

ALRRDOSE: A computer program to estimate
the population dose following a fuel meltdown
accident at the Ames Laboratory Research Reactor

by

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LIST OF SYMBOLS AND ABBREVIATIONS

- A - minimum cross sectional area of an external face of the reactor building (m^2)
- a - age group for which dose calculation is performed
- B - ratio of resonance neutron flux to thermal neutron flux in the fuel
- C - amount of each radioisotope that escapes to the atmosphere (curies)
- C' - rate of escape of each radioisotope to the atmosphere (curies/s)
- D_{β} - dose from beta radiation (rad)
- D_{γ} - dose from gamma radiation (rad)
- D_{EX} - external dose (rad)
- D_{IN} - internal total body dose (rem)
- D_{TB} - total body dose (rem)
- D_{THY} - internal thyroid dose (rem)
- $D(j,a)$ - internal dose to organ (j) in age group (a) (rem)
- $DFA(j,a)$ - inhalation dose factor for organ (j) and age group (a) (mrem/picocurie)
- E_{β} - average beta energy per disintegration (Mev/dis)
- E_{γ} - average gamma energy per disintegration (Mev/dis)
- F - fraction of each isotope that is released from the fuel to the containment room
- H - effective release height (m)

- H_d - downwash correction to the stack height (m)
- I - inside diameter of the exhaust stack (m)
- j - organ for which the dose is being calculated
- K - building shape factor
- L - exhaust rate of air from containment building (m^3/s)
- p - percent of the value of concentration on the plume axis
- Q - quantity of each radioisotope produced in the fuel
adjusted to include decay in transit (curies)
- Q_o - quantity of each radioisotope produced in the fuel
(curies)
- Q_c - activity in the containment building air (curies)
- Q_c' - rate of change of activity in the containment building
air (curies/s)
- $R(a)$ - breathing rate of age group (a) (m^3/s)
- S_v - stack velocity (m/s)
- S - horizontal wind speed (m/s)
- T - total operation time of the reactor (MW-sec)
- t - time of exposure to a plume containing radioisotopes (s)
- t_a - time of arrival of a plume containing radioisotopes (s)
- V - volume of the containment room (m^3)
- X - downwind distance of a receptor (m)
- X_{PRESS} - containment pressure (mb)
- Y - crosswind distance of a receptor (m)
- Y_p - crosswind distance where the concentration has dropped
to $p\%$ of its value on the plume axis

- ϵ - filter efficiency
- λ - decay constant of the isotope of interest (s^{-1})
- σ_y - horizontal standard deviation of a plume (m)
- σ_y' - horizontal standard deviation of a plume corrected for the turbulent wake of the reactor building (m)
- σ_z - vertical standard deviation of a plume (m)
- σ_z' - vertical standard deviation of a plume corrected for the turbulent wake of the reactor building (m)
- χ - the concentration of each radioisotope (curie/m³)
- Ψ - the concentration time integral for each radioisotope (curie s/m³)

ABSTRACT

In the event of a fuel meltdown accident at a reactor facility and subsequent release of radionuclides, one must be able to obtain a reasonable estimate of the resultant dose to the surrounding population. Although the original safety analysis report for the Ames Laboratory Research Reactor (ALRR) evaluated the consequences of the design basis accident (DBA), many of the models and assumptions used at that time are now no longer used or are considered inadequate. Using the most recent recommendations contained in the Nuclear Regulatory Commission Regulatory Guides, a computer code is developed which can evaluate the radiological consequences following a fuel meltdown accident at the ALRR. The input requirements to the code are simplified to enable a person unfamiliar with the details of the code to obtain reliable dose estimates.

The computer program, ALRRDOSE, can estimate the population dose following the DBA at the ALRR or it can estimate the population dose following other fuel meltdown accidents by varying input parameters.

The current safety analysis report for the ALRR estimates the doses following the DBA to be approximately ten times higher than those estimated by ALRRDOSE. The primary reason for the difference is that the current safety analysis

uses the Sutton model to describe atmospheric diffusion while ALRDOSE uses the Gaussian plume diffusion model. Both estimates, however, are far below the limits imposed by 10CFR100 and the dose estimates from other fuel meltdown accidents are lower than those from the DBA.

