RADIOLOGICAL DOSE ASSESSMENT for BOUNDING ACCIDENT SCENARIOS at the CRITICAL EXPERIMENT FACILITY, TA-18, LOS ALAMOS NATIONAL LABORATORY

September 1991

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EXECUTIVE SUMMARY

The N-2 Group (Advanced Nuclear Technology) at Los Alamos National Laboratory (LANL) operates a variety of experimental reactors, each with a unique inventory of nuclear material. As part of the Safety Analysis Report for the Los Alamos Critical Experiment Facility (LACEF) at TA-18, a number of postulated bounding, or maximum consequence, accident scenarios were postulated. While not necessarily realistic in risk terms, these scenarios were designed to allow modeling of the approximate maximum radiological dose effects of accidents involving these experiments.

A computer modeling code, CRIT8, was written to allow prediction of the radiological doses to workers and members of the public resulting from these postulated maximum-effect accidents. The code accounts for the relationships of the initial parent radionuclide inventory at the time of the accident to the growth of radioactive daughter products, and considers the atmospheric conditions at time of release. The code then calculates a dose at chosen receptor locations for the sum of radionuclides produced as a result of the accident. Both criticality and non-criticality accidents are examined.

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1.0 INTRODUCTION

1.1 Regulatory Guidance for Radiological Dose Assessment

The dose assessment methodology used in the calculation of radiological doses in the safety analysis are taken from DOE and NRC documentation applicable to the criticality facility. These govern issues of receptor locations, dose limit acceptance criteria, exposure pathways, dose conversion factors, nature of assumptions, and other criteria affecting the dose calculations.

Table 1-1 summarizes the guidance material used in calculating potential radiological effects resulting from postulated accidents at TA-18. Few of the guidance criteria provide explicit data values to be used when performing dose calculations. An exception to that are the dose conversion factor data provided in DOE(1988a and 1988b). For other data, the DOE Order calls for the selection of data such that when specific data is not available or is unknown, assumptions may be made which tend to maximize the resulting doses. Most important to these calculations are the meteorological data affecting air dispersion. Since specific meteorological conditions cannot be known in advance of an accident, conditions are assumed that result in doses that are maximized. Assumed conditions are judged to be representative of the local area.

1.2 Radionuclide Sources

Exposure from potential accidents may originate from two sources. Radionuclides may be produced in an accidental criticality during a routine laboratory test. Such an accident may result in various numbers of fissions of either plutonium or uranium depending upon the accident scenario. Over 900 unique isotopes are produced in a criticality, many of which are very short lived and do not contribute significantly to radiation exposure at locations downwind from the accident location. However, many of the original parents decay through several generations of radioactive daughters which may provide significant downwind exposure. A few of the radionuclides emerging from a criticality are gaseous, while most are high temperature volatilized particulates.

In both cases, the radionuclides are assumed to be instantly aerosolized into the laboratory room volume where the accident occurs. Whether this would actually happen depends on the specific energy deposited in the fissile fuel. For such accidents, the initial inventory of parent radionuclides is determined with the CINDER computer code by the LANL T-2 Group. Additional accidents were considered in which both plutonium and uranium, separately, are involved in a laboratory room fire. Those accidents are assumed to produce airborne radionuclides when bulk material burns (i.e., flameless oxidation). For those releases, release fractions are used to calculate the portion of bulk material subsequently released to the laboratory room as a result of burning. Table 1-2 summarizes the release fractions used in the analysis.

Table 1-1

Radiological Dose Assessment Guidance Documents

Document	Applicable Criteria	Value(s)
DOE Order 5480.1a	receptor location	point of unrestricted public access
	dose conversion factors	effective dose equivalent(EDE)
DOE Order 6430.1A	dose limit criteria	25 rem effective dose equivalent 300 rem bone surface 300 rem thyroid 75 rem lung 150 rem any other organ
DOE Order 5480.1A	meteorological parameters	use dispersive parameters which tend to maximize the dose - stability class F - wind speed yielding - greatest dose
DOE Order 6430.1A	engineered safety features	allow no credit
NRC Reg. Guide 1.145	exposure reduction for building wake cavity	reduction factor of from 1.0 - 4.0

Table 1-2

Radionuclide Release Fractions

Type of Radionuclide	Release Fraction	Reference
Inert Gases	1.0	Elder et al, 1986
Bulk plutonium during oxidation	0.001	Mishima, 1965
Bulk uranium	0.001	Engineering judgement based on plutonium release fraction
Uranium in solution	0.0005	NRC, 1979
Iodine	0.25	Elder et al, 1986
All other particulates	0.01	Elder et al, 1986

1.3 Receptor Locations

Receptor locations are the locations where humans are assumed to be in the event of an accident. Potential receptors can be either a member of the public or a laboratory employee. With respect to the DOE guidance, the public receptor location is at the point of unrestricted public access whether on-site (i.e., DOE/laboratory controlled land) or off-site.

That point has been determined by LANL to be on-site near Pajarito Road at distance of 1000m from of TA-18. In addition to that location, another public receptor was selected at White Rock at the junction of Pajarito Road and State Highway 4, a distance of 4400m from TA-18. The second public receptor location was evaluated to determine potential community impact following a TA-18 accident. An on-site worker receptor location was determined to exist 200m from the TA-18 experimental facilities or kivas. Potential exposure to laboratory workers resulting from possible accidents were evaluated at that location. In all, three receptor locations are evaluated for each of eight accidents postulated to occur at TA-18. Table 1-3 summarizes the receptor locations.

1.4 Calculational Considerations

As described in Section 1.2, hundreds of potentially harmful radionuclides are produced in a criticality event. Although most of the initial parent nuclides decay away during transport to a receptor, the daughter nuclides may pose a significant exposure threat. The potential for exposure, be it by the parent inventory, the

daughter inventory, or both, is primarily dependent on the time elapsed from time = zero (the onset of the accident) to receipt at the receptor location.

As mentioned, the wind speed is not known in advance of an accident and, therefore, must be selected so as to result in a maximized dose. The wind speed selection should give consideration over a justifiable range of wind speed values consistent with local meteorological measurements. Los Alamos National Laboratory wind speed measurements at a mesa top location indicate that wind speeds never exceed about 6 m/s during Pasquill stability class-F (F stability is used since is the most conservative class). However, TA-18 is located at the canyon floor for which no meteorological data is available. The canyon floor may exhibit down canyon drainage winds during F-stability of greater speed than those experienced at the mesa top. To be conservative, a wind speed range of from 1.0-10.0 m/s was determined to be an appropriate range of potential wind speeds at TA-18.

The effect of wind speed on the dose is unclear. Greater wind speeds have the effect of minimizing the transport time of the cloud of radionuclides, and thereby minimizing the decay time for the parent radionuclide inventory. Contrary to that effect, a greater wind speed also has the effect of reducing the air concentration (see Section 2.4). Accident yield calculations by LANL have determined that none of the postulated accident scenarios have sufficient release energy to damage the assembly buildings. As a result, the release of aerosolized particulates from the laboratory occurs via an infiltration/exfiltration method through the cracks around doors and windows (described in section 2.5) and is also a function of wind speed. An increased wind speed has the effect of greatly increasing the exfiltration release from the laboratory room. Consequently, it is only possible to determine the maximizing wind speed by calculating the dose separately using different wind speeds. Given the great number of initial parent nuclides, the time-dependent ingrowth of daughter nuclides, the number of receptor distances (each of which may render a unique maximizing wind speed), and the number of possible wind speeds, a computer code was developed to calculate potential doses over a range of wind speeds and distances. The computer code is described in Section 2.0.

Table 1-3

Receptor Locations for Evaluating Accident Effects

Receptor Type	Distance (m)	Direction	Location
site boundary	1000	west	on-site
nearest population center	4400	southeast	off-site
operations boundary	200	southeast	on-site

1.5 Summary of TA-18 Accidents Analyzed

A total of eight accident scenarios have been analyzed, with each scenario evaluated at three receptor distances for a total of 24 results. Table 1-4 summarizes the TA-18 accident scenarios analyzed.

Table 1-4

Summary of LACEF Accidents Analyzed

Number	Name	Location	Description	Material at Release	Risk	Building Wake Credit Taken
1	Kiva fire	Kiva 1	Kiva collapse and dispersion	Rapid	Uranium Particulates U(93) solution+	No
2	WINCO	Kiva 1	Accidental assembly Uranium solution excursion	Exfiltration	Fission Products U(5) solution+	Yes
3	SHEBA	SHEBA	Uranium solution excursion	Exfiltration	Fission Products	Yes
4	FLATTOP	Kiva 2	Plutonium excursion	Exfiltration	Fission Products and Plutonium Particulates	No
5	XGODIVA	Outside Kiva 2	Uranium metal extreme excursion	Rapid	Fission Products and Uranium Particulates	No
6	GODIVA	Kiva 3	Uranium metal extreme excursion	Exfiltration	Fission Products and Uranium Particulates	Yes
7	SKUA	Kiva 3	Plutonium excursion	Exfiltration	Fission Products and Plutonium Particulates	Yes
8	Vault	Hillside Vault	Building collapse and dispersion	Exfiltration	Uranium and Plutonium Particulates	No

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2.0 DESCRIPTION OF THE CRIT8 DOSE ASSESSMENT MODEL

2.1 Modeling Goals

The accident scenarios considered in the accident safety assessment of TA-18 involve several hundred radionuclides, many of which are short lived and give rise to multiple generation daughter products. Given such a scenario, the relatively close distances to receptor locations, and the task of identifying the wind speed which renders a maximum dose, a computer code was developed with the capability of varying those parameters of interest. Specifications for the development of the code include:

- calculation of the dose via the air immersion and inhalation pathways
- use of the DOE dose conversion factors (DOE 1988a and DOE 1988b)
- variation of wind speed from one to 10 m/s
- calculating up to 4th generation (i.e., great-granddaughter) radionuclide ingrowth
- calculating up to 99% of the dose resulting from exposure to approximately 2000 initial parent and decay product radionuclides
- calculating doses at distances as close as 100m
- accommodating variations in the receptor exposure time
- calculating reduction in dose owing to the building wake cavity effect
- accommodating variations in the rate at which material is released from the TA-18 laboratories following a possible accident
- in general, calculating maximum doses consistent with DOE guidance material

The last modeling goal pertains to a general conservatism and is reflected in the meteorological and dose assessment assumptions used in the analysis. For those calculations, the following assumptions are made:

- Pasquill stability class F is used exclusively
- the ambient wind speed yielding the greatest dose is assumed, independently, for each accident

- all releases are assumed to occur from the ground level
- all receptor locations are assumed to be along the centerline of the air dispersion plumes

The above assumptions provide for a conservative estimate (greater than expected) of dose assessment for each accident.

2.2 Model Overview

A computer program containing about 900 lines of code was developed for the TA-18 accident analysis. The code was developed using the Microsoft Quickbasic language and compiler to produce an MS-DOS stand-alone executable program. The compiled program requires about 10.0 minutes to fully execute the 10 wind speed iterations in the analysis. The program was designed for use in an IBM-PC/AT with an 80286 processor. Although special hardware or extra memory in not essential, a math co-processor and hard disk drive are highly recommended to avoid prolonged execution time.

The program performs two major functions, as illustrated in Figure 2-1. The first part of the program reads in large amounts of radionuclide and laboratory room release data from ASCII files. The data is reduced and stored in computer random access memory (RAM) in a manner designed for efficient data searches during program execution. The data files read by the program are:

(1) The *profile data file* contains information about the scenario such as scenario name, names of data files,the name of the output disk file, the receptor distance, the receptor exposure time, the time vs release fraction data, and the output print options. The profile data file is entered via an interactive prompt during program execution and contains all information and data file names required to run the code.

(2) The *parent data file* contains the list of initial radionuclide activities created in the accident which are released to the laboratory room. The activity of the parent represents the amount of activity after a bulk release fraction has been accredited. Parent radionuclide data is computed by the CINDER computer code and are unique inventories representative of specific materials and circumstances of the postulated criticality accident.

(3) The *radionuclide decay data file* which contains information about nuclide specific decay processes including daughter name(s), bi-modal decay fractions if pertinent, and half-lives. This file includes data for both parent and ingrown radionuclides. The radionuclide decay scheme is discussed in more detail in Section 2.3.

(4) The *dose conversion data file* contains nuclide-specific dose conversion factor data for the air immersion and inhalation pathways. This file includes data for both the parent and ingrown radionuclides. The dose conversion factor data is discussed in more detail in Section 2.6.

(5) The *X/Q data file* contains dose conversion factor data for both inert gas and particulate radionuclides. The values are calculated externally by the AIRDOS-EPA computer code (Moore et al, 1979) at selected distances. Using those data, the code then interpolates a X/Q values for the current receptor distance. The X/Q values are discussed in more detail in Section 2.4.

The second part of the program uses the data to perform dose calculations in a calculational loop which increments the wind speed by 1.0 m/s per iteration as illustrated in Figure 2-1. The underlying strategy of the code is:

(1) Increment the wind speed between one to 10 m/s.

(2) Calculate a decay time equal to the time required for the radionuclide cloud to arrive at the receptor location. That time is a function of both the delay time (i.e., time to escape the confines of the laboratory building containment) plus the plume travel time (i.e., receptor distance divided by wind speed). The delay time is discussed in more detail in section 2.6.

(3) Calculate the residual parent and daughter radionuclide activities using the Bateman equations and decay time.

(4) Calculate a X/Q value as a function of the wind speed, radionuclide type (i.e., inert gas or particulate), and receptor distance using the X/Q data table.

(5) Calculate the air immersion and inhalation doses.

(6) Correct the doses for building wake cavity effect if applicable. This effect is discussed in more detail in Section 2.7.

(7) Go to step (1)

A more detailed description of the calculational methodology is contained in the remainder of this chapter.

2.3 Daughter Formation

The list of radionuclides analyzed contains many nuclides with short half-lives relative to the transport and confinement times required to convey the radionuclide cloud to a receptor location. The ingrowth of radioactive daughters from parents of high activity must be considered in the dose assessment.

Several of the initial parents decay through four or more generations of radioactive products on a time frame equivalent to the cloud transport time. The formation of daughter products is calculated in the CRIT8 code with a maximum fourth generation ingrowth. Fifth generation and greater decay products are not accounted for due to their greater calculational complexity. Any potential irradiation produced by the fifth or greater generation is not accredited in the dose calculation. However,

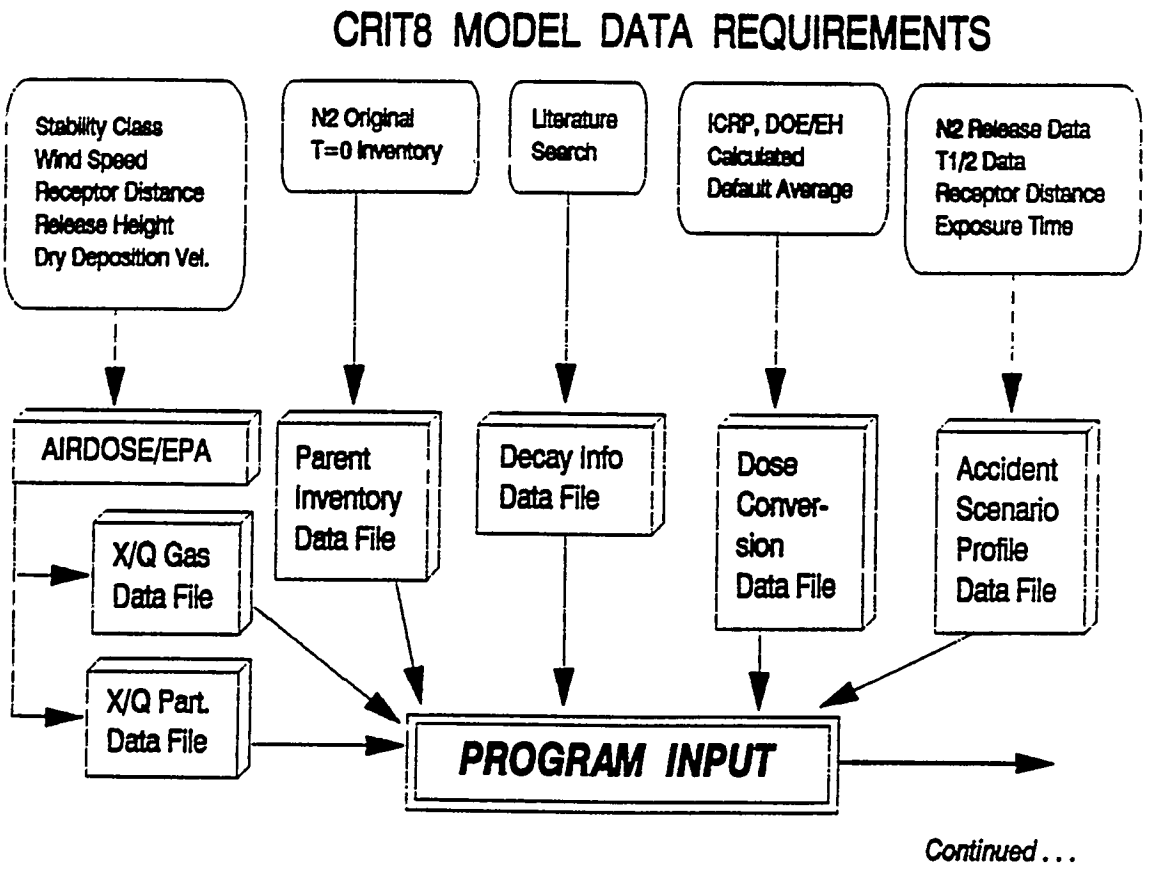

Figure 2-1: CRIT8 Model Data Requirements and Functions

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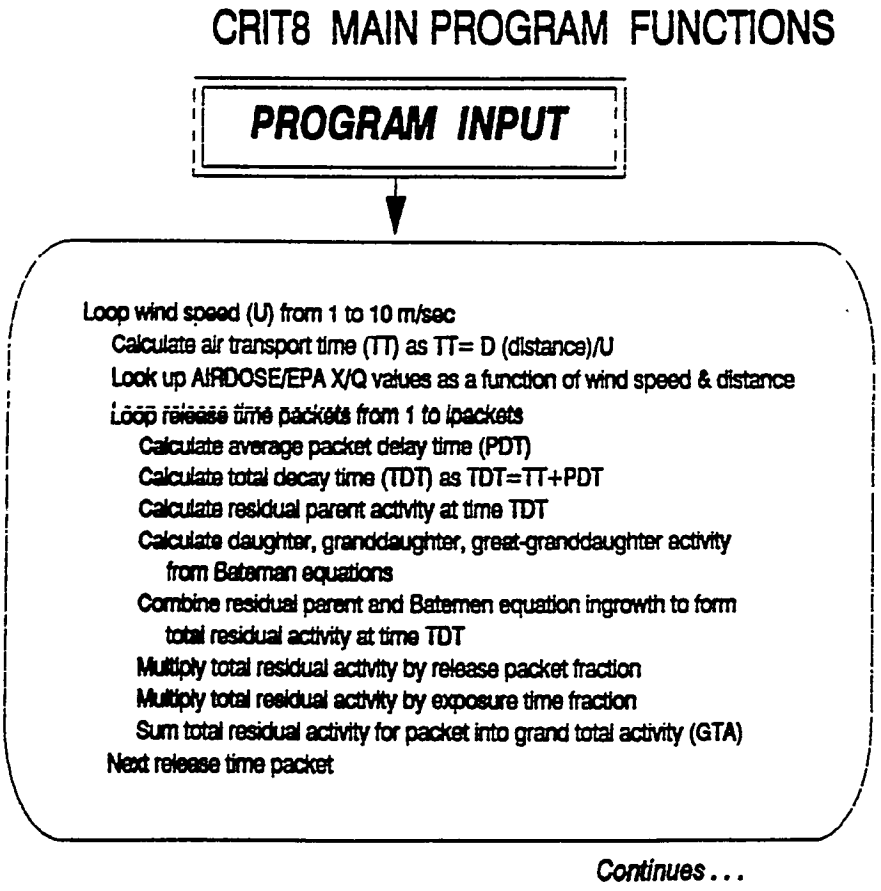

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CRIT8 MAIN PROGRAM FUNCTIONS

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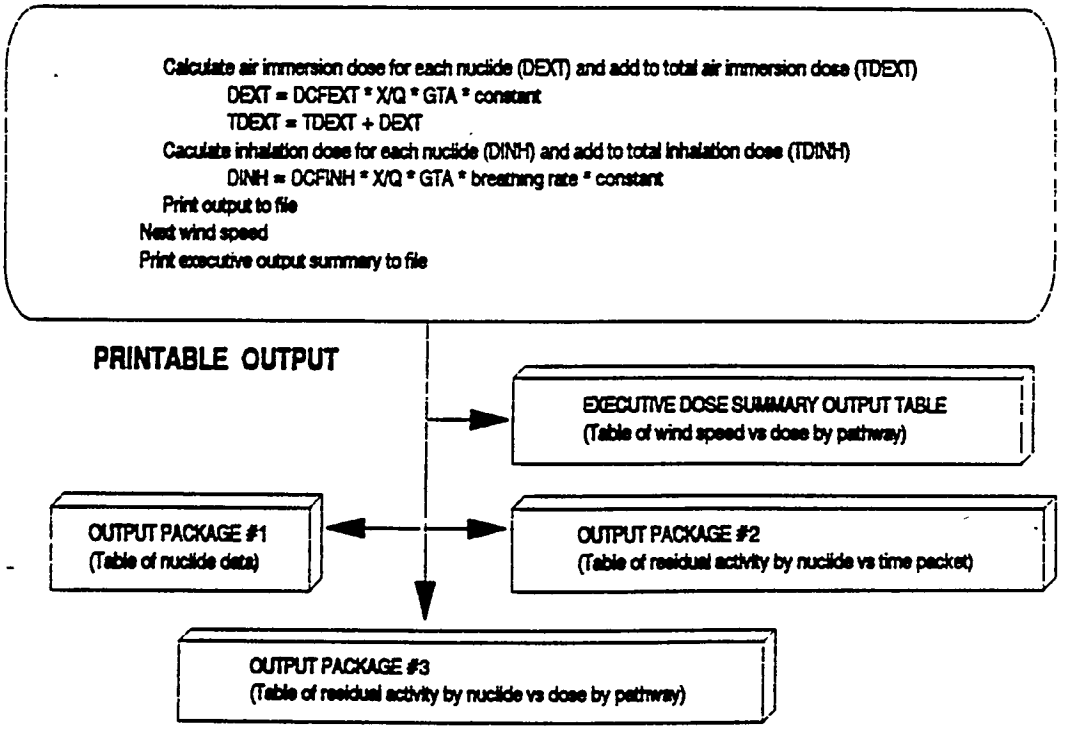


results have shown that the initial parent and first generation decay products are responsible for nearly all of the resulting dose.

