	27668.	46179.	54000.	1.	1.	1.	4.	1.
173.	330.	2346.	4451.	8037.	13252.	18832.	22171.	21000.	1.	1.	1.	2.	1.
1387.	330.	2346.	4454.	8045.	13276.	18889.	22265.	23000.	1.	0.	1.	2.	1.
174.	330.	2353.	4478.	8130.	13538.	19528.	23351.	22000.	1.	1.	1.	2.	1.
341.	280.	2084.	4137.	8150.	15822.	29837.	53249.	69000.	1.	1.	1.	4.	1.
232.	280.	2084.	4138.	8154.	15833.	29880.	53399.	52000.	1.	1.	1.	4.	1.
409.	290.	2140.	4213.	8165.	15346.	27217.	43505.	56000.	1.	1.	1.	1.	1.
265.	280.	2086.	4144.	8177.	15924.	30216.	54558.	69000.	1.	1.	1.	4.	1.
159.	330.	2357.	4493.	8181.	13696.	19920.	24034.	22000.	1.	1.	1.	2.	1.
200.	290.	2149.	4249.	8301.	15851.	28966.	48794.	43000.	1.	1.	1.	4.	1.
300.	290.	2155.	4269.	8379.	16146.	30021.	52193.	61000.	1.	1.	1.	4.	1.
279.	300.	2216.	4365.	8472.	15968.	28473.	45932.	50000.	1.	1.	1.	1.	1.
283.	300.	2235.	4442.	8768.	17090.	32481.	58825.	67000.	1.	1.	1.	4.	1.
1114.	360.	2559.	4857.	8770.	14463.	20559.	24211.	25000.	1.	0.	1.	2.	1.
1434.	360.	2559.	4857.	8770.	14463.	20559.	24211.	25000.	1.	0.	1.	2.	1.
789.	320.	2353.	4613.	8870.	16426.	28347.	43275.	59000.	1.	0.	1.	1.	1.
216.	370.	2620.	4951.	8874.	14444.	20134.	23259.	23000.	1.	1.	1.	2.	1.
238.	310.	2302.	4560.	8946.	17221.	31952.	55333.	55000.	1.	1.	1.	4.	1.
273.	320.	2359.	4640.	8973.	16800.	29584.	46713.	50000.	1.	1.	1.	1.	1.
179.	370.	2632.	4999.	9038.	14940.	21312.	25188.	24000.	1.	1.	1.	2.	1.
182.	2592.	8150.	9158.	9298.	9300.	9300.	9300.	9300.	1.	1.	1.	3.	1.
205.	2592.	8150.	9158.	9298.	9300.	9300.	9300.	9300.	1.	1.	1.	3.	1.
252.	320.	2385.	4741.	9367.	18282.	34844.	63439.	66000.	1.	1.	1.	4.	1.