The calculation of daughter ingrowth is performed using the Bateman equations (Friedlander et al, 1981) which may be used to calculate any generation decay product given the initial parent inventory. Technically speaking, the Bateman equations calculate only the number of atoms of a given decay product:

$$N_i = N_p \times f(t, \lambda_i, \lambda_{i-1}, \lambda_{i-2}, \ldots, \lambda_p)$$

where N_i = Number of atoms of the ith generation nuclide,
N_p = Number of atoms of the parent nuclide,
λ = decay constant (lambda)
f()= function of time, t, and decay constants for the parent, daughter, granddaughter, etc. to the ith generation.

The complexity of f() increases disproportionately as the generation increases. The relationship between activity and atoms is

$$A = \lambda \times N$$

where N = Number of atoms
A = Activity of the number of atoms
λ = decay constant

Combining the Bateman equation above with the definition of activity yields

$$\begin{aligned} A_i &= N_i \times \lambda_i \\ &= N_p \times f() \times \lambda_i \\ &= \lambda_i \times f() \times A_p / \lambda_p \end{aligned}$$

where A_i = Daughter activity
A_p = Parent activity
λ_i = Daughter decay constant
λ_p = Parent decay constant

Simply put, the daughter activity equals the parent activity times the ratio of the daughter to parent decay constants, times f(). The daughter activity acquires the units of Curies (Ci) when the parent activity is expressed in Ci.

2.4 X/Q Calculations

The X/Q (chi/Q) value expresses the dispersion characteristics of the plume carrying the radioactive cloud. X/Q is a function of many parameters including receptor distance, atmospheric stability, wind speed, release height, receptor location relative to the axis of the plume, and plume depletion effects. The X/Q calculation in this analysis uses a standard Gaussian plume analysis:

$$X/Q = \frac{1}{Pi \times S_y \times S_z \times U} \times DF$$

where X/Q= air concentration per unit source rate, s/m^3,
Pi = 3.142
S_y = Lateral dispersion coefficient, m,
S_z = Vertical dispersion coefficient, m,
U = Ambient wind speed, m/s,
DF = plume depletion fraction.

The above X/Q equation models the dispersion as though the release occurs at ground level and places the receptor on the center axis of the plume. Both of those assumptions are conservative in that they result in a maximized air concentration. The dispersion coefficients, S_y and S_z, are functions of downwind receptor distance and stability class, and increase with increasing distance and less stable atmospheric classes (i.e., Pasquill class A-C). The depletion fraction accounts for the effect of dry deposition, gravitational settling , and precipitation scavenging. Of these, only dry deposition may be accredited in a conservative analysis. Dry deposition accounts for the chemical and mechanical attachment of radionuclides on surface vegetation, and is function of wind speed, stability class, and dry deposition velocity. The dry deposition velocity is a function of the particulates' chemistry and the local flora, although a more generic approach has been established and will be used in this analysis. The X/Q values calculated by AIRDOS-EPA code (Moore et al, 1977) and used in this analysis are presented in Section 3.6

2.5 Packet Analysis Methodology

Once a postulated accident occurs, radionuclides are released to the laboratory room hosting the accident. In all but two accident scenarios analyzed, the laboratory room is not damaged or otherwise affected by the accident event. Consequently, the radionuclides inside the laboratory room have no direct path to the outside. For the most part, the material is contained in the laboratory. The only release is that which occurs via the infiltration-exfiltration of air through the cracks around doors and windows, or which otherwise permeates through the structure. Such a release is strongly dependent on the outside ambient wind speed. An exfiltration type room release requires significant time to occur and greatly affects the way in which room material is introduced into the air dispersion stream.

Section 3.5 provides a detailed description of the release curve calculational methodology. The methodology shows that the release fraction is a function of wind speed and that a decreasing fraction of room material is released to the outside as time progresses. Each building has its own characteristic release curve consistent with that building's construction and geometry. Release curves for the kivas and the hillside vault were computed using ASHRAE methodology by the N-2 Group and supplied as inputs to CRIT8. From a given release curve, the total fraction of material may be integrated over a fixed period of time. The quantity of material released over such a period is a release packet and represents, in effect, the digitization of the release curve. A given scenario release is analyzed by breaking the release curve into a number of continuous sequential release packets each of which stipulates a fractional release of room material over a fixed period of time.

Release fraction time intervals are chosen so that potential exposure from shorter lived radionuclides will not go unnoticed. For example, if a release of material were to occur over a 30 minute period, the radionuclide inventory averaged over 30 minutes would not contain short-lived radionuclides (i.e., half-lives less than a few minutes) since they would have decayed away. However, if the thirty minute release were divided into ten 3-minute releases, the first release or packet would contain the short-lived radionuclides. Release packets are designed to be shorter at first and subsequently increase in duration as time progresses. Packets start at about one minute in duration (midpoint at 30 seconds) since a minimum decay time of at least 20 seconds (200m minimum receptor distance at 10 m/s wind speed) are anticipated. Tables A-1 through A-6 summarize the release packets used for the accident analysis.

For the purposes of dose assessment, the exposure time to the radioactive release never exceeds 120 minutes by definition. Therefore, releases occurring after 120 minutes has elapsed are of no interest.

2.6 Dose Assessment

The radiation dose assessment presented in this analysis utilizes the methodology promulgated in DOE Order 5480.1a, and DOE (1988a and 1988b). Fifty-year committed effective dose equivalents (CEDE) are calculated for both internal and external exposures via the airborne pathway. All the doses presented in this analysis occur as a result of a calculated release of radioactivity from a postulated accident. Potential contributions to the accident dose include only exposure modes which are unavoidable following the accident. This includes radiation doses acquired via the inhalation and air immersion pathways only. Doses resulting from ingestion of contaminated food or water, or prolonged exposure to radionuclides deposited on the ground are precluded as part of the facility's post accident emergency preparedness plans following an accidental release.

2.6.1 Air Immersion Dose

The air immersion dose calculated for a given accident scenario is the sum of air immersion doses over all nuclides

$$D_{ai} = SUM_i \ (D_{ai})_i$$

where D_{ai} = Total air immersion dose summed over all nuclides, rem,
$(D_{ai})_i$ = Air immersion dose from the ith nuclide, rem.

The air immersion dose calculated for an individual radionuclide is

$$(D_{ai})_i = A_i \times (X/Q)_i \times DCF_i \times (1x10^{6}) \times (1x10^{-6}) \times (2.78x10^{-4})$$

where A_{i1} = Activity of the ith nuclide arriving at the receptor location, Ci,

$(X/Q)_i$ = X/Q for the ith nuclide calculated at the receptor distance, s/m^3,

DCF_i = Air immersion dose conversion factor for the ith nuclide, rem-cm^3/uCi-hr,

$1x10^6$ = uCi/Ci,

$1x10^{-6}$ = cm^3/m^3,

$2.78x10^{-4}$ = s/hr.

The air immersion dose conversion factor data is discussed in more detail in section 3.3.

2.6.2 Inhalation Dose Assessment

The inhalation dose calculated for a given accident is scenario is the sum of inhalation doses over all radionuclides

$$D_i = SUM_j (D_j)$$

where D_i = Total inhalation dose summed over all nuclides, rem,
D_j = Inhalation dose from the jth nuclide, rem.

The inhalation dose calculated for the jth nuclide is

$$D_j = A_j \times (X/Q)_j \times DCF_j \times BR \times (1x10^6)$$

where A_j = Activity of the jth nuclide arriving at the receptor location, Ci,

$(X/Q)_j$ = X/Q for the jth nuclide calculated at the receptor distance, s/m^3,

DCF_j = Inhalation dose conversion factor for the jth nuclide, rem/uCi,

BR = Standard man breathing rate, $3.4x10^{-4}$ m^3/s,

$1x10^6$ = uCi/Ci.

2.6.3 Effective Dose Equivalent

The calculation of the 50-year committed effective dose equivalent (EDE) is the

sum of the external air immersion dose and the internal inhalation dose, although the external dose is, in effect, not a true 50-year committed dose since exposure occurs only during the passage of the radioactive cloud. With the inhalation dose, bodily exposure continues, in the EDE model, over 50 years or until the radionuclide(s) are removed through biochemical or radioactive decay processes. In any event, the EDE model calculates a time-integrated absorbed dose that does not exceed 50 years of bodily irradiation. Both the external and internal conversion factors result in an effective dose equivalent defined in the ICRP publication 30 (ICRP, 1978) as a weighted dose calculated for 12 critical organs of the body. Summing both the external and internal EDE's together results in a meaningful total EDE expressing the combined effects of both internal and external exposure. Dose conversion factors used in this analysis are discussed further in Section 3.4.

2.6.4 Receptor Exposure Time

The dose equations presented above assume that the receptor is present during the entire passage of the radionuclide cloud. In many of the accident scenarios analyzed, this assumption is invalid and a partial exposure based on limited exposure time must be calculated. Given the packet methodology employed for calculating the room release, the exposure time is implemented by assigning an exposure fraction to each packet. The packet exposure fraction represents the fraction of packet material to which the receptor is exposed. Table 2-1 summarizes the exposure fractions for the accident scenarios.

For the confined release scenarios at 200m downwind distance, a 30 minute exposure time was evaluated. From Table A-1, for the first accident scenario, the first packet releases material over a one minute period. The packet exposure fraction is 1.0 since the receptor will be present for 30 minutes, longer than the duration of the first packet. The second packet also lasts one minute. The total expired time is now two minutes and the packet exposure fraction for the second packet will also be 1.0. Similarly, the next five packets' exposure fraction is 1.0. However, the eighth packet occurs after 30 minutes has elapsed and since the receptor has only 30 minutes of exposure, the packet exposure fraction is 0.0. All other subsequent packets exposure fractions are 0.0 since the receptor is gone. If exposure is terminated in the middle of a packet an appropriate fraction between 0.0 and 1.0 is calculated.

The dose is evaluated by calculating a separate independent dose for each packet. Packet doses vary by virtue of the decay time used to calculate to packets' activity. Each packet dose is then multiplied by the packet exposure fraction to yield a packet dose corrected for exposure time. The corrected doses are summed over all packets to yield the cumulative dose.

2.7 Building Wake Cavity Effect

The presence of a building or structure near the location of an air effluent can have a significant impact on the effluent air concentrations downwind. The structure has the effect of dispersing the effluent material before it actually enters the airstream. Several of the effects of the accident scenarios are mitigated by the presence of the laboratory structures hosting the accident.

The effects of the building wake cavity is documented in NRC, 1983. That methodology is used in these analysis to assess the potential air concentration reduction owing to the structure. The regulatory guide contains a correction factor which may be applied to conventional X/Q values calculated using the methods described in section 2.5. Since both inhalation and air immersion doses are directly proportional to the X/Q value, the building wake correction factor may be directly applied to the uncorrected doses.

The correction factor as described in the NRC Regulatory Guide 1.145, is a function of both wind speed and atmospheric stability class. As described in Section 3.5, the F-stability class is used exclusively for the accident analysis. Table 2-2 lists the building wake correction factors by wind speed for the F-stability class. Correction factors range from a maximum of 4.0 at a wind speed of 1 m/s to 1.4 at 5 m/s. At greater wind speeds, the correction factor is 1.0 and the building wake cavity has no effect. Table 1-4 describes the TA-18 accident doses and indicates whether a building wake correction factor is applicable in each.

Table 2-1

Packet Exposure Fractions

Type Release	Receptor Distance (m)	Packet Number 1	2	3	4	5	6	7	8	9	10
Confined	200	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0
	1000	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0	0.0	0.0
	4400	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Unconfined	200	1.0	1.0	1.0	1.0	NA	NA	NA	NA	NA	NA
	1000	1.0	1.0	1.0	1.0	NA	NA	NA	NA	NA	NA
	4400	1.0	1.0	1.0	1.0	NA	NA	NA	NA	NA	NA

NA = Not applicable. Unconfined releases use only four release packets.

Table 2-2

Building Wake Cavity Correction Factors[1]

Wind Speed (m/s)	Correction Factor[2]
1.0	4.0
2.0	4.0
3.0	2.6
4.0	1.8
5.0	1.4
6.0	1.0
7.0	1.0
8.0	1.0
9.0	1.0
10.0	1.0

1 - Source, NRC, 1983.

2 - Calculated for Pasquill stability class-F, only.

3.0 CRIT8 DATA REQUIREMENTS

A number of data are required to run the CRIT8 code. These data include specific radionuclide data relating to radioactive decay, source terms, and dose conversion factors. In addition, detailed data is required which describes the release of material from a laboratory room via the infiltration-exfiltration process. Also, specific X/Q data tables are imported into CRIT8 from the AIRDOS-EPA code. Lastly, discrete data items such as receptor distance and exposure times must be specified. All data are contained in data files that reside externally to the CRIT8 executable code.

3.1 The Profile Data File

The profile data file is an executive file which contains the name of the scenario, the names of all data files to be called, output file names and options, and the receptor distance and exposure time. When the CRIT8 code executes it responds by prompting the user for the profile data file name.

3.2 Radionuclide Inventories Analyzed

A criticality event creates an initial inventory of over 900 radionuclides. Many of the initial radionuclides quickly decay, at least in part, into daughter, granddaughter, great-granddaughter, etc., decay products. After a relatively short period of time, the number of radionuclides present will increase to several thousand. Such a large number of radionuclides must be supported by an equally long list of support data described in section 2.1. Computer RAM constraints and potentially long code execution time imposed by the PC environment make it imperative to reduce the initial number of parent nuclides to those which contribute most to the resulting doses.

The initial activities of the parent inventory vary over many orders of magnitude. Ideally, an index of relative dose contribution could be formed as the product of initial activity and dose conversion factor since those are the only nuclide specific variations contained in the dose equation (see section 2.7). However, a criticality event results in uncommon radionuclides, most of which are not included in the dose conversion factors references (DOE, 1988a and DOE, 1988b) used in this analysis. Therefore, for the purposes of eliminating the majority of parent radionuclides which contribute very little to the overall dose, the following assumptions are made:

(1) For the external exposure pathway, the radionuclides contributing most are ranked by initial parent activity. Parent radionuclides of greatest activity are retained until a level of 99% of the total initial activity is accounted for.

(2) For the internal pathway, the inhalation dose is insignificant compared with the air immersion dose for radionuclides with half-lives less than one hour, and may, therefore, be disregarded (i.e., inhalation dose conversion factor value of 0.0). For radionuclides of half-life greater than one hour, virtually all dose conversion

factors are found in the reference material. Consequently, all parent radionuclides are retained if their half-lives are greater than one hour.

The first assumption reduces the number of initial parent radionuclides from more than about 900 nuclides to about 100 nuclides. The 100 or so nuclides retained account for over 99% of the initial activity of the original 900 initial parents. Note that all actinides present in the initial inventory are retained, regardless of their activity.

To justify the elimination of approximately 800 radionuclides, it is assumed that the eliminated radionuclides have air immersion dose conversion factors equal to the maximum (i.e., ~$1x10^4$ mrem-m^3/uCi-hr, DOE, 1988a). The relative dose contribution is the product of dose conversion factor and activity. The eliminated nuclides have a maximum activity of less than about 100 Ci so that the relative dose contribution has a maximum of about $1x10^4$ x 100 Ci or $1x10^6$. On the other hand, the maximum retained radionuclides have activities greater than about $1.0x10^5$ Ci with a dose conversion factor of about $1.0x10^4$ (i.e., Kr-90). The maximum hazard product is then $1.0x10^5$ Ci x $1.0x10^4$ or $1.0x10^9$. Consequently, dose contributions from the eliminated radionuclides is at lease three order of magnitude less than those for the maximum contributors, and may be safely eliminated.

While the initial parent radionuclides may be eliminated in the above argument, the potential for particularly bad daughter formation from eliminated parent radionuclides is possible. However, the potential daughter threat can only exist from daughter nuclides which are harmful as internally deposited radionuclides (i.e., those with high inhalation dose conversion factors). Therefore daughters formed by a parent with a maximum of 100 Ci or less initial activity would be of insufficient activity to produce significant external exposure.

The potential inhalation dose from a daughter product is greatest when the daughter happens to be a long-lived alpha emitting radionuclide. Inhalation dose conversion factors are greatest for radionuclides with half-lives greater than about 100 years. A daughter formed from a maximum of 100 Ci of a parent of half-life of one hour or less will yield a maximum of about $1.0x10^{-3}$ Ci of daughter product. Although many significant alpha/beta inhalation nuclides display half-lives less than 100 years and would, in the example above yield greater daughter activities, their inhalation dose conversion factors would necessarily be lower by virtue of their shorter half-lives. It can be shown that the dose resulting from the inhalation of the daughter will be much less than the air immersion dose resulting from exposure to the 99% activity of the initial parents retained.

In summary, the approximately 900 initial parent radionuclides created during a postulated criticality event are reduced to about 100 radionuclides. The shortened list contains the most active radionuclides which together account for over 99% of the total activity. In addition, the shortened list contains all radionuclides with half-lives greater than one hour. From the discussion above, the shortened list will result in internal and external doses that are equivalent in magnitude to those that would be calculated using the long list of about 900 radionuclides.

The name and activity of the initial significant radionuclides must be specified

in the parent inventory file. The code can accommodate up to 375 radionuclides including parent and daughter nuclides. Since each parent gives rise to from two to three daughters, no more than about 100 initial parents should be specified.

The initial list of radionuclides is generated by the CINDER code in LANL's T-2 Group. CINDER generates a unique set of initial parent radionuclides for a criticality event incorporating specific user defined characteristics of the event. That list is shortened to the most significant totaling from about 80 to 100 radionuclides depending on the accident scenario. Tables A-7 through A-13 summarize the short list of initial parents for each accident scenario. As discussed in section 2.3, the short lists contain about 99% of the initial beta/gamma activity and 100% of all radionuclides with half-lives greater than one hour, plus all actinides. Maximum activities occur for the krypton, bromine, and xenon isotopes at levels of several hundreds of thousands of Ci. Minimum retained activities are generally in the range of 100 Ci and greater.

3.3 Radioactive Decay Chain Data

Each parent radionuclide and future daughter radionuclide name must be specified in the decay data file. Each name is accompanied by that nuclide's half-life, decay daughter(s), and the fractional component along each decay path in the event of bi-modal decay. These data form a large data file whose name is entered into the profile data file. Table A-14 summarizes the data contained in the decay data file.

3.4 Dose Conversion Data

Dose conversion factors are used to convert the exposure received by a receptor into a radioactive dose measured in units of rem. Each radionuclide has unique dose conversion factors depending upon its own individual decay energies, half-life, and biochemical properties. Two dose conversion factors, air immersion and inhalation, are required for each parent and daughter radionuclide in these analysis.

Dose conversion factors calculated using the ICRP 26/30 methodology are required for performing DOE dose assessments. A partial list of dose conversion factors are provided in DOE, 1988. However, a criticality event generates many uncommon radionuclides for which dose conversion factors are not available. The remainder of this section describes the methodology used in selecting dose conversion factors for uncommon radionuclides. Dose conversion factors used in this analysis are presented in Table A-15.

3.4.1 Air immersion Dose Conversion

Approximately 350 radionuclide parents and daughters are analyzed in these studies. Of those only about 20% are referenced in the DOE dose conversion factor (DOE, 1988a and DOE, 1988b) documentation and/or ICRP 26/30 (ICRP, 1978) source material. The remaining radionuclides were either assigned a dose conversion factor according to its characteristic gamma energy, or in the case of a radionuclide for which no gamma energy data is available, assigned a value equal to the average air immersion dose conversion factor. The gamma energy method is preferable but many of the radionuclides are so uncommon that not even that information is available.

For radionuclides listed in DOE, 1988a reference, gamma energy functions were plotted against their air immersion dose conversion factors. The gamma energy function is the sum of the discrete gamma energies times its relative intensities. The gamma function data was taken from Gusev et al, 1979. The gamma functions vs air immersion dose conversion factor is plotted in figure 3-1 and demonstrates a reasonable correlation of data. From the correlation, air immersion dose conversion factors were calculated for radionuclides not contained in DOE, 1988 by multiplying the gamma function by 48.2. Radionuclides not contained in DOE, 1988a and with gamma energies not found in Gusev et al, 1979 were assigned a dose conversion factor of 4000 mrem-m^3/uCi-yr. That average was made over a set of short-lived radionuclides contained in DOE, 1988, having atomic numbers less than 150, similar to the radionuclides having no gamma energy data.

3.4.2 Inhalation Dose Conversion

As with the air immersion dose conversion factors, only a small percentage of the radionuclides analyzed are referenced in the DOE, 1988 documentation listing inhalation dose conversion factors. However, nearly all of the radionuclides not listed possess radioactive half-lives that are less than one hour. That characteristic suggests that the inhalation dose may be insignificantly small compared with a nuclides external air immersion dose. Table 3-1 summarizes a plot of the ratio of the air immersion dose to the inhalation dose for a random sample of radionuclides posing both half-lives less than one hour and dose conversion factors listed in DOE, 1988b. Those data indicate that the ratio of doses falls between about 10 and 50. Consequently, the inhalation dose conversion factor is assumed to be zero for all beta-gamma emitting radionuclides with half-lives less than one hour. That assumption implies that the dose is adequately represented by the air immersion dose. Inhalation dose conversion factors for radionuclides posing half-lives greater than one hour were found in DOE, 1988b and used in the dose calculations.

Lung clearance classes categorize internal dose conversion factors for a given radionuclide according to the nuclide's chemical form. Up to three sets of dose conversion factors are provided in DOE, 1988b per radionuclide. In general, the chemical form yielding the greatest dose conversion factor is used. The only exception to this method occurs for plutonium. When bulk plutonium oxidizes, plutonium dioxide particulates are formed which have a lung clearance class of years (class Y), (NRC, 1983). For oxide forms of plutonium, the inhalation dose conversion factors are less than for other chemical forms of plutonium as referenced in DOE, 1988b. Inhalation dose conversion factors presented in Table A-15 pertain to oxide forms of plutonium only.

3.5 Radionuclides Release Methodology

Several of the accident scenarios addressed result in radionuclide releases into one of several possible laboratory rooms. The room material is subsequently released to the outside either by the infiltration-exfiltration process or released directly through a breach in the building structure. The infiltration-exfiltration process is the normal exchange of room air that occurs through the cracks around doors and windows, or that which, otherwise, permeates through the structure. Nearly all structures exhibit some degree of air infiltration from the outside resulting in a slow

exchange of air with the outside. The rate of exchange is strongly related to the outside ambient wind speed. Tables A-1 through A-6 summarizes the accident analysis release fractions calculated for each release packet as a function of wind speed.

Table 3-1

Ratio of the Air immersion Dose to Inhalation Dose for Short Lived Radionuclides[1]

Radio-Nuclide	Air immersion Dose Conversion Factor[2] (mrem-m3/ uCi-yr)	Inhalation Dose Conversion Factor[3] (rem/ uCi)	Ratio Air immersion to Inhalation Dose	Half-life (min)
Ba-141	4.59E+03	7.40E-05	5.78E+00	1.83E+01
Ba-142	4.67E+03	3.60E-05	1.21E+01	1.07E+01
Br-84	1.02E+04	8.70E-05	1.09E+01	3.18E+01
Cs-138	1.27E+04	8.80E-05	1.35E+01	3.34E+01
I-134	1.38E+04	1.10E-04	1.17E+01	5.26E+01
Mo-101	7.94E+03	3.60E-05	2.06E+01	1.46E+01
Pr-144	1.79E+02	4.20E-05	3.97E-01	1.73E+01
Pr-147	3.84E+03	2.70E-05	1.33E+01	1.20E+01
Rb-88	3.58E+03	8.00E-05	4.17E+00	1.78E+01
Rb-89	1.14E+04	3.70E-05	2.87E+01	1.54E+01
Rh-103m	9.99E-01	4.60E-06	2.02E-02	5.61E+01
Tc-101	1.73E+03	1.60E-05	1.01E+01	1.42E+01
Te-131	2.16E+03	9.90E-05	2.03E+00	2.50E+01
Te-134	4.44E+03	1.00E-04	4.14E+00	4.18E+01
Y-91m	2.68E+03	3.10E-05	8.06E+00	4.97E+01

[1] - Half-lives are less than 60.0 minutes.
[2] - Source, DOE,1988a.
[3] - Source, DOE, 1988b.

3.6 X/Q Data Values

Calculation of the X/Q values was performed using the AIRDOS-EPA computer code (Moore et al, 1979) by selecting AIRDOS-EPA input values to represent the scenario described above. Two groups of X/Q values were calculated:

(1) Particulates X/Q values which use a dry deposition velocity of 0.0018 m/s as suggested by Moore et al, 1979

(2) Inert gas X/Q values which use a dry deposition velocity of 0.

The inert gases in these analysis are confined to isotopes of krypton, bromine, xenon,

and iodine. Inert gases result in air concentrations that are higher than particulate concentrations since material is not removed during plume transport. Although iodine is not an inert gas, its reactivity in the atmosphere is not well known and it is conservative, therefore, to treat iodine as an inert gas.

Tables A-16 and A-17 summarize the X/Q values used in these analysis. The X/Q values were calculated by the AIRDOS-EPA code at selected downwind distances ranging from 100m to 10,000m. At distances less than 100m the equations describing the dispersion coefficients become invalid, while 10,000m represents a practical upper bound to the receptor distances needed. User defined receptor distances which fall outside that range will be rejected by the CRIT8 code during execution. Any distance that falls within the range is acceptable and CRIT8 will interpolate a X/Q value using the distances and X/Q values provided in table A-16 and A-17.

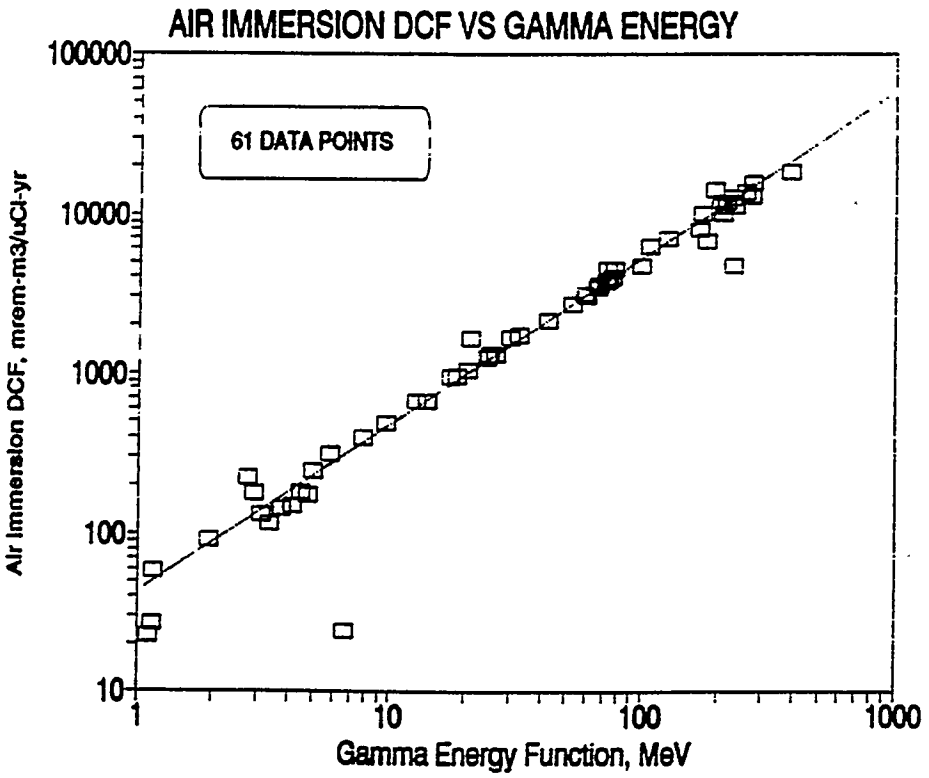


Figure 3-1: Air Immersion DCF vs Gamma Energy Function

4.0 EFFECTIVE DOSE EQUIVALENTS FROM ACCIDENT SCENARIOS

Effective dose equivalents were calculated for each accident scenario summarized in table 1-4 at each of three receptor distances summarized in table 1-3 for a total of 24 dose results. Those results are summarized in table 4-1 together with the significant exposure pathway and most significant radionuclides contributing to the final EDE. Figures 4-1 through 4-16 summarize dose results and pathway contribution for each accident scenario.

The greatest dose occurred for XGODIVA accident scenario with a calculated EDE of 43.5 rem at 200m primarily from an external exposure to Rb-90, a daughter of Kr-90 and granddaughter of Br-90, which are both very large activities in the initial parent inventory. The second greatest dose occurred for the SKUA accident with an EDE of 21.1 rem at 200m resulting from the inhalation of plutonium and americium particulates.

In general, the isotopes of rubidium including Rb-89, Rb-90, and Rb-91 provide the greatest overall exposure from excursion accident scenarios at distances less than 1km. Between 1km and 4400m a mixture of isotopes of rubidium, cesium, krypton, and xenon compete for most significant radionuclide contribution. Beyond 4400m, the excursion accident scenarios display the tendency towards a decreasing contribution from the air immersion pathway. In fact, in both the GODIVA and XGODIVA analysis, the inhalation pathway becomes the most significant pathway at distances of 4400m or greater. This is due to the decay of the fission products and relative longevity of the actinide radionuclides with large inhalation pathway contribution.

The plutonium particulate releases display a consistent maximum contribution from the Pu-239 and Am-241 radionuclides via the inhalation pathway irrespective of receptor distance. This is consistent with the longevity of those contributing radionuclides compared with the decay time.

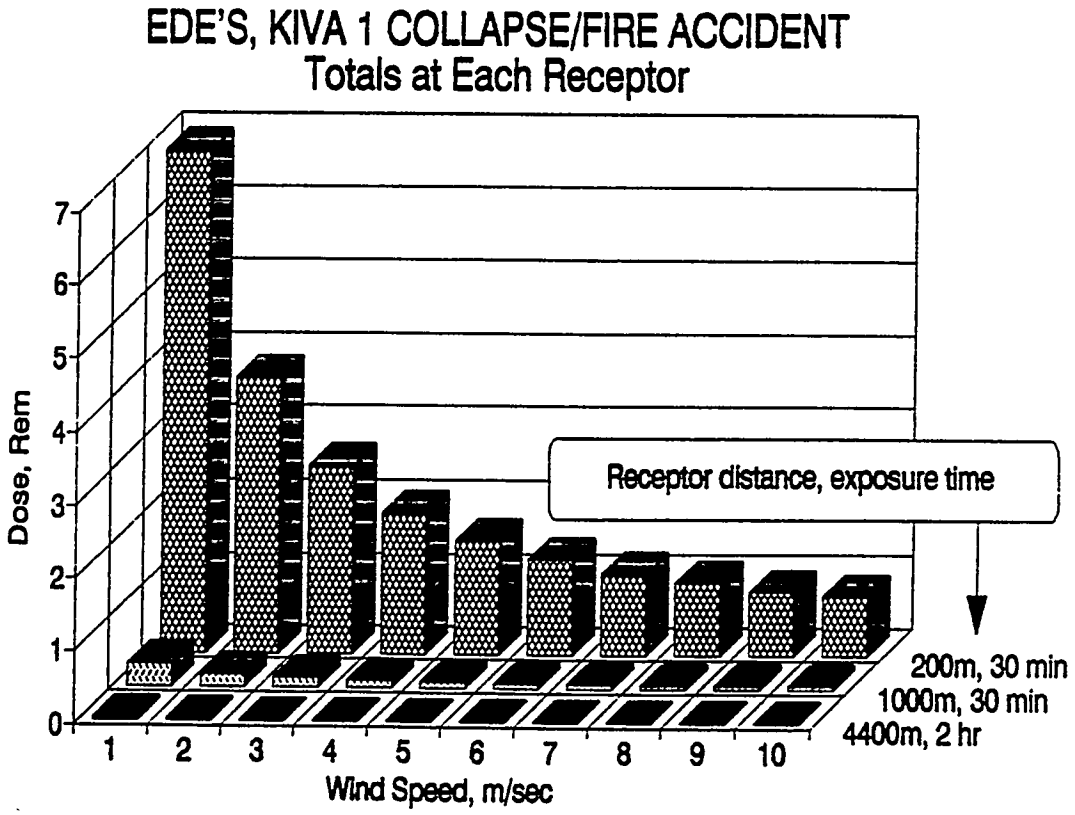
Table 4-1

Summary of EDE's Calculated for TA-18 Postulated Accident Scenarios

Scenario	Receptor Distance (m)	Wind Speed with Maximum EDE (m/s)	(rem)	Exposure Mode Contribution Pathway	%	Effective Dose Equivalent[1] Dose Contribution Nuclide	%	Origination
Kiva fire	200	1	6.90	Inhalation	100	U-234	97	Parent
	1000	1	0.30		100	U-234	97	Parent
	4400	1	0.033		100	U-234	97	Parent
WINCO	200	10	5.02	Air Immersion	98	Rb-90	13	Kr-90 D
								Br-90 GD
						Cs-140	11	Xe-140 D
						Rb-91	10	Kr-91 D
								Br-91 GD
	1000	10	0.17		97	Rb-90	15	Kr-90 D
								Br-90 GD
						Kr-89	9	Parent
								Br-89 GD
						Kr-93	9	Parent
	4400	7	0.022		89	Cs-138	24	Xe-138 D
						Rb-89	15	Kr-89 D
								Br-89 GD
						Xe-138	12	Parent D
SHEBA	200	10	4.31	Air Immersion	99	Rb-90	16	Kr-90 D
						Cs-140	14	Xe-140 D
						Rb-91	13	Kr-91 D
								Br-91 GD
	1000	10	0.13		98	Rb-90	21	Kr-90 D
								Br-90 GD
						Kr-89	13	Parent
								Br-89 GD
						Cs-140	11	Xe-140 D
	4400	10	0.0068		93	Rb-89	19	Kr-89 D
								Br-89 GD
						Xe-138	17	Parent
						Cs-138	14	Xe-138 D
FLATTOP	200	10	13.0	Inhalation	100	Pu-239	61	Parent
						Am-241	20	Parent
						Pu-240	14	Parent
	1000	7	0.64		100	Pu-239	60	Parent
						Am-241	20	Parent
						Pu-240	14	Parent
	4400	7	0.28		100	Pu-239	60	Parent
						Am-241	20	Parent
						Pu-240	14	Parent

[1] - Origination is either the initial parent, daughter(D) or granddaughter(GD)

Scenario	Receptor Distance (m)	Wind Speed with Maximum EDE (m/s)	(rem)	Exposure Mode Contribution Pathway	%	Effective Dose Equivalent[1] Dose Contribution Nuclide	%	Origination
GODIVA	200	10	0.77	Air Immersion	90	Rb-90	12	Kr-90 D Br-90 GD
						Cs-140	9	Xe-140 D
						Kr-89	8	Parent Br-89 D
	1000	10	0.28		86	Rb-90	12	Kr-90 D Br-90 GD
						Rb-89	10	Kr-89 D Br-89 GD
						Xe-138	7	Parent
	4400	7	0.0054	Inhalation	53	U-234	39	Parent
						Rb-89	10	Kr-89 D Br-89 GD
						Xe-138	7	Parent
XGODIVA	200	1	43.5	Air Immersion	94	Rb-90	21	Kr-90 D Br-90 GD
						Kr-89	14	Parent
						Cs-140	11	Xe-140 D
	1000	4	0.68		90	Rb-90	18	Kr-90 D Br-90 GD
						Kr-89	12	Parent Br-89 D
						Rb-89	7	Kr-89 D Br-89 GD
	4400	1	0.032	Inhalation	67	U-234	50	Parent
						Rb-89	9	Kr-89 D Br-89 GD
						Xe-138	8	Parent
SKUA	200	7	21.1	Inhalation	100	Pu-239	61	Parent
						Am-241	20	Parent
						Pu-240	14	Parent
	1000	7	1.03			Pu-239	60	Parent
						Am-241	20	Parent
						Pu-240	14	Parent
	4400	6	0.40			Pu-239	60	Parent
						Am-241	20	Parent
						Pu-240	14	Parent
Vault	200	10	5.03	Inhalation	100	Pu-239	61	Parent
						Am-241	20	Parent
						Pu-240	14	Parent
	1000	9	0.24			Pu-239	61	Parent
						Am-241	20	Parent
						Pu-240	14	Parent
	4400	8	0.12			Pu-239	60	Parent
						Am-241	20	Parent
						Pu-240	14	Parent


EDE'S, KIVA 1 COLLAPSE/FIRE ACCIDENT
Totals at Each Receptor
Dose, Rem
0
1
2
3
4
5
6
7
1
2
3
4
5
6
7
8
9
10
Wind Speed, m/sec
Receptor distance, exposure time
200m, 30 min
1000m, 30 min
4400m, 2 hr