252.	380.	2715.	5176.	9431.	15803.	23018.	27817.	28000.	1.	1.	1.	2.	1.
237.	2592.	8273.	9342.	9498.	9500.	9500.	9500.	9500.	1.	1.	1.	3.	1.
243.	330.	2452.	4858.	9536.	18378.	34183.	59461.	60000.	1.	1.	1.	4.	1.
342.	330.	2454.	4865.	9564.	18488.	34581.	60784.	78000.	1.	1.	1.	4.	1.
373.	330.	2455.	4872.	9591.	18590.	34954.	62041.	85000.	1.	1.	1.	4.	1.
274.	400.	2854.	5434.	9875.	16471.	23822.	28567.	29000.	1.	1.	1.	2.	1.
181.	410.	2912.	5521.	9952.	16363.	23153.	27140.	26000.	1.	1.	1.	2.	1.
2276.	2736.	8715.	9835.	9997.	10000.	10000.	10000.	10000.	1.	0.	1.	3.	1.
463.	2736.	8715.	9835.	9997.	10000.	10000.	10000.	10000.	1.	1.	1.	3.	1.
123.	2736.	8715.	9835.	9997.	10000.	10000.	10000.	10000.	1.	1.	1.	3.	1.
220.	2736.	8715.	9835.	9997.	10000.	10000.	10000.	10000.	1.	1.	1.	3.	1.
268.	350.	2596.	5136.	10052.	19259.	35416.	60340.	65000.	1.	1.	1.	4.	1.
258.	350.	2605.	5170.	10181.	19751.	37200.	66233.	70000.	1.	1.	1.	4.	1.
246.	370.	2725.	5352.	10326.	19246.	33607.	52322.	53000.	1.	1.	1.	1.	1.
153.	420.	2994.	5698.	10343.	17218.	24822.	29665.	27000.	1.	1.	1.	2.	1.
152.	420.	2995.	5700.	10349.	17234.	24864.	29737.	27000.	1.	1.	1.	2.	1.
329.	360.	2674.	5297.	10395.	20020.	37185.	64520.	80000.	1.	1.	1.	4.	1.
137.	430.	3060.	5811.	10510.	17382.	24813.	29348.	26000.	1.	1.	1.	2.	1.
196.	430.	3063.	5824.	10556.	17525.	25162.	29939.	29000.	1.	1.	1.	2.	1.
214.	370.	2741.	5416.	10574.	20163.	36744.	61591.	57000.	1.	1.	1.	1.	1.
181.	430.	3067.	5837.	10600.	17659.	25490.	30503.	29000.	1.	1.	1.	2.	1.
255.	370.	2744.	5427.	10616.	20321.	37303.	63353.	66000.	1.	1.	1.	4.	1.
257.	380.	2803.	5513.	10667.	19993.	35273.	55877.	58000.	1.	1.	1.	1.	1.
186.	380.	2803.	5513.	10669.	19999.	35295.	55941.	48000.	1.	1.	1.	1.	1.
267.	380.	2820.	5580.	10926.	20954.	38610.	66023.	71000.	1.	1.	1.	4.	1.
126.	2736.	9297.	10736.	10994.	11000.	11000.	11000.	11000.	1.	1.	1.	3.	1.
902.	2880.	9456.	10783.	10996.	11000.	11000.	11000.	11000.	1.	0.	1.	3.	1.
121.	2880.	9456.	10783.	10996.	11000.	11000.	11000.	11000.	1.	1.	1.	3.	1.
163.	2880.	9456.	10783.	10996.	11000.	11000.	11000.	11000.	1.	1.	1.	3.	1.
214.	2880.	9456.	10783.	10996.	11000.	11000.	11000.	11000.	1.	1.	1.	3.	1.
130.	2880.	9456.	10783.	10996.	11000.	11000.	11000.	11000.	1.	1.	1.	3.	1.
172.	450.	3202.	6081.	10999.	18192.	25971.	30721.	29000.	1.	1.	1.	2.	1.
346.	450.	3210.	6110.	11099.	18500.	26726.	32009.	33000.	1.	1.	1.	2.	1.
231.	380.	2832.	5630.	11123.	21709.	41373.	75320.	73000.	1.	1.	1.	4.	1.
160.	460.	3272.	6213.	11231.	18559.	26458.	31252.	29000.	1.	1.	1.	2.	1.
218.	410.	3022.	5939.	11475.	21445.	37635.	59087.	56000.	1.	1.	1.	4.	1.

196.	470.	3343.	6348.	11477.	18966.	27042.	31945.	31000.	1.	1.	1.	2.	1.
184.	400.	2983.	5931.	11724.	22914.	43784.	80110.	64000.	1.	1.	1.	4.	1.
117.	3168.	10343.	11771.	11996.	12000.	12000.	12000.	12000.	1.	1.	1.	3.	1.
122.	3168.	10343.	11771.	11996.	12000.	12000.	12000.	12000.	1.	1.	1.	3.	1.
143.	3168.	10343.	11771.	11996.	12000.	12000.	12000.	12000.	1.	1.	1.	3.	1.
199.	3168.	10343.	11771.	11996.	12000.	12000.	12000.	12000.	1.	1.	1.	3.	1.
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386.	430.	3187.	6300.	12309.	23507.	42962.	72391.	96000.	1.	1.	1.	4.	1.
213.	510.	3627.	6886.	12444.	20551.	29272.	34545.	34000.	1.	1.	1.	2.	1.
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220.	460.	3415.	6760.	13248.	25450.	47041.	80899.	76000.	1.	1.	1.	4.	1.
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82.	4176.	14306.	16573.	16989.	17000.	17000.	17000.	17000.	1.	1.	1.	3.	1.
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91.	4320.	14472.	16624.	16992.	17000.	17000.	17000.	17000.	1.	1.	1.	3.	1.
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162.	830.	5908.	11225.	20317.	33645.	48124.	57036.	53000.	1.	1.	1.	2.	1.
194.	830.	5939.	11341.	20722.	34904.	51250.	62492.	60000.	1.	1.	1.	2.	1.
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23.	5904.	19682.	22568.	23053.	23064.	23064.	23064.	23000.	1.	1.	1.	3.	1.

85.	6336.	20686.	23543.	23991.	24000.	24000.	24000.	24000.	1.	1.	1.	3.	1.
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88.	6912.	21857.	24605.	24994.	25000.	25000.	25000.	25000.	1.	1.	1.	3.	1.
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182.	1000.	7416.	14665.	28681.	54876.	100654.	170699.	140000.	1.	1.	1.	1.	1.
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143.	1300.	9557.	18739.	36036.	66737.	115177.	175855.	130000.	1.	1.	1.	1.	1.
75.	8640.	30579.	35886.	36966.	37000.	37000.	37000.	37000.	1.	1.	1.	3.	1.
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47.	11520.	37825.	43134.	43983.	44000.	44000.	44000.	44000.	1.	1.	1.	3.	1.
12.	14400.	48953.	56543.	57901.	57935.	57935.	57935.	55000.	1.	1.	1.	3.	1.
7.	21600.	71667.	82034.	83750.	83787.	83787.	83787.	70000.	1.	1.	1.	3.	1.

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