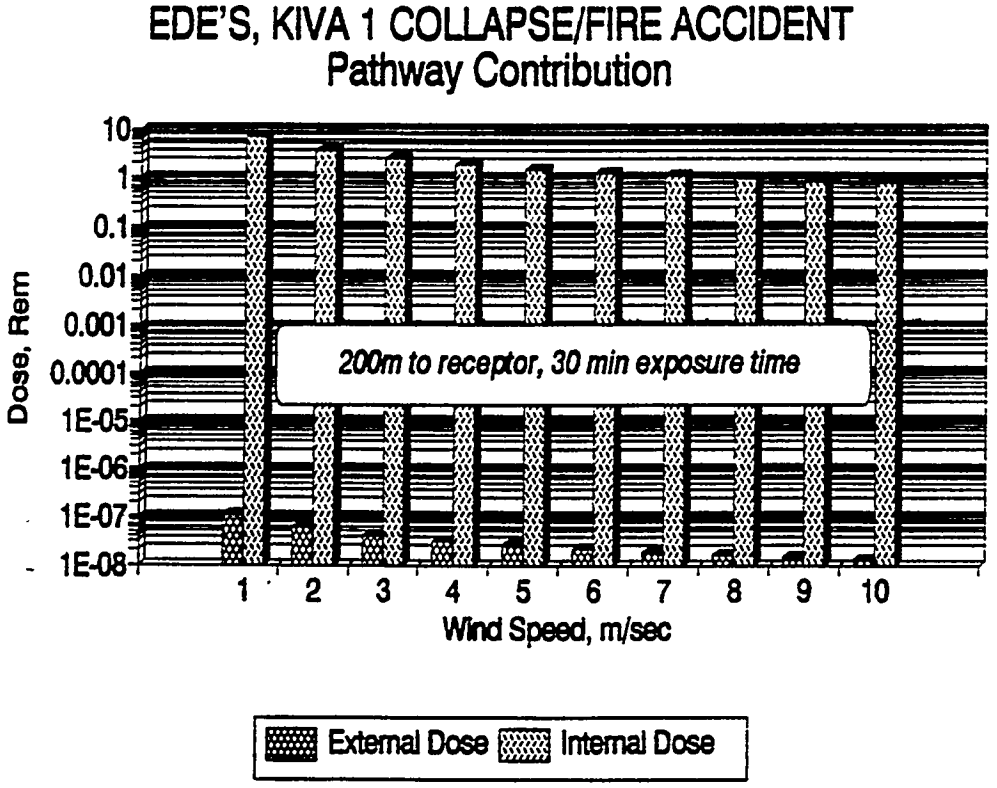


Figure 4-2: Pathway Contribution EDE's - Kiva 1 Collapse/Fire

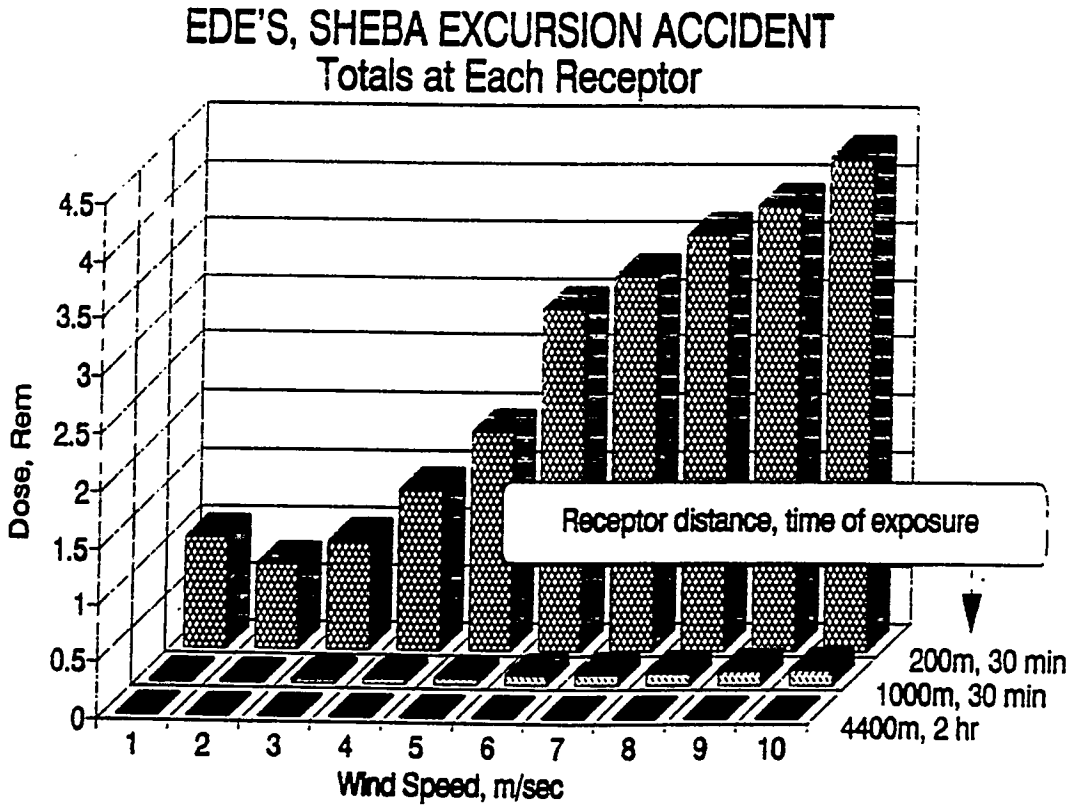


Figure 4-3: Receptor Total EDE's - SHEBA Excursion Accident

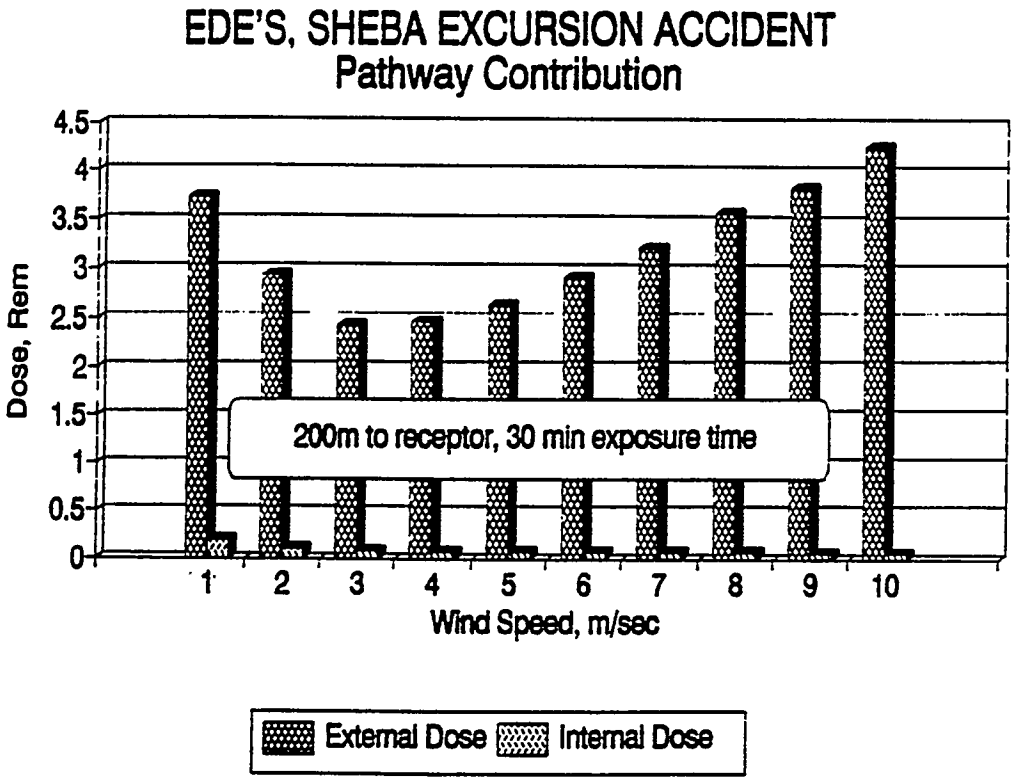


Figure 4-4: Pathway Contribution EDE's - SHEBA Excursion Accident

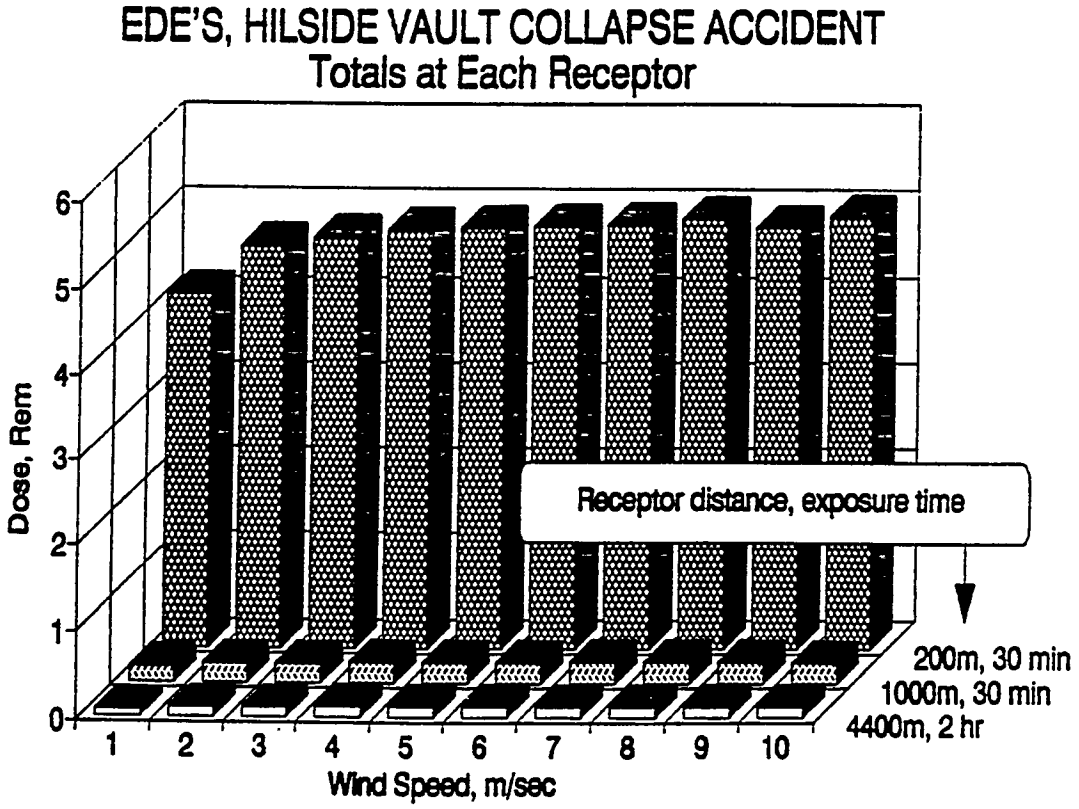


Figure 4-5: Receptor Total EDE's - Hillside Vault Collapse Accident

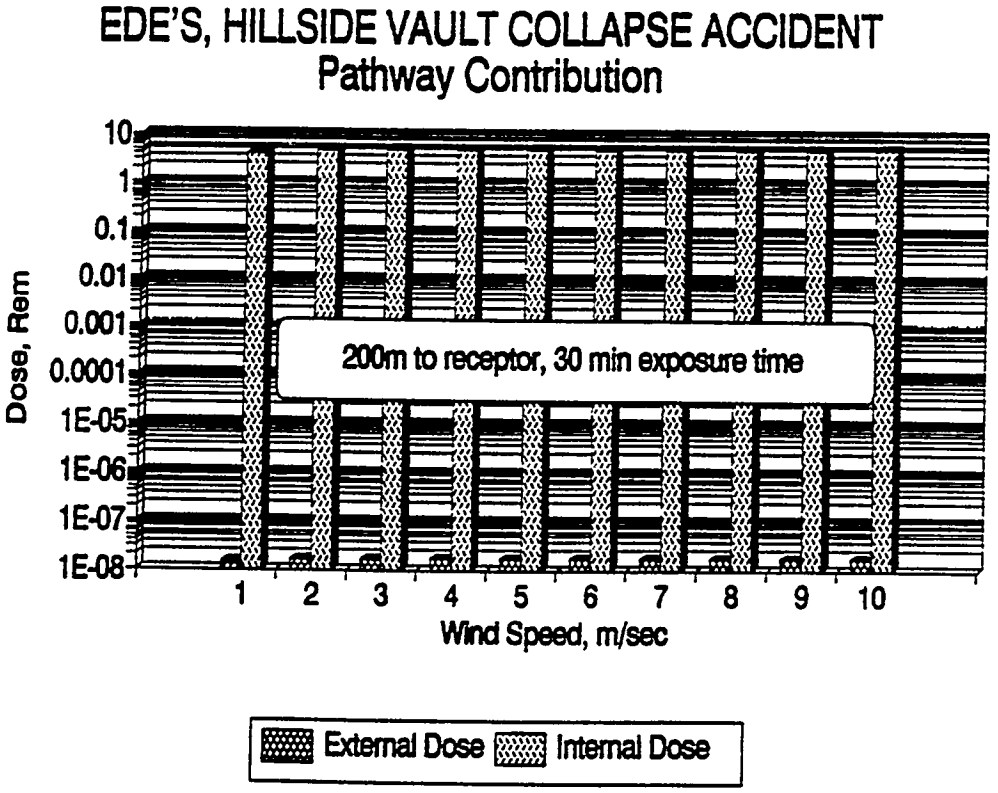


Figure 4-6: Pathway Contribution EDE's - Hillside Vault Collapse Accident

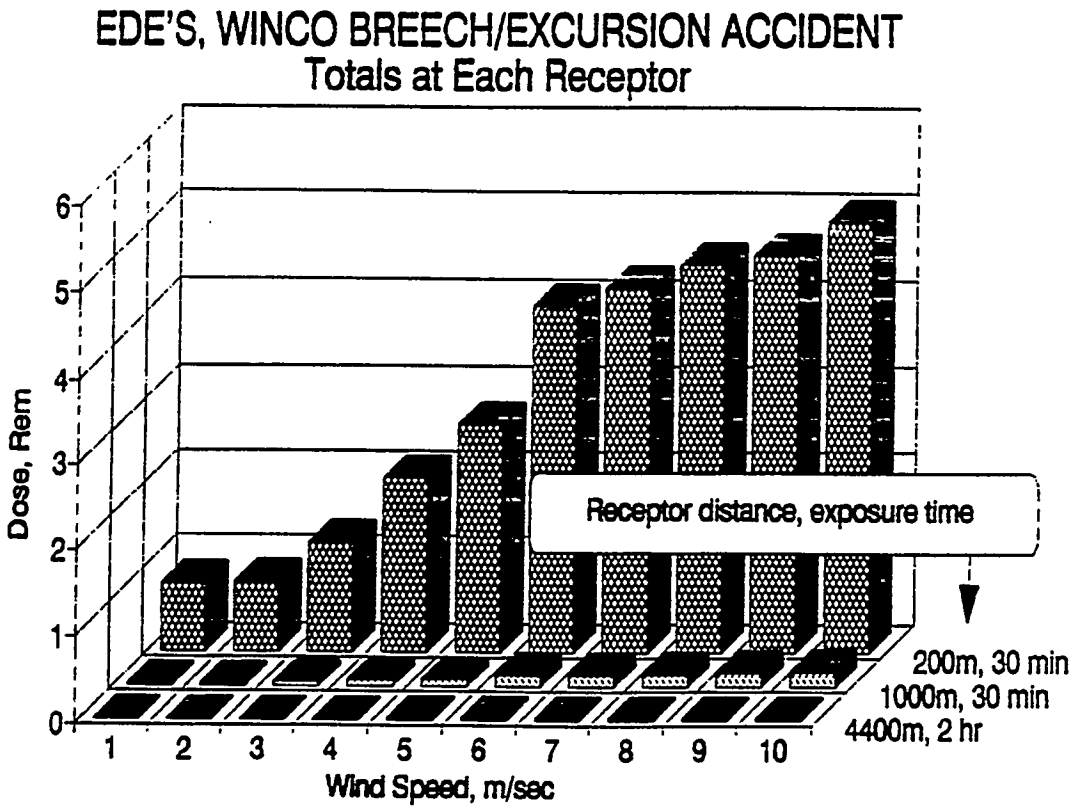


Figure 4-7: Receptor Total EDE's - WINCO Breech/Excursion Accident

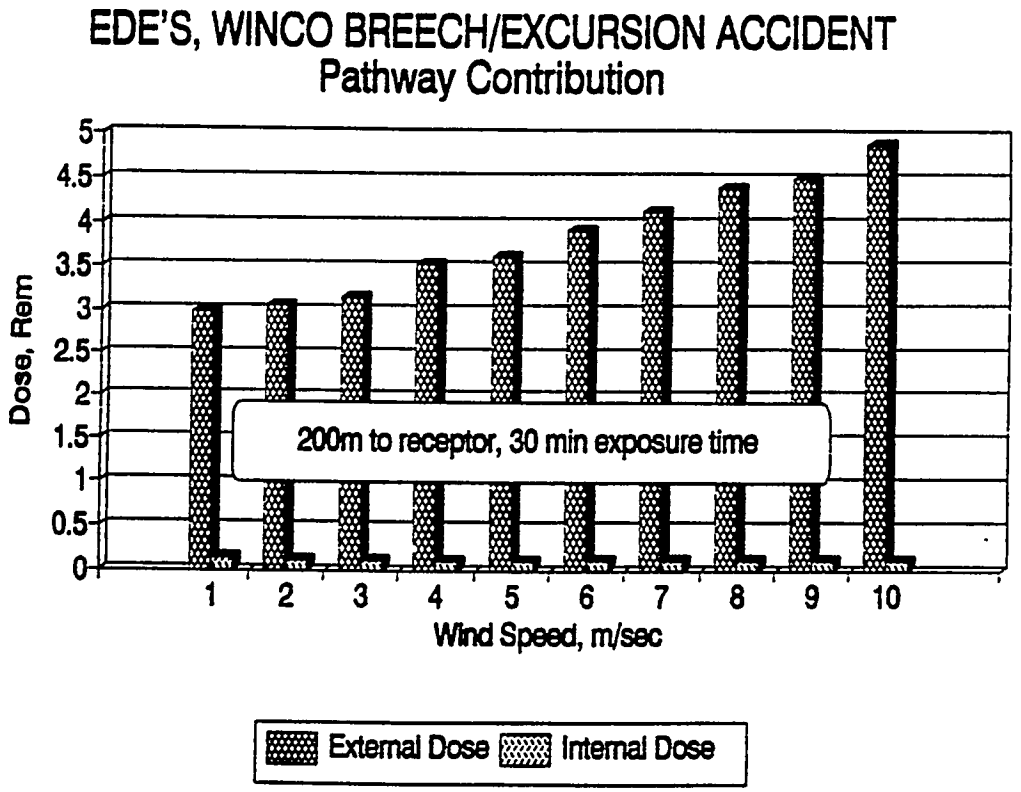


Figure 4-8: Pathway Contribution EDE's - WINCO Breech/Excursion Accident

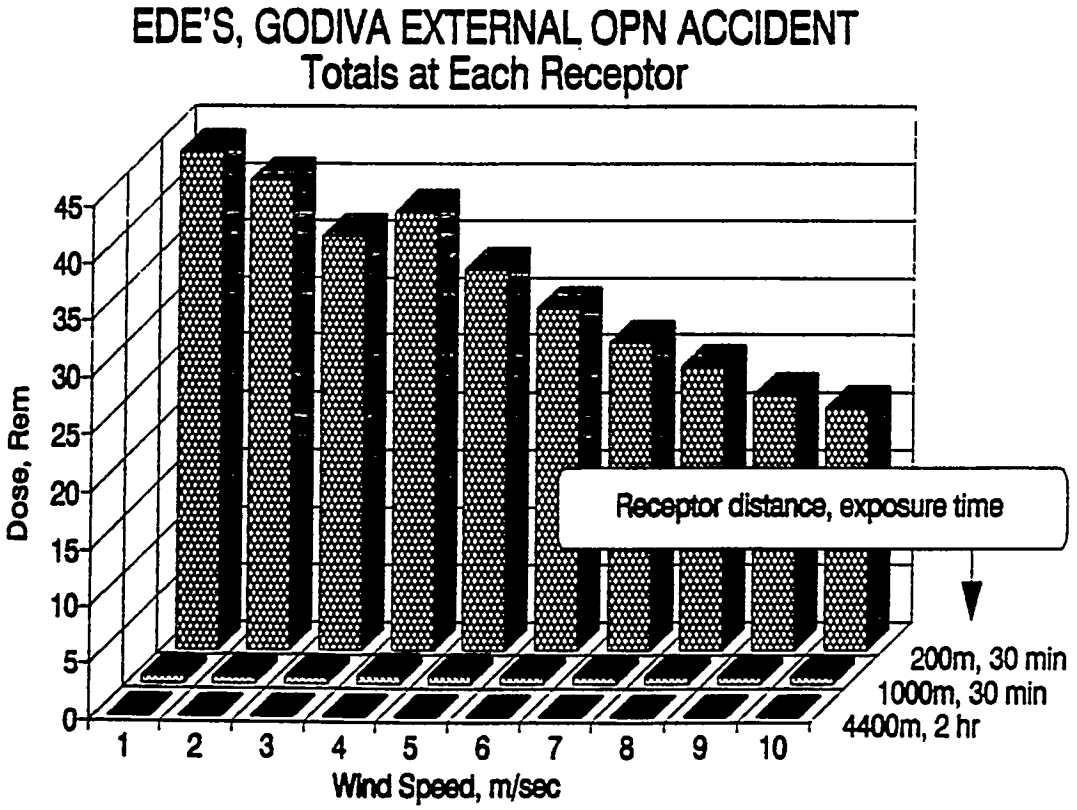


Figure 4-9: Receptor Total EDE's - GODIVA External Operation Accident

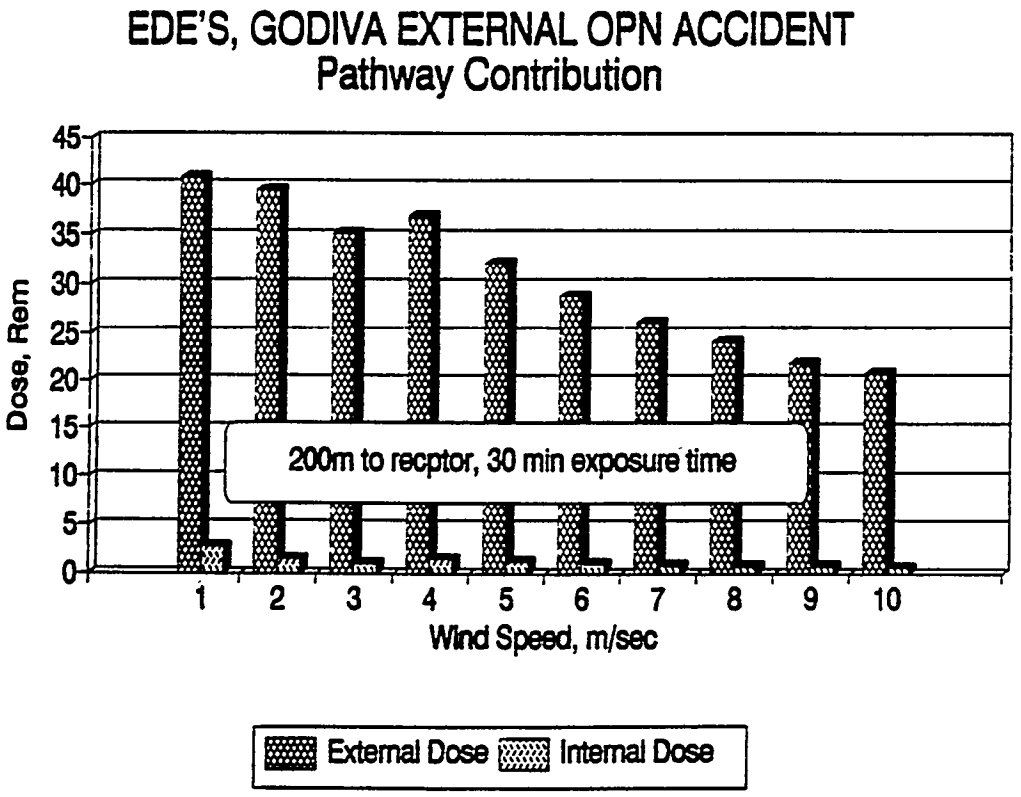


Figure 4-10: Pathway Contribution EDE's - GODIVA External Operation Accident

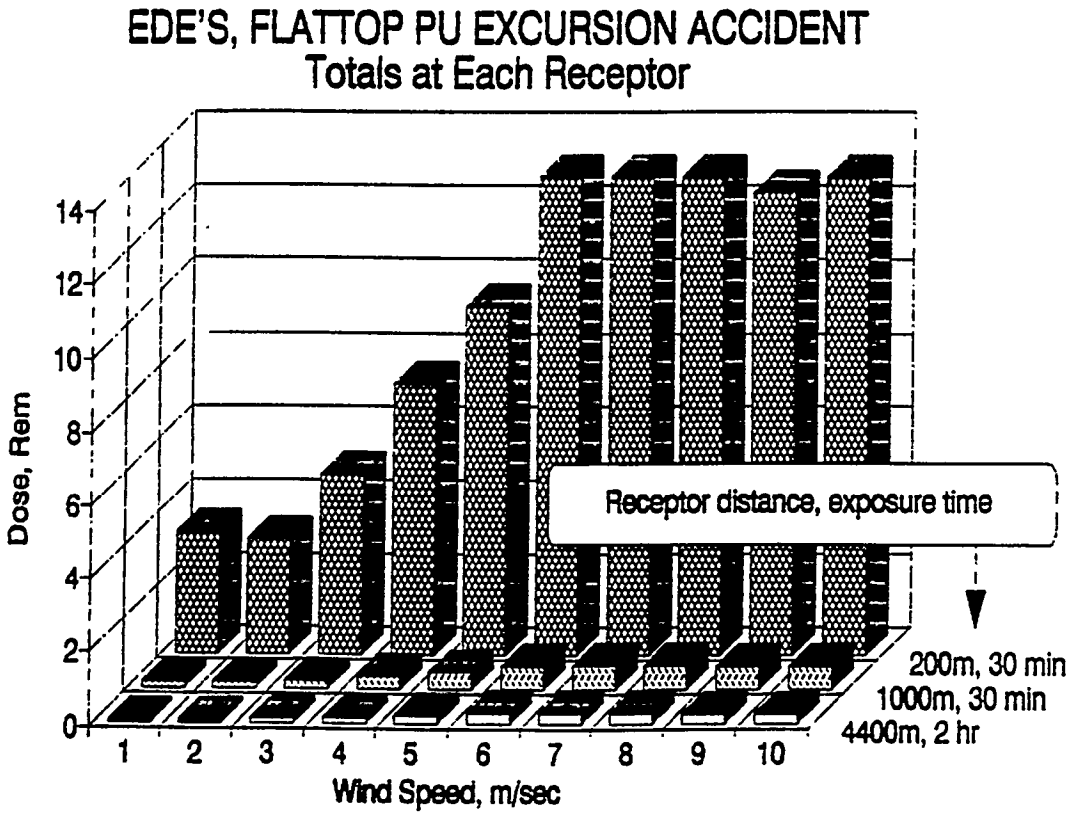


Figure 4-11: Receptor Total EDE's - FLATTOP Pu Excursion Accident

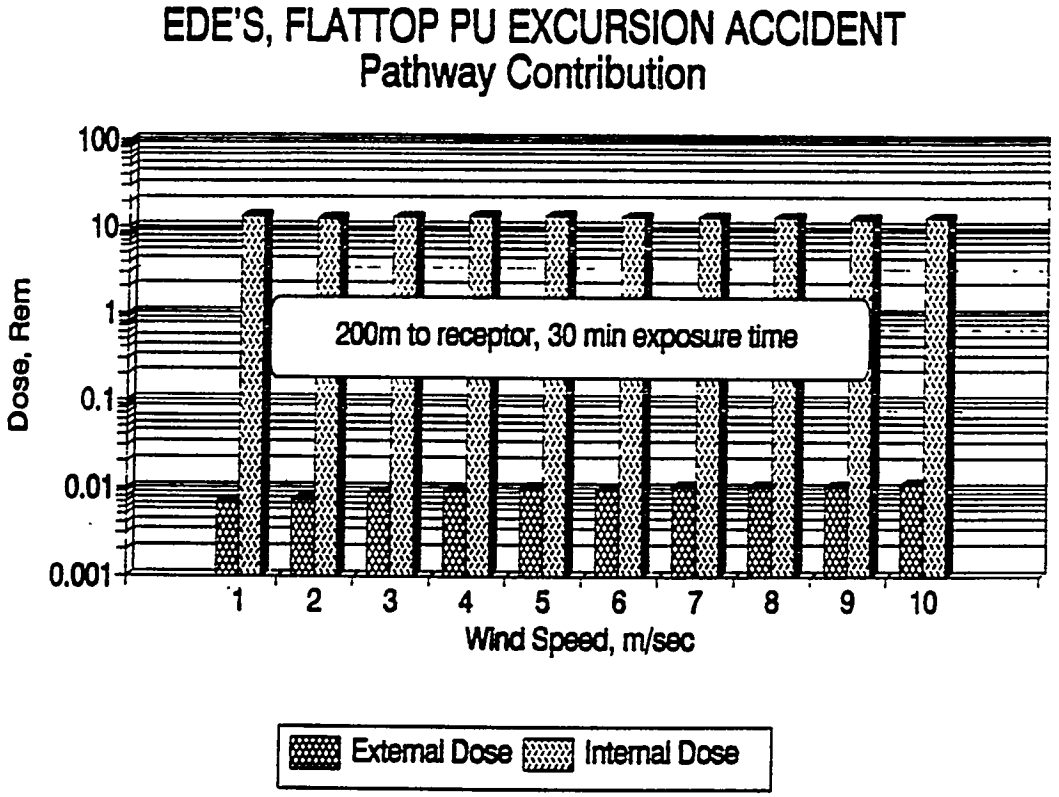


Figure 4-12: Pathway Contribution EDE's - FLATTOP Pu Excursion Accident

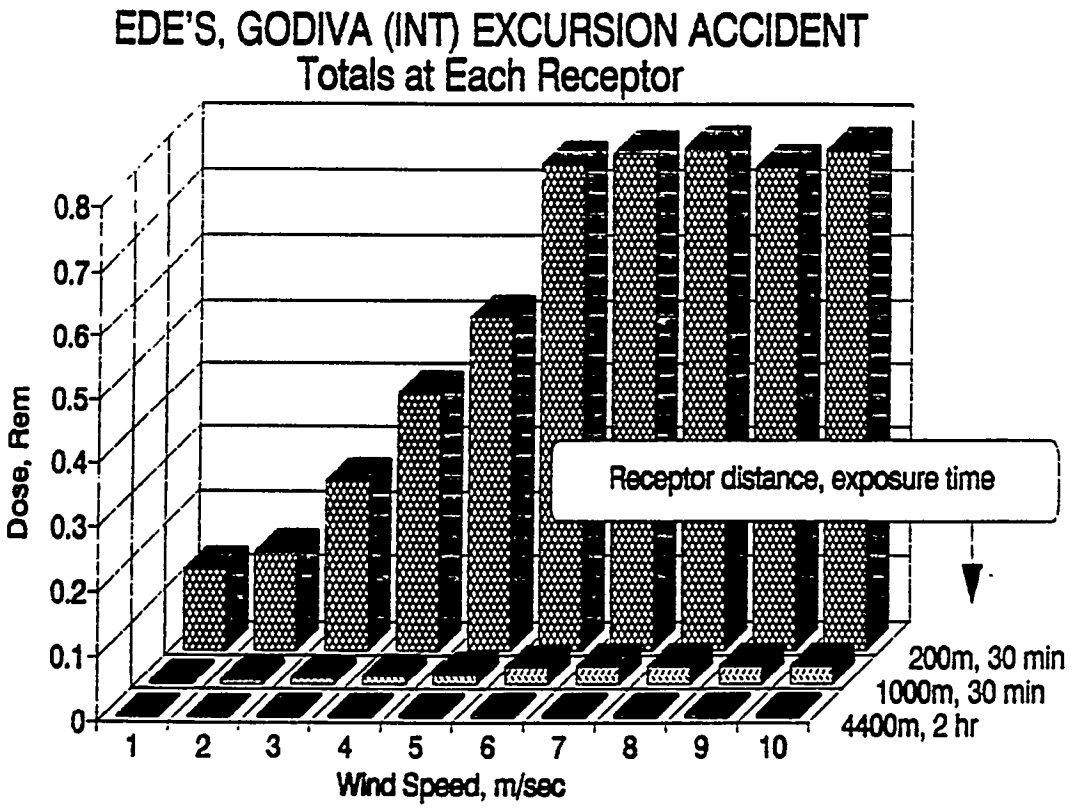


Figure 4-13: Receptor Total EDE's - GODIVA Kiva 3 Excursion Accident

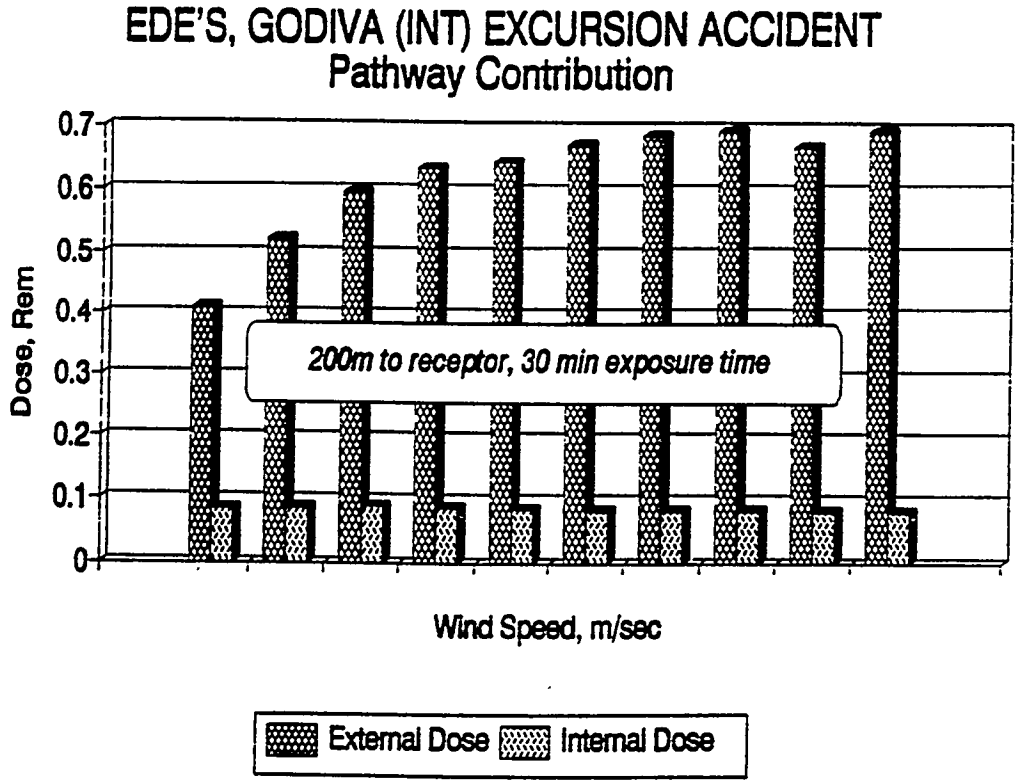


Figure 4-14: Pathway Contribution EDE's - GODIVA Kiva 3 Excursion Accident

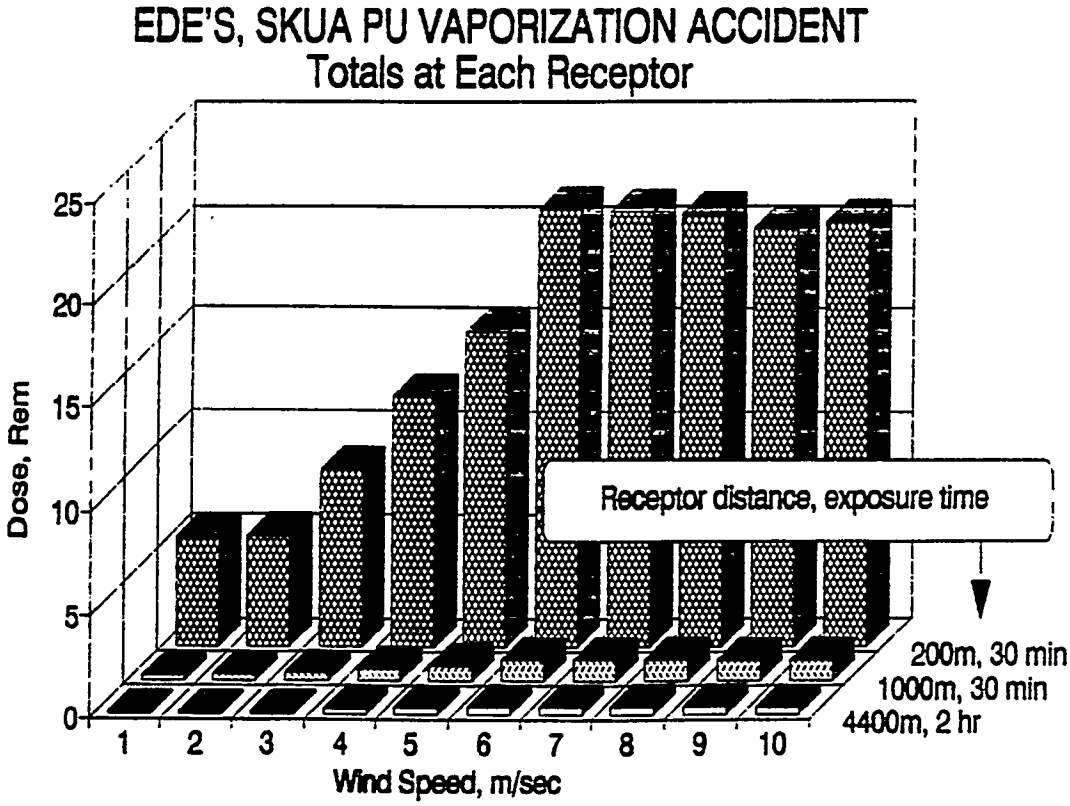


Figure 4-15: Receptor Total EDE's - SKUA Pu Vaporization Accident

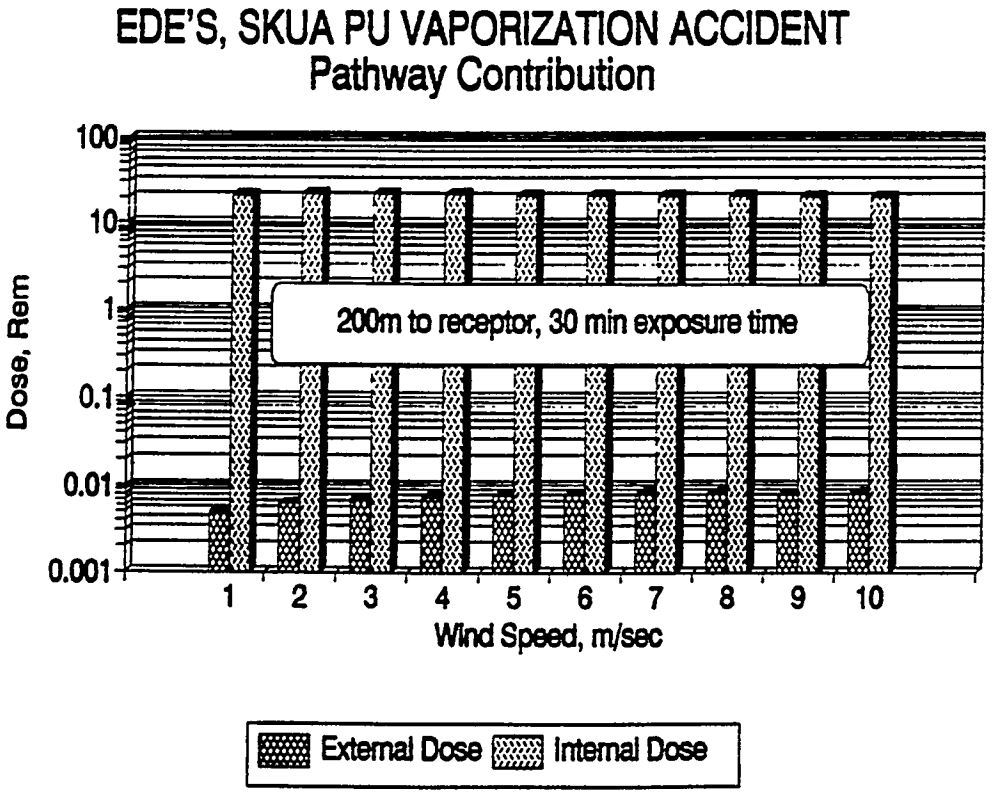


Figure 4-16: Pathway Contribution EDE's - SKUA Pu Vaporization Accident

5.0 HAND CALCULATION OF THE ACTIVITY AND DOSE CONTRIBUTION OF THE SELENIUM-89 DECAY SCHEME

A hand calculation was performed to validate, in part, the method in which the CRIT8 code calculates multiple generation daughter products. The somewhat tedious calculation is supplied in detail as Appendix B at the end of this document. The calculation tracks the Se-89 decay scheme of the XGODIVA accident scenario from initial parent (Se-89) to daughter (Br-89) to granddaughter (Kr-89) and finally to great-granddaughter (Rb-89). This particular decay scheme was used for several reasons

1) The decay is a significant contributor to the resulting dose.

2) The decay scheme has non-zero initial daughters (i.e., Br-89 and Kr-89) and therefore represents sufficiently complex parent decay and daughter ingrowth of the same radionuclide.

3) The decay tests the bimodal decay strategy and associated path fractions for the decay of Br-90 to Kr-89 and Kr-88.

Results from the hand calculation show only insignificant differences from values calculated using the CRIT8 code. The differences are attributed to the third digit rounding performed throughout the hand calculation. Floating point calculations performed in the computer use six digits. The results of the hand calculation are reproduced in Appendix B.

APPENDIX A

DATA TABLES USED IN THE CRIT8 MODELING PROCESS

Table A-1

Exfiltration Release Fractions for the Kiva 1 Facility

Packet Number	Begin Time (min)	End Time (min)	Wind Speed (m/s) 1	2	3	4	5	6	7	8	9	10
1	0.0	1.0	.002	.003	.004	.006	.007	.009	.011	.013	.015	.018
2	1.0	2.0	.002	.003	.004	.006	.007	.009	.011	.013	.015	.018
3	2.0	4.0	.004	.006	.008	.011	.014	.018	.021	.025	.030	.034
4	4.0	6.0	.004	.006	.008	.011	.014	.017	.021	.025	.029	.033
5	6.0	12.0	.011	.018	.025	.032	.041	.050	.060	.070	.081	.092
6	12.0	20.0	.015	.023	.032	.042	.052	.063	.074	.086	.097	.108
7	20.0	30.0	.018	.028	.038	.049	.061	.073	.084	.095	.106	.115
8	30.0	45.0	.027	.040	.055	.069	.083	.097	.110	.121	.130	.138
9	45.0	60.0	.026	.038	.051	.063	.075	.085	.093	.099	.103	.105
10	60.0	120.0	.097	.138	.175	.206	.229	.244	.250	.248	.239	.224

Table A-2

Exfiltration Release Fractions for the Kiva 2 Facility

Packet Number	Begin Time (min)	End Time (min)	Wind Speed (m/s) 1	2	3	4	5	6	7	8	9	10
1	0.0	1.0	.001	.001	.002	.002	.003	.003	.004	.005	.005	.006
2	1.0	2.0	.001	.001	.002	.002	.003	.003	.004	.004	.005	.006
3	2.0	4.0	.001	.002	.003	.005	.006	.007	.008	.009	.010	.011
4	4.0	6.0	.001	.002	.003	.005	.006	.007	.008	.009	.010	.011
5	6.0	12.0	.004	.007	.010	.013	.017	.020	.023	.026	.029	.032
6	12.0	20.0	.005	.009	.013	.018	.022	.026	.030	.034	.037	.041
7	20.0	30.0	.006	.011	.016	.022	.026	.031	.036	.040	.045	.049
8	30.0	45.0	.009	.017	.024	.031	.038	.045	.051	.057	.063	.069
9	45.0	60.0	.009	.016	.024	.030	.037	.043	.048	.053	.058	.063
10	60.0	120.0	.034	.063	.088	.112	.132	.150	.167	.181	.194	.205

Table A-3

Exfiltration Release Fractions for the Kiva 3 Facility

Packet Number	Begin Time (min)	End Time (min)	Wind Speed (m/s) 1	2	3	4	5	6	7	8	9	10
1	0.0	1.0	.001	.002	.003	.004	.005	.006	.007	.008	.008	.009
2	1.0	2.0	.001	.002	.003	.004	.005	.006	.007	.007	.008	.009
3	2.0	4.0	.002	.004	.006	.008	.009	.011	.013	.015	.017	.018
4	4.0	6.0	.002	.004	.006	.007	.009	.011	.013	.015	.016	.018
5	6.0	12.0	.006	.011	.017	.022	.027	.032	.038	.042	.047	.052
6	12.0	20.0	.008	.015	.022	.029	.035	.042	.048	.054	.060	.065
7	20.0	30.0	.010	.018	.027	.035	.042	.049	.056	.063	.069	.075
8	30.0	45.0	.014	.027	.039	.050	.060	.069	.078	.086	.093	.100
9	45.0	60.0	.014	.026	.037	.047	.056	.063	.070	.076	.082	.087
10	60.0	120.0	.054	.097	.133	.162	.187	.206	.221	.232	.240	.246

Table A-4

Exfiltration Release Fractions for the Sheba Facility

Packet Number	Begin Time (min)	End Time (min)	Wind Speed (m/s) 1	2	3	4	5	6	7	8	9	10
1	0.0	1.0	.012	.013	.014	.017	.022	.029	.037	.047	.059	.072
2	1.0	2.0	.012	.013	.013	.017	.021	.028	.036	.045	.055	.067
3	2.0	4.0	.023	.025	.026	.032	.041	.053	.067	.083	.101	.12
4	4.0	6.0	.023	.024	.025	.031	.04	.05	.062	.076	.089	.103
5	6.0	12.0	.065	.069	.072	.088	.109	.134	.161	.188	.212	.231
6	12.0	20.0	.079	.084	.088	.104	.124	.146	.165	.179	.186	.184
7	20.0	30.0	.089	.093	.097	.111	.128	.141	.148	.146	.135	.118
8	30.0	45.1	.015	.119	.123	.135	.145	.148	.14	.122	.097	.072
9	45.0	60.0	.096	.098	.1	.105	.104	.096	.079	.059	.039	.023
10	60.0	120.0	.25	.249	.247	.231	.195	.145	.094	.053	.026	.011

Table A-5

Exfiltration Release Fractions for the Vault Facility

Packet Number	Begin Time (min)	End Time (min)	Wind Speed (m/s) 1	2	3	4	5	6	7	8	9	10
1	0.0	1.0	.0001	.0002	.0004	.0005	.0006	.0007	.0009	.0010	.0011	.0012
2	1.0	2.0	.0001	.0002	.0004	.0005	.0006	.0007	.0009	.0010	.0011	.0012
3	2.0	4.0	.0002	.0005	.0007	.0010	.0012	.0015	.0017	.0020	.0022	.002
4	4.0	6.0	.0002	.0005	.0007	.0010	.0012	.0015	.0017	.0020	.0022	.002
5	6.0	12.0	.0007	.0015	.0022	.0029	.0037	.0044	.0051	.0058	.0066	.007
6	12.0	20.0	.0010	.0020	.0029	.0039	.0049	.0058	.0068	.0077	.0087	.009
7	20.0	30.0	.0012	.0024	.0036	.0048	.0060	.0072	.0084	.0096	.0107	.011
8	30.0	45.0	.0018	.0036	.0054	.0072	.0090	.0107	.0125	.0142	.0159	.016
9	45.0	60.0	.0018	.0036	.0054	.0072	.0089	.0106	.0123	.0140	.0156	.016
10	60.0	120.0	.0073	.0144	.0214	.0282	.0348	.0414	.0477	.0539	.0600	.060

Table A-6

Unconfined Release Fractions for the Kiva 1 Facility

Packet Number	Begin Time (min)	End Time (min)	Wind Speed (m/s) 1	2	3	4	5	6	7	8	9	10
1	0.0	0.5	.7	.7	.7	.7	.7	.7	.7	.7	.7	.7
2	0.5	2.0	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
3	2.0	10.0	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1
4	10.0	30.0	.1	.1	.1	.1	.1	.1	.1	.1	.1	.1

Table A-7

List of Initial Radionuclide Inventory Used in the Fire Accident Scenario at Kiva 1

Radionuclide	Initial Activity (Ci)
U-234	1.38E-02
U-235	4.04E-04
U-236	2.58E-05
U-238	3.64E-06

Table A-8

List of Initial Radionuclide Inventory Used in the WINCO Collapse Accident Scenario

Radionuclide	Initial Activity (Ci)	Radionuclide	Initial Activity (Ci)	Radionuclide	Initial Activity (Ci)
As-84	2.94E+03	Nb-100m	1.27E+03	Y-101	2.57E+03
As-84m	1.47E+03	Nb-101	1.06E+03	Zr-99	7.46E+03
Ba-143	1.33E+03	Nb-102	1.15E+03	Zr-100	3.03E+03
Ba-144	1.63E+03	Nb-102m	3.79E+03	Zr-101	7.77E+03
Ba-145	1.90E+03	Nb-103	5.93E+03	Zr-102	3.08E+03
Ba-146	1.70E+03	Nb-104m	1.95E+03	Zr-103	2.18E+03
Br-86	1.20E+03	Rb-92	3.33E+03		
Br-87	5.52E+03	Rb-93	3.33E+03		
Br-88	2.69E+04	Rb-94	3.45E+03		
Br-89	8.88E+04	Rb-95	1.20E+04		
Br-90	1.07E+05	Rb-96	6.14E+03		
Br-91	7.50E+04	Rb-97	1.48E+03		
Br-92	1.69E+04	Sb-134m	2.37E+03		
Br-93	2.19E+03	Se-87	7.28E+02		
Br-94	8.87E+02	Se-88	1.48E+03		
Ce-149	6.27E+02	Se-89	1.48E+03		
Cs-141	6.61E+02	Sr-95	8.14E+02		
Cs-142	7.07E+03	Sr-96	1.61E+04		
Cs-143	3.94E+03	Sr-97	2.34E+04		
Cs-144	2.53E+03	Sr-98	5.62E+03		
Cs-145	8.90E+02	Sr-99	1.32E+03		
I-133m	5.02E+03	Te-135	8.03E+02		
I-134m	7.16E+02	U-234	9.98E-04		
I-136	4.68E+03	U-235	2.93E-05		
I-136m	8.42E+03	U-236	1.88E-06		
I-137	2.97E+04	U-238	2.64E-07		
I-138	6.00E+04	Xe-134m	1.34E+05		
I-139	6.32E+04	Xe-137	1.16E+04		
I-140	3.79E+04	Xe-138	4.95E+03		
I-141	8.95E+03	Xe-139	9.54E+04		
I-142	2.79E+03	Xe-140	1.98E+05		
In-131m	6.36E+02	Xe-141	5.25E+05		
Kr-89	1.28E+04	Xe-142	3.43E+05		
Kr-90	1.18E+05	Xe-143	3.22E+04		
Kr-91	2.58E+05	Xe-143m	1.03E+05		
Kr-92	5.37E+05	Xe-144	9.29E+03		
Kr-93	1.37E+05	Xe-145	6.56E+02		
Kr-94	7.76E+05	Y-96m	9.00E+02		
Kr-95	2.87E+04	Y-97	2.12E+03		
Kr-96	7.69E+03	Y-97m	7.08E+03		
Kr-97	1.23E+03	Y-98	3.63E+03		
La-146	6.53E+02	Y-98m	1.12E+04		
La-147	9.24E+02	Y-99	7.06E+03		
La-148	1.32E+03	Y-100	6.15E+03		

Table A-9

List of Initial Radionuclide Inventory
Used in the SHEBA Accident Scenario

Radio-nuclide	Initial Activity (Ci)
As-84	1787
Se-87	441.8
Se-88	900.4
Se-89	898.7
Br-92	5123
Br-88	8169
Br-87	1675
Br-89	26950
Br-91	22760
Br-90	32450
Kr-95	8714
Kr-94	235600
Kr-97	373.7
Kr-96	2336
Kr-93	41660
Kr-90	35740
Kr-89	3873
Kr-92	163100
Kr-91	78230
Rb-94	2096
Rb-93	2021
Rb-92	2020
Rb-97	898.8
Rb-96	3728
Rb-95	7313
Sr-97	14180
Sr-99	801
Sr-96	9790
Sr-98	3415
Sr-95	494.1
Y-96m	546.7
Y-97	1290
Y-99	4289
Y-100	3732
Y-97m	4300
Y-98m	6775
Y-98	2206
Zr-101	4715
Zr-100	1837
Zr-99	4532
Zr-102	1868
Nb-104m	1187
Nb-102	696.1
Nb-102m	2303
Nb-100m	770.4
Nb-101	643.3
Nb-103	3599
In-131m	386.1
Sb-134m	1438
Te-135	487.6
I-139	19200
I-141	2718
I-140	11520
I-136	1421
I-133m	1522
I-136m	2557
I-138	18200
I-137	9013
Xe-138	1502
Xe-139	28950
Xe-134m	40800
Xe-137	3526
Xe-143m	31250
Xe-144	2819
Xe-143	9765
Xe-140	59970
Xe-141	159500
Cs-143	2393
Cs-142	4292
Cs-144	1537
Cs-141	401.6
Cs-145	540.6
Ba-145	1153
Ba-146	1033
Ba-143	805.1
Ba-144	988
La-147	561.3
La-146	396.2
La-148	800
Ce-149	380.5
U-238	2.2E-05
U-236	2.26E-06
U-235	7.45E-06
U-234	0.000118

Table A-10

List of Initial Radionuclide Inventory
Used in the Flattop Accident Scenario at Kiva 2

Radionuclide	Initial Activity (Ci)
Am-241	0.07
As-84	24.1
Ba-143	26.7
Ba-144	23.1
Ba-145	19.8
Ba-146	12.8
Br-86	10.0
Br-87	33.1
Br-88	107.4
Br-89	249.6
Br-90	233.7
Br-91	198.4
Br-92	51.3
Br-93	9.9
Ce-149	14.0
Cs-141	13.1
Cs-142	100.2
Cs-143	37.2
Cs-144	14.5
In-126	10.8
In-128	9.1
I-133m	206.7
I-134m	19.6
I-136	62.3
I-136m	112.3
I-137	227.3
I-138	503.9
I-139	223.9
I-140	95.0
I-141	18.0
Kr-89	73.5
Kr-90	512.1
Kr-91	1437.3
Kr-92	3491.3
Kr-93	1395.3
Kr-94	1633.6
Kr-95	50.8
Kr-96	10.9
La-146	13.6
La-147	13.0
La-148	13.7
Mo-105	11.3
Mo-106	31.8
Mo-107	24.2
Nb-100	34.1
Nb-100m	70.4
Nb-101	58.7
Nb-102	55.1
Nb-102m	182.3
Nb-103	287.1
Nb-104	26.6
Nb-104m	127.6
Nb-105	28.8
Nb-106	15.9
Pr-150	11.3
Pr-151	10.7
Pu-238	.023
Pu-239	.349
Pu-240	.082
Pu-241	.459
Rb-92	46.0
Rb-93	31.9
Rb-94	34.9
Rb-95	103.5
Rb-96	42.9
Rh-112	9.0
Ru-111	10.9
Sb-134m	17.9
Sr-95	14.2
Sr-96	226.8
Sr-97	271.7
Sr-98	49.7
Sr-99	9.5
Tc-107	10.4
Tc-108	17.5
Tc-109	22.3
Te-135	12.2
Xe-134m	9836.8
Xe-135m	11.0
Xe-137	214.5
Xe-138	54.9
Xe-139	886.9
Xe-140	1293.7
Xe-141	2940.2
Xe-142	813.8
Xe-143	63.4
Xe-143m	202.9
Y-100	81.3
Y-101	28.5
Y-93m	9.3
Y-96m	27.1
Y-97	52.5
Y-97m	175.1
Y-98	72.1
Y-98m	221.7
Y-99	116.2
Zr-100	77.2
Zr-101	180.6
Zr-102	66.5
Zr-103	47.3
Zr-98	12.2
Zr-99	237.6

Table A-11

List of Initial Radionuclide Inventory Used in the Godiva Accident Scenarios

Radionuclide	Initial Activity (Ci)	Radionuclide	Initial Activity (Ci)	Radionuclide	Initial Activity (Ci)
As-84	1.54E+03	Nb-102	5.99E+02	Zr-100	1.58E+03
As-84m	7.69E+02	Nb-102m	1.98E+03	Zr-101	4.06E+03
Ba-143	6.93E+02	Nb-103	3.10E+03	Zr-102	1.61E+03
Ba-144	8.50E+02	Nb-104m	1.02E+03	Zr-103	1.14E+03
Ba-145	9.92E+02	Rb-92	1.74E+03		
Ba-146	8.89E+02	Rb-93	1.74E+03		
Br-87	1.44E+03	Rb-94	1.80E+03		
Br-88	7.03E+03	Rb-95	6.29E+03		
Br-89	2.32E+04	Rb-96	3.21E+03		
Br-90	2.79E+04	Rb-97	7.73E+02		
Br-91	1.96E+04	Sb-134m	1.24E+03		
Br-92	4.41E+03	Se-87	3.80E+02		
Br-93	5.71E+02	Se-88	7.75E+02		
Ce-149	3.27E+02	Se-89	7.73E+02		
Cs-141	3.46E+02	Sr-95	4.25E+02		
Cs-142	3.69E+03	Sr-96	8.42E+03		
Cs-143	2.06E+03	Sr-97	1.22E+04		
Cs-144	1.32E+03	Sr-98	2.94E+03		
Cs-145	4.65E+02	Sr-99	6.89E+02		
I-133m	1.31E+03	Te-135	4.20E+02		
I-136	1.22E+03	U-234	4.54E-03		
I-136m	2.20E+03	U-235	1.33E-04		
I-137	7.75E+03	U-236	8.51E-06		
I-138	1.57E+04	U-238	1.20E-06		
I-139	1.65E+04	Xe-134m	3.51E+04		
I-140	9.91E+03	Xe-137	3.03E+03		
I-141	2.34E+03	Xe-138	1.29E+03		
I-142	7.27E+02	Xe-139	2.49E+04		
In-131m	3.32E+02	Xe-140	5.16E+04		
Kr-89	3.33E+03	Xe-141	1.37E+05		
Kr-90	3.08E+04	Xe-142	8.95E+04		
Kr-91	6.73E+04	Xe-143	8.40E+03		
Kr-92	1.40E+05	Xe-143m	2.69E+04		
Kr-93	3.58E+04	Xe-144	2.43E+03		
Kr-94	2.03E+05	Y-96m	4.70E+02		
Kr-95	7.50E+03	Y-97	1.11E+03		
Kr-96	2.01E+03	Y-97m	3.70E+03		
Kr-97	3.22E+02	Y-98	1.90E+03		
La-146	3.41E+02	Y-98m	5.83E+03		
La-147	4.83E+02	Y-99	3.69E+03		
La-148	6.88E+02	Y-100	3.21E+03		
Nb-100m	6.63E+02	Y-101	1.34E+03		
Nb-101	5.53E+02	Zr-99	3.90E+03		

Table A-12

List of Initial Radionuclide Inventory Used in the SKUA Accident Scenario at Kiva 3

Radionuclide	Initial Activity (Ci)
Am-241	0.0716
As-84	11.4
As-84m	5.7
Ba-143	12.6
Ba-144	10.9
Ba-145	9.3
Ba-146	6.0
Br-86	4.7
Br-87	15.7
Br-88	50.8
Br-89	118.0
Br-90	110.5
Br-91	93.8
Br-92	24.3
Br-93	4.7
Ce-149	6.6
Cs-141	6.2
Cs-142	47.4
Cs-143	17.6
Cs-144	6.8
I-133m	97.7
I-134m	9.3
I-136	29.4
I-136m	53.1
I-137	107.4
I-138	238.2
I-139	105.8
I-140	44.9
I-141	8.5
In-126	5.1
In-128	4.3
Kr-89	34.8
Kr-90	242.0
Kr-91	679.4
Kr-92	1650.2
Kr-93	659.5
Kr-94	772.2
Kr-95	24.0
Kr-96	5.1
La-146	6.4
La-147	6.2
La-148	6.5
Mo-105	5.3
Mo-106	15.1
Mo-107	11.4
Nb-100	16.1
Nb-100m	33.3
Nb-101	27.7
Nb-102	26.1
Nb-102m	86.2
Nb-103	135.7
Nb-104	12.6
Nb-104m	60.3
Nb-105	13.6
Nb-106	7.5
Pr-150	5.4
Pr-151	5.1
Pu-238	0.0234
Pu-239	0.3490
Pu-240	0.0818
Pu-241	0.4592
Rb-92	21.7
Rb-93	15.1
Rb-94	16.5
Rb-95	48.9
Rb-96	20.3
Rh-112	4.2
Ru-111	5.2
Sb-134m	8.5
Sr-95	6.7
Sr-96	107.2
Sr-97	128.4
Sr-98	23.5
Sr-99	4.5
Tc-107	4.9
Tc-108	8.3
Tc-109	10.5
Te-135	5.8
Xe-134m	4649.6
Xe-135m	5.2
Xe-137	101.4
Xe-138	25.9
Xe-139	419.2
Xe-140	611.5
Xe-141	1389.8
Xe-142	384.6
Xe-143	30.0
Xe-143m	95.9
Y-93m	4.4
Y-96m	12.8
Y-97	24.8
Y-97m	82.8
Y-98	34.1
Y-98m	104.8
Y-99	54.9
Y-100	38.4
Y-101	13.5
Zr-98	5.8
Zr-99	112.3
Zr-100	36.5
Zr-101	85.3
Zr-102	31.4
Zr-103	22.3

Table A-13

List of Initial Radionuclide Inventory
Used in the Vault Collapse Accident Scenario

Radionuclide	Initial Activity (Ci)
U-234	6.88E-03
U-235	2.02E-04
U-236	1.29E-05
U-238	1.82E-06
Pu-238	3.90e-02
Pu-239	5.82e-01
Pu-240	1.36e-01
Pu-241	7.65e-01
Am-241	1.19e-01

Table A-14

Radionuclide Decay Data[1]

Radionuclide	Half-Life (min)	Daughter Radionuclide	Bimodal Decay Fraction
Ag-109m	6.60E-01	STABLE	
Ag-111	1.07E+04	STABLE	
Ag-111m	1.23E+00	Ag-111	0.997
		STABLE	0.003
Ag-112	1.87E+02	STABLE	
Am-241	2.27E+08	STABLE	
As-84	9.67E-02	Se-84	
As-84m	.0108	Se-84	
Ba-137m	2.52E+00	STABLE	
Ba-139	8.49E+01	STABLE	
Ba-140	1.84E+04	La-140	
Ba-141	1.83E+01	La-141	
Ba-142	1.07E+01	La-142	
Ba-143	3.33E-01	La-143	
Ba-144	1.98E-01	La-144	
Ba-145	1.03E-01	La-145	
Ba-146	3.18E-02	La-146	
Br-84	3.18E+01	STABLE	
Br-86	9.83E-01	STABLE	
Br-87	9.25E-01	Kr-87	
Br-88	2.78E-01	Kr-88	
Br-89	7.28E-02	Kr-89	0.938
		Kr-88	0.062
Br-90	3.27E-02	Kr-90	0.744
		Kr-89	0.226
Br-91	9.00E-03	Kr-91	
Br-92	6.10E-03	Rb-92	
Br-93	.017	Kr-93	
Br-94	.0033	Kr-94	
Ce-143	1.98E+03	STABLE	
Ce-144	4.10E+05	Pr-144	
Ce-145	3.00E+00	Pr-145	
Ce-146	1.42E+01	Pr-146	
Ce-147	9.40E-01	Pr-147	
Ce-148	8.02E-01	Pr-148	
Ce-149	1.67E-02	Pr-149	
Cs-135	1.00E+12	STABLE	
Cs-137	1.60E+07	STABLE	0.053
		Ba-137m	0.947
Cs-138	3.34E+01	STABLE	
Cs-139	9.40E+00	Ba-139	

[1] - Source, Gusev et al, 1979

Radio-nuclide	Half-Life (min)	Daughter Radionuclide	Bimodal Decay Fraction
Cs-140	1.12E+00	Ba-140	
Cs-141	4.16E-01	Ba-141	
Cs-142	2.82E-02	Ba-142	
Cs-143	2.97E-02	Ba-143	
Cs-144	1.67E-02	Ba-144	
Cs-145	9.70E-03	Ba-145	
I-131	1.16E+04	STABLE	
I-133	1.25E+03	Xe-133	0.9712
		Xe-133m	0.0288
I-133m	1.50E-01	I-133	
I-134	5.26E+01	STABLE	
I-134m	3.56E+00	I-134	0.98
		Xe-134m	0.02
I-135	3.97E+02	Xe-135	0.835
		Xe-135m	0.165
I-136	7.67E-01	STABLE	
I-136m	1.38E+00	I-136	0.2
		STABLE	0.8
I-137	3.67E-01	Xe-137	
I-138	1.08E-01	Xe-138	
I-139	3.83E-02	Xe-139	
I-140	9.80E-03	Xe-140	
I-141	8.00E-03	Xe-141	
I-142	8.05E-03	Xe-142	
In-126	2.55E-02	Sn-126	
In-128	1.83E-01	Sn-128	
In-131m	5.00E-03	Sn-131	
Kr-87	7.63E+01	Rb-87	
Kr-88	1.70E+02	Rb-88	
Kr-89	3.07E+00	Rb-89	
Kr-90	5.39E-01	Rb-90m	0.2116
		Rb-90	0.7884
Kr-91	1.44E-01	Rb-91	
Kr-92	3.07E-02	Rb-92	
Kr-93	2.12E-02	Sr-93	
Kr-94	3.70E-03	Rb-94	
Kr-95	1.30E-02	Sr-95	
Kr-96	8.30E-03	Rb-96	
Kr-97	1.70E-03	Rb-97	
La-140	2.42E+03	STABLE	
La-141	2.36E+02	STABLE	
La-142	9.20E+01	STABLE	
La-143	1.43E+01	Ce-143	
La-144	6.78E-01	Ce-144	
La-145	5.50E-01	Ce-145	
La-146	1.47E-01	Ce-146	
La-147	2.17E-01	Ce-147	

	Half-		Bimodal

Radio-nuclide	Life (min)	Daughter Radionuclide	Decay Fraction
La-148	2.15E-02	Ce-148	
Mo-100	-1.58E+23	STABLE	
Mo-101	1.46E+01	Tc-101	
Mo-101	1.46E+01	Tc-101	
Mo-102	1.18E+01	Tc-102	
Mo-103	1.00E+00	Tc-103	
Mo-104	1.30E+00	Tc-104	
Mo-105	7.00E-01	Tc-105	
Mo-106	1.58E-01	Tc-106	
Mo-107	4.83E-02	Tc-107	
Mo-99	3.96E+03	STABLE	
Nb-100	3.10E+00	Mo-100	
Nb-100m	4.67E-02	Mo-100	
Nb-101	1.18E-01	Mo-101	
Nb-102	7.17E-02	Mo-102	
Nb-102m	2.17E-02	Mo-102	
Nb-103	2.50E-02	Mo-103	
Nb-104	8.00E-02	Mo-104	
Nb-104m	1.33E-02	Mo-104	
Nb-105	3.00E-02	Mo-105	
Nb-106	1.67E-02	Mo-106	
Nb-95	5.04E+04	STABLE	
Nb-95m	5.20E+03	Nb-95	
Nb-97	7.21E+01	STABLE	
Nb-97m	1.00E+00	Nb-97	
Nb-98	4.77E-02	STABLE	
Nb-98m	5.13E+01	Nb-98	
Nb-99	2.50E-01	Mo-99	
Nb-99m	4.33E-02	Mo-99	0.5
		Tc-99	0.5
Nd-144	1.20E+21	STABLE	
Nd-147	1.58E+04	Pm-147	
Nd-149	1.04E+02	Pm-149	
Nd-150	2.63E+23	STABLE	
Nd-151	1.24E+01	Pm-151	
Np-237	1.12E+12	STABLE	
Pd-107	3.42E+12	STABLE	
Pd-109	8.08E+02	STABLE	0.00051
		Ag-109m	0.99949
Pd-111m	330	Ag-111m	0.217
		Pd-111	0.713
Pd-111	2.20E+01	Ag-111	0.0072
		Ag-111m	0.9928
Pd-112	1.27E+03	Ag-112	
Pm-147	1.40E+06	STABLE	
Pm-149	3.18E+03	Sm-149	

Radio-	Half-Life	Daughter	Bimodal Decay

nuclide	(min)	Radionuclide	Fraction
Pm-151	1.70E+03	Sm-151	
Pr-142	1.15E+03	STABLE	
Pr-144	1.73E+01	Nd-144	
Pr-144m	7.20E+00	Nd-144	0.0006
		Pr-144	0.9944
Pr-145	3.59E+02	STABLE	
Pr-146	2.41E+01	STABLE	
Pr-147	1.20E+01	Nd-147	
Pr-148	2.28E+00	STABLE	
Pr-149	2.50E+00	STABLE	
Pr-150	1.03E-01	Nd-150	
Pr-151	6.67E-02	Nd-151	
Pu-238	4.61E+07	STABLE	
Pu-239	1.26E+10	STABLE	
Pu-240	3.44E+09	STABLE	
Pu-241	7.97E+06	STABLE	
Rb-87	2.60E+16	STABLE	
Rb-88	1.78E+01	STABLE	
Rb-89	1.54E+01	Sr-89	
Rb-90	2.55E+00	Sr-90	
Rb-90m	4.30E+00	Rb-90	0.047
		Sr-90	0.953
Rb-91	1.11E+00	Sr-91	
Rb-92	7.23E-02	Sr-92	
Rb-93	9.75E-02	Sr-92	0.01164
		Sr-93	0.98836
Rb-94	4.48E-02	Sr-94	
Rb-95	6.70E-03	Sr-95	
Rb-96	3.40E-03	Sr-96	
Rb-97	2.90E-03	Sr-97	
Rh-103m	5.61E+01	STABLE	
Rh-105	2.12E+03	STABLE	
Rh-105m	7.50E-01	Rh-105	
Rh-106	4.98E-01	STABLE	
Rh-107	2.17E+01	STABLE	
Rh-108	2.80E-01	STABLE	
Rh-109	1.50E+00	Pd-109	
Rh-109m	1.05E+00	Pd-109	
Rh-111	1.05E+00	Pd-111	0.9957
		Pd-111m	0.0043
Rh-112	7.75E-02	Pd-112	
Ru-103	5.65E+04	STABLE	
Ru-104	1.00E+16	STABLE	
Ru-105	2.66E+02	Rh-105	0.762
		Rh-105m	0.238
Ru-106	5.37E+05	STABLE	
Ru-107	4.20E+00	Rh-107	
Ru-108	4.50E+00	Rh-108	

Radio-nuclide	Half-Life (min)	Daughter Radionuclide	Bimodal Decay Fraction
Ru-109	5.75E-01	Rh-109	0.5
		Rh-109m	0.5
Ru-111	1.67E-02	Rh-111	
Sb-128	5.46E+02	STABLE	
Sb-128m	1.00E+01	Sb-128	0.036
		STABLE	0.946
Sb-131	1.30E+01	Te-131	0.901
		Te-131m	0.099
Sb-134m	1.42E-02	Te-134	
Se-84	3.30E+00	Br-84	
Se-87	9.58E-02	Br-87	
Se-88	2.55E-02	Br-88	
Se-89	6.80E-03	Br-89	
Sm-149	1.00E+16	STABLE	
Sm-151	4.73E+07	STABLE	
Sn-126	5.26E+11	STABLE	
Sn-128	5.93E+01	Sb-128m	
Sn-131	1.08E+00	Sb-131	
Sr-89	7.27E+04	STABLE	
Sr-90	1.52E+07	STABLE	
Sr-91	5.85E+02	Y-91	0.424
		Y-91m	0.576
Sr-92	1.63E+02	Y-92	
Sr-93	7.43E+00	Y-93	
Sr-93	7.43E+00	Y-93	0.5
		Y-93m	0.5
Sr-94	1.24E+00	Y-94	
Sr-95	4.07E-01	Y-95	
Sr-96	1.67E-02	Y-96	
Sr-97	6.70E-03	Y-97	
Sr-98	1.08E-02	Y-98	
Sr-99	1.00E-02	Y-99	
Tc-101	1.42E+01	STABLE	
Tc-102	8.80E-02	STABLE	
Tc-103	8.42E-01	Ru-103	
Tc-104	1.82E+01	Ru-104	
Tc-105	7.60E+00	Ru-105	
Tc-106	6.00E-01	Ru-106	
Tc-107	4.83E-01	Ru-107	
Tc-108	8.75E-02	Ru-108	
Tc-109	2.33E-02	Ru-109	
Tc-99	1.10E+11	STABLE	
Tc-99m	3.60E+02	STABLE	
Te-131	2.50E+01	STABLE	
Te-131m	4.67E+04	STABLE	
Te-134	4.18E+01	I-134	
Te-135	3.00E-01	I-135	
	Half-		Bimodal

Radio-nuclide	Life (min)	Daughter Radionuclide	Decay Fraction
Th-230	4.05E+10	STABLE	
Th-231	1.53E+03	STABLE	
Th-232	7.38E+15	STABLE	
Th-234	3.47E+04	STABLE	
U-233	8.30E+10	STABLE	
U-234	1.30E+11	Th-230	
U-235	3.70E+14	STABLE	
U-236	1.23E+13	STABLE	
U-238	2.30E+15	Th-234	
Xe-133	7.60E+03	STABLE	
Xe-133m	3.20E+03	Xe-133	
Xe-134m	4.83E-03	STABLE	
Xe-135	5.45E+02	Cs-135	
Xe-135m	1.57E+01	Cs-135	0.004
		Xe-135	0.996
Xe-137	3.83E+00	Cs-137	
Xe-138	1.41E+01	Cs-138	
Xe-139	6.58E-01	Cs-139	
Xe-140	2.67E-01	Cs-140	
Xe-141	2.87E-02	Cs-141	
Xe-142	2.03E-02	Cs-142	
Xe-143	5.00E-03	Ba-143	
Xe-143m	1.60E-02	Ba-143	
Xe-144	1.92E-02	Ba-144	
Xe-145	.015	Cs-145	
Y-100	8.30E-03	Zr-100	
Y-101	1.67E-02	Zr-101	
Y-91	8.42E+04	STABLE	
Y-91m	4.97E+01	Y-91	
Y-92	2.12E+02	STABLE	
Y-93	6.12E+02	Zr-93	
Y-93m	1.37E-02	Y-93	
Y-94	1.91E+01	STABLE	
Y-95	1.03E+01	Zr-95	
Y-96	2.30E+00	STABLE	
Y-96m	1.00E-01	STABLE	
Y-97	1.85E-02	Zr-97	
Y-97m	1.67E-02	Y-97	
Y-98	3.33E-02	Zr-98	
Y-98m	1.08E-02	Zr-98	
Y-99	2.42E-02	Zr-99	
Y-100	.008	Zr-100	
Y-101	.008	Zr-101	
Zr-100	1.18E-01	Nb-100m	
Zr-101	5.50E-02	Nb-101	
Zr-102	1.33E-02	Nb-102	
Zr-103	1.67E-02	Nb-103	

Radio-	Half-Life	Daughter	Bimodal Decay

nuclide	(min)	Radionuclide	Fraction
Zr-93	7.88E+11	STABLE	
Zr-95	9.22E+04	Nb-95	0.994
		Nb-95m	0.006
Zr-97	1.01E+03	STABLE	
Zr-98	5.12E-01	Nb-98	0.053
		Nb-98m	0.947
Zr-99	4.00E-02	Nb-99	0.7
		Nb-99m	0.3

Table A-15

Dose Conversion Factors

Radio-nuclide	Air-Immersion DCF (mrem-m^3/ uCi-yr)	Source[1] of Value	Inhalation DCF[2] (rem/ uCi)	Radio-nuclide	Air-Immersion DCF (mrem-m^3/ uCi-yr)	Source[1] of Value	Inhalation DCF[2] (rem/ uCi)
Ag-109m	2.25E+01	ICRP	0.00E+00	Cs-143	4.00E+03	AVG	0.00E+00
Ag-111	1.32E+02	ICRP	5.90E-03	Cs-144	4.00E+03	AVG	0.00E+00
Ag-111m	4.00E+03	AVG	0.00E+00	Cs-145	4.00E+03	AVG	0.00E+00
Ag-112	4.00E+03	AVG	6.20E-04	I-131	1.91E+03	ICRP	3.20E-02
Am-241	9.50E+01	ICRP	5.20E+02	I-133	3.07E+03	ICRP	5.40E-03
As-84	4.00E+03	AVG	0.00E+00	I-133m	4.00E+03	AVG	0.00E+00
As-84m	4.00E+03	AVG	0.00E+00	I-134	1.38E+04	ICRP	1.10E-04
Ba-137m	3.06E+03	ICRP	0.00E+00	I-134m	4.00E+03	AVG	0.00E+00
Ba-139	1.80E+02	ICRP	1.60E-04	I-135	8.43E+03	ICRP	1.10E-03
Ba-140	9.41E+02	ICRP	3.60E-03	I-136	1.41E+04	ICRP	0.00E+00
Ba-141	4.59E+03	ICRP	7.40E-05	I-136m	1.12E+04	CALC	0.00E+00
Ba-142	4.67E+03	ICRP	3.60E-05	I-137	4.00E+03	AVG	0.00E+00
Ba-143	4.00E+03	AVG	0.00E+00	I-138	1.20E+03	CALC	0.00E+00
Ba-144	4.00E+03	AVG	0.00E+00	I-139	4.00E+03	AVG	0.00E+00
Ba-145	4.00E+03	AVG	0.00E+00	I-140	1.11E+03	CALC	0.00E+00
Ba-146	4.00E+03	AVG	0.00E+00	I-141	4.00E+03	AVG	0.00E+00
Br-84	1.02E+04	ICRP	8.70E-05	I-142	4.00e+03	AVG	0.0
Br-86	0.00E+00	CALC	0.00E+00	In-126	4.00E+03	AVG	0.00E+00
Br-87	2.83E+03	CALC	0.00E+00	In-128	4.00E+03	AVG	0.00E+00
Br-88	6.83E+03	CALC	0.00E+00	In-131m	4.00E+03	AVG	0.00E+00
Br-89	4.00E+03	AVG	0.00E+00	Kr-87	4.47E+03	ICRP	0.00E+00
Br-90	4.00E+03	AVG	0.00E+00	Kr-88	1.13E+04	ICRP	0.00E+00
Br-91	4.00E+03	AVG	0.00E+00	Kr-89	1.02E+04	ICRP	0.00E+00
Br-92	4.00E+03	AVG	0.00E+00	Kr-90	6.73E+03	ICRP	0.00E+00
Br-93	4.00E+03	AVG	0.00E+00	Kr-91	3.64E+03	CALC	0.00E+00
Br-94	4.00E+03	AVG	0.00	Kr-92	3.39E+03	CALC	0.00E+00
Ce-143	1.32E+03	ICRP	3.20E-03	Kr-93	4.00E+03	AVG	0.00E+00
Ce-144	9.09E+01	ICRP	3.50E-01	Kr-94	4.00E+03	AVG	0.00E+00
Ce-145	3.92E+03	CALC	0.00E+00	Kr-95	4.00E+03	AVG	0.00E+00
Ce-146	4.00E+03	AVG	0.00E+00	Kr-96	4.00E+03	AVG	0.00E+00
Ce-147	4.00E+03	AVG	0.00E+00	Kr-97	4.00E+03	AVG	0.00E+00
Ce-148	4.00E+03	AVG	0.00E+00	La-140	1.23E+04	ICRP	4.40E-03
Ce-149	4.00E+03	AVG	0.00E+00	La-141	2.23E+02	ICRP	5.40E-04
Cs-135	0.00E+00	ICRP	4.50E-03	La-142	1.57E+04	ICRP	2.20E-04
Cs-137	0.00E+00	ICRP	3.20E-02	La-143	4.00E+03	AVG	5.50E-05
Cs-138	1.27E+04	ICRP	8.80E-05	La-144	5.02E+03	CALC	0.00E+00
Cs-139	1.67E+03	ICRP	0.00E+00	La-145	4.00E+03	AVG	0.00E+00
Cs-140	1.02E+04	CALC	0.00E+00	La-146	4.00E+03	AVG	0.00E+00
Cs-141	4.00E+03	AVG	0.00E+00	La-147	4.00E+03	AVG	0.00E+00
Cs-142	4.00E+03	AVG	0.00E+00	La-148	4.00E+03	AVG	0.00E+00

Mo-100	4.00E+03	AVG	0.00E+00
Mo-101	7.94E+03	ICRP	3.60E-05
Mo-102	4.00E+03	AVG	0.00E+00
Mo-103	4.00E+03	AVG	0.00E+00
Mo-104	4.00E+03	AVG	0.00E+00
Mo-105	0.00E+00	CALC	0.00E+00
Mo-106	4.00E+03	AVG	0.00E+00
Mo-107	4.00E+03	AVG	0.00E+00
Mo-99	7.99E+02	ICRP	3.60E-03
Nb-100	0.00E+00	CALC	0.00E+00
Nb-100m	4.00E+03	AVG	0.00E+00
Nb-101	1.46E+03	CALC	0.00E+00
Nb-102	4.00E+03	AVG	0.00E+00
Nb-102m	4.00E+03	AVG	0.00E+00
Nb-103	4.00E+03	AVG	0.00E+00
Nb-104	4.00E+03	AVG	0.00E+00
Nb-104m	4.00E+03	AVG	0.00E+00
Nb-105	4.00E+03	AVG	0.00E+00
Nb-106	4.00E+03	AVG	0.00E+00
Nb-95	3.97E+03	ICRP	4.50E-03
Nb-95m	3.04E+02	ICRP	2.20E-03
Nb-97	3.41E+03	ICRP	7.10E-05
Nb-97m	3.78E+03	ICRP	0.00E+00
Nb-98	3.32E+02	CALC	1.00E-04
Nb-98m	1.13E+04	CALC	0.00E+00
Nb-99	7.55E+02	CALC	0.00E+00
Nb-99m	4.00E+03	AVG	0.00E+00
Nd-144	4.00E+03	AVG	0.00E+00
Nd-147	6.65E+02	ICRP	6.20E-03
Nd-149	4.00E+03	AVG	0.00E+00
Nd-150	4.00E+03	AVG	0.00E+00
Nd-151	4.00E+03	AVG	2.60E-05
Np-237	1.15E+02	ICRP	4.90E+02
Pd-109	3.45E+00	ICRP	1.10E-03
Pd-111	4.00E+03	AVG	0.00E+00
Pd-111m	4.00E+03	AVG	0.00E+00
Pd-112	4.00E+03	AVG	0.00E+00
Pm-147	1.83E-02	ICRP	3.40E-02
Pm-149	5.86E+01	ICRP	2.80E-03
Pm-151	1.68E+03	ICRP	1.60E-03
Pr-142	3.10E+02	ICRP	2.70E-03
Pr-144	1.79E+02	ICRP	4.20E-05
Pr-144m	2.67E+01	ICRP	0.00E+00
Pr-145	7.94E+01	CALC	6.40E-04
Pr-146	5.72E+03	CALC	0.00E+00
Pr-147	3.84E+03	ICRP	2.70E-05
Pr-148	4.00E+03	AVG	0.00E+00
Pr-149	5.86E+02	CALC	0.00E+00
Pr-150	4.00E+03	AVG	0.00E+00
Pr-151	4.00E+03	AVG	0.00E+00
Pu-238	4.41E-01	ICRP	300
Pu-239	4.11E-01	ICRP	330
Pu-240	4.32E-01	ICRP	330
Pu-241	0.00E+00	ICRP	5.7
Rb-87	0.00E+00	ICRP	3.30E-03
Rb-88	3.58E+03	ICRP	8.00E-05
Rb-89	1.14E+04	ICRP	3.70E-05
Rb-90	1.29E+04	ICRP	0.00E+00
Rb-90m	1.86E+04	ICRP	0.00E+00
Rb-91	1.36E+04	CALC	0.00E+00
Rb-92	1.32E+03	CALC	0.00E+00
Rb-93	4.00E+03	AVG	0.00E+00
Rb-94	4.00E+03	AVG	0.00E+00
Rb-95	4.00E+03	AVG	0.00E+00
Rb-96	4.00E+03	AVG	0.00E+00
Rb-97	4.00E+03	AVG	0.00E+00
Rh-103m	9.99E-01	ICRP	4.60E-06
Rh-105	3.90E+02	ICRP	8.90E-04
Rh-105m	1.45E+02	ICRP	0.00E+00
Rh-106	1.05E+03	ICRP	0.00E+00
Rh-107	4.00E+03	AVG	2.00E-05
Rh-108	4.00E+03	AVG	0.00E+00
Rh-109	4.00E+03	AVG	0.00E+00
Rh-109m	4.00E+03	AVG	0.00E+00
Rh-111	4.00E+03	AVG	0.00E+00
Rh-112	4.00E+03	AVG	0.00E+00
Ru-103	2.42E+03	ICRP	7.80E-03
Ru-104	4.00E+03	AVG	0.00E+00
Ru-105	4.02E+03	ICRP	4.10E-04
Ru-106	0.00E+00	ICRP	4.40E-01
Ru-107	4.00E+03	AVG	0.00E+00
Ru-108	4.00E+03	AVG	0.00E+00
Ru-109	4.00E+03	AVG	0.00E+00
Ru-111	4.00E+03	AVG	0.00E+00
Sb-128	4.00E+03	AVG	1.60E-03
Sb-128m	4.00E+03	AVG	0.00E+00
Sb-131	4.00E+03	AVG	1.30E-04
Sb-134m	4.00E+03	AVG	0.00E+00
Se-84	2.09E+03	CALC	0.00E+00
Se-87	4.00E+03	AVG	0.00E+00
Se-88	4.00E+03	AVG	0.00E+00
Se-89	4.00E+03	AVG	0.00E+00
Sm-149	4.00E+03	AVG	0.00E+00
Sm-151	4.56E-03	ICRP	2.90E-02
Sn-126	2.44E+02	ICRP	8.60E-02
Sn-128	4.00E+03	AVG	1.80E-04
Sn-131	4.00E+03	AVG	0.00E+00
Sr-89	7.17E-01	ICRP	3.70E-02
Sr-90	0.00E+00	ICRP	1.30E+00
Sr-91	3.59E+03	ICRP	1.40E-03
Sr-92	6.93E+03	ICRP	7.70E-04
Sr-93	1.19E+04	ICRP	0.00E+00
Sr-94	6.01E+03	CALC	0.00E+00
Sr-95	4.00E+03	AVG	0.00E+00

Sr-96	4.00E+03	AVG	0.00E+00
Sr-97	4.00E+03	AVG	0.00E+00
Sr-98	4.00E+03	AVG	0.00E+00
Sr-99	4.00E+03	AVG	0.00E+00
Tc-101	1.73E+03	ICRP	1.60E-05
Tc-102	4.00E+03	AVG	0.00E+00
Tc-103	4.00E+03	AVG	0.00E+00
Tc-104	7.29E+03	CALC	6.80E-05
Tc-105	4.00E+03	AVG	0.00E+00
Tc-106	4.00E+03	AVG	0.00E+00
Tc-107	4.00E+03	AVG	0.00E+00
Tc-108	0.00E+00	CALC	0.00E+00
Tc-109	4.00E+03	AVG	0.00E+00
Tc-99	2.65E-03	ICRP	7.50E-03
Tc-99m	6.63E+02	ICRP	3.20E-05
Te-131	2.16E+03	ICRP	9.90E-05
Te-131m	7.44E+03	ICRP	5.50E-03
Te-134	4.44E+03	ICRP	1.00E-04
Te-135	4.00E+03	AVG	0.00E+00
Th-230	1.96E+00	ICRP	3.20E+02
Th-231	5.28E+01	ICRP	8.10E-04
Th-232	9.33E-01	ICRP	1.60E+03
Th-234	3.88E+01	ICRP	3.30E-02
U-233	1.20E+00	ICRP	1.30E+03
U-234	7.65E-01	ICRP	1.30E+02
U-235	7.70E+02	ICRP	1.20E+02
U-236	6.05E-01	ICRP	1.20E+02
U-238	5.19E-01	ICRP	1.20E+02
Xe-133	1.76E+02	ICRP	0.00E+00
Xe-133m	1.49E+02	ICRP	0.00E+00
Xe-134m	4.00E+03	AVG	0.00E+00
Xe-135	1.25E+03	ICRP	0.00E+00
Xe-135m	2.15E+03	ICRP	0.00E+00
Xe-137	9.55E+02	ICRP	0.00E+00
Xe-138	6.27E+03	ICRP	0.00E+00
Xe-139	4.00E+03	AVG	0.00E+00
Xe-140	4.00E+03	AVG	0.00E+00
Xe-141	4.00E+03	AVG	0.00E+00
Xe-142	4.00E+03	AVG	0.00E+00
Xe-143	4.00E+03	AVG	0.00E+00
Xe-143m	4.00E+03	AVG	0.00E+00
Xe-144	4.00E+03	AVG	0.00E+00
Xe-145	4.00E+03	AVG	0.00
Y-100	4.00E+03	AVG	0.00E+00
Y-101	4.00E+03	AVG	0.00E+00
Y-91	1.87E+01	ICRP	4.40E-02
Y-91m	2.68E+03	ICRP	3.10E-05
Y-92	1.32E+03	ICRP	6.20E-04
Y-93	4.82E+02	ICRP	2.10E-03
Y-93m	4.00E+03	AVG	0.00E+00
Y-94	4.99E+03	CALC	6.70E-05
Y-95	2.59E+03	CALC	3.60E-05
Y-96	4.00E+03	AVG	0.00E+00
Y-96m	4.00E+03	AVG	0.00E+00
Y-97	4.59E+03	CALC	0.00E+00
Y-97m	4.00E+03	AVG	0.00E+00
Y-98	4.00E+03	AVG	0.00E+00
Y-98m	4.00E+03	AVG	0.00E+00
Y-99	4.00E+03	AVG	0.00E+00
Y-100	4.00E+03	AVG	0.0
Y-101	4.00E+03	AVG	0.0
Zr-100	4.00E+03	AVG	0.00E+00
Zr-101	1.75E+03	CALC	0.00E+00
Zr-102	4.00E+03	AVG	0.00E+00
Zr-103	4.00E+03	AVG	0.00E+00
Zr-93	0.00E+00	ICRP	3.20E-01
Zr-95	3.81E+03	ICRP	1.90E-02
Zr-97	9.41E+02	ICRP	4.00E-03
Zr-98	4.00E+03	AVG	0.00E+00
Zr-99	3.95E+03	CALC	0.00E+00

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[1] - Source of air immersion dose conversion factors are
ICRP - DOE, 1988a
CALC - Calculated from gamma energy
AVG - Average of DOE, 1988a dose conversion factors

[2] - Source, DOE 1988b, if listed, else assumed to be 0.0 if the half-life is less than one hours

Table A-16

X\Q Values for an Inert Gas at Selected Distances[1]

Downwind Distance (m)	Wind Speed (m/s) 1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
100	.46e-1	.23e-1	.15e-1	.11e-1	.91e-2	.76e-2	.65e-2	.57e-2	.51e-2	.46e-2
200	.13e-1	.63e-2	.42e-2	.32e-2	.25e-2	.21e-2	.18e-2	.16e-2	.14e-2	.13e-2
300	.60e-2	.30e-2	.20e-2	.15e-2	.12e-2	.99e-3	.85e-3	.74e-3	.66e-3	.60e-3
500	.23e-2	.12e-2	.77e-3	.58e-3	.46e-3	.38e-3	.33e-3	.29e-3	.26e-3	.23e-3
700	.12e-2	.62e-3	.41e-3	.31e-3	.25e-3	.21e-3	.18e-3	.15e-3	.14e-3	.12e-3
1000	.64e-3	.32e-3	.21e-3	.16e-3	.13e-3	.11e-3	.91e-4	.80e-4	.71e-4	.64e-4
1500	.35e-3	.17e-3	.12e-3	.87e-4	.69e-4	.58e-4	.50e-4	.43e-4	.39e-4	.35e-4
2000	.23e-3	.11e-3	.76e-4	.57e-4	.45e-4	.38e-4	.32e-4	.28e-4	.25e-4	.23e-4
3000	.12e-3	.62e-4	.41e-4	.31e-4	.25e-4	.21e-4	.18e-4	.16e-4	.14e-4	.12e-4
5000	.67e-4	.33e-4	.22e-4	.17e-4	.13e-4	.11e-4	.95e-5	.84e-5	.74e-5	.67e-5
10000	.29e-4	.14e-4	.95e-5	.71e-5	.57e-5	.48e-5	.41e-5	.36e-5	.32e-5	.29e-5

[1] - X/Q values are calculated from the AIRDOSO-EPA code (Moore et al, 1977) using a dry deposition velocity of 0.0 m/s.

Table A-17

X\Q Values for Particulates at Selected Distances[1]

Downwind Distance (m)	Wind Speed (m/s) 1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
100	.43e-1	.22e-1	.15e-1	.11e-1	.90e-2	.75e-2	.65e-2	.57e-2	.50e-2	.45e-2
200	.11e-1	.60e-2	.41e-2	.31e-2	.25e-2	.21e-2	.18e-2	.16e-2	.14e-2	.13e-2
300	.51e-2	.28e-2	.19e-2	.14e-2	.12e-2	.97e-3	.83e-3	.73e-3	.65e-3	.59e-3
500	.19e-2	.10e-2	.72e-3	.55e-3	.44e-3	.37e-3	.32e-3	.28e-3	.25e-3	.23e-3
700	.97e-3	.55e-3	.38e-3	.29e-3	.24e-3	.20e-3	.17e-3	.15e-3	.13e-3	.12e-3
1000	.48e-3	.28e-3	.19e-3	.15e-3	.12e-3	.10e-3	.88e-4	.77e-4	.69e-4	.62e-4
1500	.25e-3	.15e-3	.10e-3	.80e-4	.65e-4	.55e-4	.47e-4	.42e-4	.37e-4	.34e-4
2000	.16e-3	.94e-4	.67e-4	.52e-4	.42e-4	.36e-4	.31e-4	.27e-4	.24e-4	.22e-4
3000	.82e-4	.50e-4	.36e-4	.28e-4	.23e-4	.19e-4	.17e-4	.15e-4	.13e-4	.12e-4
5000	.40e-4	.26e-4	.19e-4	.15e-4	.12e-4	.10e-4	.89e-5	.78e-5	.70e-5	.63e-5
10000	.14e-4	.99e-5	.75e-5	.60e-5	.49e-5	.42e-5	.37e-5	.33e-5	.29e-5	.27e-5

[1] - X/Q values are calculated from the AIRDOSO-EPA code (Moore et al, 1977) using a dry deposition velocity of 0.0018 m/s.

APPENDIX B

HAND CALCULATION
FOR THE SELENIUM-89 NUCLIDE

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JOB	DATE	SHEET NO
		1
DESCRIPTION	CALC. BY	APPROVED BY

Consider the XGODIVA accident scenario and the decay scheme:

Se-89 ⟶ Br-89 ⟶ Kr-89 ⟶ Rb-89
Br-89 ⟶ Kr-88

for which we have the following initial values

Nuclide	Half-life (min)	λ (1/min)	Initial Activity (Ci)
Se-89	6.80×10^{-3}	1.02×10^{2}	7.73×10^{2}
Br-89	7.28×10^{-2}	9.52×10^{0}	2.32×10^{4}
Kr-89	3.07×10^{0}	2.26×10^{-1}	3.33×10^{3}
Rb-89	15.4×10^{0}	4.50×10^{-2}	0.0
Kr-88	1.70×10^{2}	4.08×10^{-3}	0.0

Using the Bateman equations, we calculate the amount of activity for parent (Se-89), daughter (Br-89), granddaughter (Kr-89), and great granddaughter (Rb-89). It is noted that the Br-89 bimodal decay goes 93.8% to Kr-89 and 6.2% to Kr-88. The results are to be compared with the CRIT8 results for the first time packet which have a building fraction release of 0.70 and a decay time of 3.583 minutes to the closest receptor at 200m.

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Residual Parent

The Bateman equation for the number of atoms of the residual parent is

(1) $N_1 = N_1^\circ e^{-\lambda t}$

where

N_1 = No. atoms of residual parent (Se-89)
N_2 = Initial number of parent (Se-89)
λ_1 = Parent decay constant (1/min)
t = decay time (3.583 minutes)

The equation defining activity is

(2) $A = \lambda \cdot N$

where,

A = Activity (Ci).

Combining equations (1) and (2) gives

$$A_1 = \lambda_1 N_1^\circ e^{-\lambda_1 t}$$

$$= A_0 e^{-\lambda_1 t}$$

where

A_0 = Initial Parent Activity (Ci).
A_1 = Residual Parent Activity (Ci).

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DESCRIPTION	CALC. BY	APPROVED BY

Hence,

$$A_1 = 7.73 \times 10^2 \text{ Ci } e^{-(102.0)(3.583)} \qquad (0.70)$$

$$= \underline{0.0 \text{ Ci}}$$

This result agrees with the CRITS result

Daughter Activity

- The daughter activity of Br-89 is composed of (1) a daughter product from the decay of the Se-89 parent and (2) residual initial Br-89.

(1) The number of atoms of daughter product

$$(3)_2 \quad N_2 = \frac{\lambda_1 \lambda_2 N_1^0 e^{-\lambda_1 t}}{\lambda_2 - \lambda_1} + \left[\frac{\lambda_1 N_1^0}{\lambda_1 - \lambda_2} + N_2^0\right] e^{-\lambda_2 t}$$

where,

D = number of atoms of daughter

D_0 = Initial number of atoms of daughter

λ_2 = decay constant for the daughter

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Multiplying boths sides of equation (3) by λ_2 the daughter activity, A_2, is

$$A_2 = \lambda_2 N_2$$

$$(4) \quad A_2 = \frac{\lambda_2 A_1^\circ}{\lambda_2 - \lambda_1} e^{-\lambda_1 t} + \left[\frac{\lambda_2 A_1^\circ}{\lambda_1 - \lambda_2} + A_2^\circ\right] e^{-\lambda_2 t}$$

where,

A_2° = Initial daughter activity(Ci)

In equation (4), we have made the substition for activities: of

$$A_1^\circ = \lambda_1 N_1^\circ$$

$$A_2^\circ = \lambda_2 N_2^\circ$$

Here, the daughter activity is

$$A_2 = \frac{9.52}{9.52 - 102.} (773) e^{-102.(3.583)} + \left[\frac{9.52}{102. - 9.52} 773. + 23200.\right] e^{-(9.52)(3.583)}$$

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$$A_2 = (-.103)(773)(0.0) + (79.6 + 23200)(1.54 \times 10^{-15})$$

$$= 3.59 \times 10^{-11}$$

Multiplying this value by the release fraction of 0.70, the daughter activity of Br-89 is 2.51×10^{-11} Ci. The CRRR code calculates a value of 2.50×10^{-11} Ci.

Granddaughter Activities

The Bateman equation for granddaughter (^{GD}) growth is

$$(5) \quad N_3 = \frac{\lambda_1 \lambda_2 N_1^0}{(\lambda_2-\lambda_1)(\lambda_3-\lambda_1)} e^{-\lambda_1 t} + \left[\frac{\lambda_1 \lambda_2 N_1^0}{(\lambda_1-\lambda_2)(\lambda_3-\lambda_2)} + \frac{\lambda_2 N_2^0}{\lambda_3-\lambda_2}\right] e^{-\lambda_2 t} + \left[\frac{\lambda_1 \lambda_2 N_1^0}{(\lambda_1-\lambda_3)(\lambda_2-\lambda_3)} + \frac{\lambda_2 N_2^0}{\lambda_2-\lambda_3} + N_3^0\right] e^{-\lambda_3 t}$$

where,

N_3 = number of atoms of the GD.
N_3^0 = Initial number of atoms of GD
λ_3 = GD decay constant

Multiplying each side of equation (5) by λ_3 gives

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(6) $$A_3 = \lambda_3 N_3 = \frac{\lambda_2 \lambda_3 A_1^o}{(\lambda_2-\lambda_1)(\lambda_3-\lambda_1)} e^{-\lambda_1 t} + \left[\frac{A_1^o \lambda_2 \lambda_3}{(\lambda_1-\lambda_2)(\lambda_3-\lambda_2)} + \frac{\lambda_3 A_2^o}{\lambda_3-\lambda_2}\right]$$

$$e^{-\lambda_2 t} + \left[\frac{\lambda_2 \lambda_3 A_1^o}{(\lambda_1-\lambda_3)(\lambda_2-\lambda_3)} + \frac{\lambda_3 A_2^o}{\lambda_2-\lambda_3} + A_3^o\right] e^{-\lambda_3 t}$$

The GD activity for Kr-89 is

$$(A_3)_{Kr\text{-}89} = 0.0 + \left[\frac{(773)(9.52)(.226)}{(102-9.52)(.226-9.52)} + \frac{(.226)(23200)}{(.226-9.52)}\right]$$

$$e^{-(9.52)(3.583)} + \left[\frac{(9.52)(.226)(773)}{(102.-.226)(9.52-.226)} + \frac{(.226)(23200)}{(9.52-.226)} + 3330\right] \cdot e^{-(.226)(3.583)}$$

$$= \left[\frac{1660}{(92.5)(-9.29)} + \frac{-5249}{(-9.29)}\right] (1.54\times10^{-15}) +$$

$$\left[\frac{1660}{(102.)(9.29)} + \frac{5548}{9.29} + 3330\right] (.445)$$

$$= (-1.93 - 564)(1.54\times10^{-15}) + (1.75 + 564 + 3330)(.445)$$

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$= 1730$ Ci

Multiplying this result by the packet release fraction of 0.70 and by the bi-modal release fraction of 0.938 gives

$$A_{Kr\text{-}89} = 1140 \text{ Ci}$$

The CRTB code calculates a Kr-89 activity of 1230 Ci. which includes 34 Ci owing to the decay of Br-90 to Kr-89.

Great Granddaughter Activity (GGD)

The Bateman equation for the GGD activity is

$$(7) \quad N_4 = T_1 e^{-\lambda_1 t} + T_2 e^{-\lambda_2 t} + T_3 e^{-\lambda_3 t} + T_4 e^{-\lambda_4 t}$$

where,

N_4 = number of atoms of the GGD

λ_4 = GGD decay constant

and,

$$T_1 = \frac{\lambda_1 \lambda_2 \lambda_3}{(\lambda_2 - \lambda_1)(\lambda_3 - \lambda_1)(\lambda_4 - \lambda_1)} N_1^0$$

$$T_2 = \frac{\lambda_1 \lambda_2 \lambda_3}{(\lambda_1 - \lambda_2)(\lambda_3 - \lambda_2)(\lambda_4 - \lambda_2)} N_1^0 + \frac{\lambda_2 \lambda_3}{(\lambda_3 - \lambda_2)(\lambda_4 - \lambda_2)} N_2^0$$

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ENGINEERING CALCULATIONS

JOB	DATE	SHEET NO 8
DESCRIPTION	CALC. BY	APPROVED BY

$$T_3 = \frac{\lambda_1\lambda_2\lambda_3}{(\lambda_1-\lambda_3)(\lambda_2-\lambda_3)(\lambda_4-\lambda_3)} N_1^\circ + \frac{\lambda_2\lambda_3}{(\lambda_2-\lambda_3)(\lambda_4-\lambda_3)} N_2^\circ + \frac{\lambda_3}{\lambda_4-\lambda_3} N_3^\circ$$

$$T_4 = \frac{\lambda_1\lambda_2\lambda_3}{(\lambda_1-\lambda_4)(\lambda_2-\lambda_4)(\lambda_3-\lambda_4)} N_1^\circ + \frac{\lambda_2\lambda_3}{(\lambda_2-\lambda_4)(\lambda_3-\lambda_4)} N_2^\circ + \frac{\lambda_3}{\lambda_3-\lambda_4} N_3^\circ + N_4^\circ$$

where,

N_4° = Initial number of atoms of the GGD

Multiplying each side of equation (7) by λ_4 gives

$$A_4 = \lambda_4 N_4 = T_1\lambda_4 e^{-\lambda_1 t} + T_2\lambda_4 e^{-\lambda_2 t} + T_3\lambda_4 e^{-\lambda_3 t} + T_4\lambda_4 e^{-\lambda_4 t}$$

$$(8) \qquad A_4 = U_1 e^{-\lambda_1 t} + U_2 e^{-\lambda_2 t} + U_3 e^{-\lambda_3 t} + U_4 e^{-\lambda_4 t}$$

where,

$$U_1 = \frac{\lambda_2\lambda_3\lambda_4}{(\lambda_2-\lambda_1)(\lambda_3-\lambda_1)(\lambda_4-\lambda_1)} A_1^\circ$$

$$U_2 = \frac{\lambda_2\lambda_3\lambda_4}{(\lambda_1-\lambda_2)(\lambda_3-\lambda_2)(\lambda_4-\lambda_2)} A_1^\circ + \frac{\lambda_3\lambda_4}{(\lambda_3-\lambda_2)(\lambda_4-\lambda_2)} A_2^\circ$$

$$U_3 = \frac{\lambda_2\lambda_3\lambda_4}{(\lambda_1-\lambda_3)(\lambda_2-\lambda_3)(\lambda_4-\lambda_3)} A_1^\circ + \frac{\lambda_3\lambda_4}{(\lambda_2-\lambda_3)(\lambda_4-\lambda_3)} A_2^\circ + \frac{\lambda_4}{\lambda_4-\lambda_3} A_3^\circ$$

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$$U_4 = \frac{\lambda_2\lambda_3\lambda_4}{(\lambda_1-\lambda_4)(\lambda_2-\lambda_4)(\lambda_3-\lambda_4)} A_1^o + \frac{\lambda_3\lambda_4}{(\lambda_2-\lambda_4)(\lambda_3-\lambda_4)} A_2^o + \frac{\lambda_4}{\lambda_3-\lambda_4} A_3^o + A_4^o$$

where,

A_4^o = Initial activity of the GGD

To calculate the GGD activity for Rb-99, the terms U_2, U_3, and U_4 are calculated. U_1 need not be calculated since, as we have seen, $e^{-\lambda t} = 0$.

$$U_2 = \frac{(9.52)(.226)(.045)}{(102-9.52)(.226-9.52)(.045-9.52)}(773) + \frac{(.226)(.045)}{(.226-9.52)(.045-9.52)}(2.32\times10^4)$$

$$= \frac{(9.68\times10^{-2})}{(92.5)(-9.29)(-9.48)}(773) + \frac{.0102}{(-9.29)(-9.48)}(2.32\times10^4)$$

$$= 9.19\times10^{-3} + 2.68$$

$$= 2.69$$

$$U_3 = \frac{.0968}{(102-.226)(9.52-.226)(.045-.226)}(773) + \frac{.0102}{(9.52-.226)(.045-.226)}(2.32\times10^4)$$

$$+ \frac{.045}{.045-.226}(3330.)$$

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$$= \frac{.0986\ (773)}{(102)(9.29)(-.181)} + \frac{.0102\ (2.32\times10^{4})}{(9.29)(-.181)} + \frac{.045\ (3330)}{-.181}$$

$$= -.444 - 141 - 828$$

$$= -969$$

$$U_4 = \frac{.0986\ (773)}{(102-.045)(9.52-.045)(.226-.045)} + \frac{.0102\ (2.32\times10^{4})}{(9.52-.045)(.226-.045)}$$

$$+ \frac{.045}{.226-.045}\ (3330) + 0.0$$

$$= \frac{.0986\ (773)}{(102)(9.48)(-.181)} + \frac{.0102\ (2.32\times10^{4})}{(9.48)(-.181)} + \frac{.045\ (3330)}{(-.181)}$$

$$= .435 + 138 + 828$$

$$= 966$$

Substituting the U's in equation (B) gives

$$A_4 = 2.69\ e^{(-9.52)(3.583)} - 969\ e^{(-.226)(3.583)} + 966\ e^{(-.045)(3.583)}$$

$$= 4.13\times10^{-15} - 431 + 822$$

$$= 391\ Ci$$

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DESCRIPTION	CALC. BY	APPROVED BY

Multiplying this result by the packet release fraction of 0.70 gives

$A_{Rb\text{-}89} = 274$ ci

The CRIT8 code calculates a Rb-89 activity of 277 ci.

The minor differences in results between the hand calculation and the CRIT8 code are due to the retention of only the third significant figure for the decay constants. Whereas, the computer retains six significant figures, an error on the order of 1% may be expected.

APPENDIX C

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