INTRODUCTION

In the event of an accidental release of radionuclides to the atmosphere from a reactor, one must be able to obtain a reasonable estimate of the resultant dose to the surrounding population. At a reactor facility, the situation of greatest consequence is the design basis accident (DBA), the accident which has the potential of releasing the largest amount of radionuclides to the atmosphere.

In early dose determinations, simplified diffusion equations and dose estimates were adequate, but as the need for more reliable dose estimates developed, the models and equations became extremely detailed and nearly impossible to solve by hand. Numerous computer codes have been developed to describe release, diffusion, and inhalation, and to calculate the resulting dose. The codes use a wide variety of models and an equally wide variety of assumptions in applying the models.

Although the original safety analysis report for the Ames Laboratory Research Reactor (ALRR) (1) evaluated the consequences of the DBA, many of the models and assumptions used at that time are now no longer used or are considered inadequate. As a result, the dose estimate, although not necessarily less accurate, is not comparable with present day dose estimates. The need has arisen to use a standard set of

models and consistent assumptions so that dose estimates from different facilities and different situations can be compared.

The United States Nuclear Regulatory Commission (NRC) has developed a set of recommendations for the power reactor industry to use as guides in evaluating specific problems or postulated accidents (2). Included in the guidelines are recommendations for models and assumptions to be used in the estimation of population dose from release of radionuclides to the atmosphere (3-6). Therefore in the development of a computer program to estimate the dose, the most recent recommendations of the NRC's Regulatory Guides will be followed as closely as possible.

In describing ALRRDOSE, the first section is the development of the computer program. The first topic discussed in this section is the selection of major equations to be used in the program. The next topic, the description of the final package, begins with the calculation of the fission product buildup and is followed by a description of the release of nuclides to the atmosphere, the dispersion in the atmosphere, and the resultant dose to the human population. The final topics discussed in this section are the input description and the output description. In the next section describing the results of the program, the output from the program is shown for the different types of accidents considered. The

final section of the program description summarizes the results and compares the dose estimates of ALRRDOSE with those previously calculated. Recommendations for future work on the code are also presented.

OBJECTIVES

The primary objective of this study is to incorporate the most recent NRC recommendations into a computer code which will then be used to evaluate the radiological consequences following a fuel meltdown accident at the Ames Laboratory Research Reactor facility. Another objective of this study is to simplify the input requirements to the computer code in a way that will enable a person unfamiliar with the details of the code to obtain reliable dose estimates. The computer program will be able to estimate the population dose following the DBA at the ALRR by specifying the "worst possible case" for the input parameters. It will also estimate the population dose following other fuel meltdown cases by varying the input parameters describing core history, atmospheric conditions, and containment pressure.

LITERATURE REVIEW

The radiation dose following an accidental fuel meltdown and subsequent atmospheric release of fission products has been studied since the building of the first reactor. Determination of the dose requires the incorporation of a wide variety of information. Three major areas of investigation concerning the human body dose following a fuel meltdown accident are: the physics and chemistry of the buildup of fission products in the fuel and their subsequent release upon melting, the behavior of these radionuclides after their release to the atmosphere, and the radiation dose to the body once these radionuclides are inhaled or ingested. No attempt was made to review all the literature concerning these subjects because of the extremely large volume written on all of them and a reference cited will in many cases be only a representative sample. The literature reviewed on each major field will be discussed as it relates to the writing of a computer program to describe the dose following a fuel meltdown accident at the Ames Laboratory Research Reactor.

Fission Product Buildup in the Fuel

Before extensive use of computers to calculate fission product buildup in the fuel, the activity of a fission prod-

uct isotope was simply assumed to be the saturation activity of that isotope (7). The saturation activity was used in the current safety analysis for the ALRR. This, of course, does not account for the possible increase in activity of an isotope through decay of its parents, nor does it account for the change in activity due to neutron interactions (n,γ), ($n,2n$), etc. However, some computer codes requiring the fission product inventory used the saturation activity as a rough approximation, Blain and Bramblett (8), for example. Kenfield, et al. (9) and others attempted to solve the well-known buildup and decay equations directly. This, however, lead to inaccuracies if the total decay constants of two isotopes were nearly equal. Stallmann and Kam (10), Duane (11), and Van Tuyl (12) among others developed codes to circumvent this difficulty by finding approximations or alternate solutions to the differential equations or by rearranging the equations into forms which were not sensitive to these difficulties. Van Tuyl's code, ISOGEN, was shown to have accuracy within 0.1% for each time step calculation and was also adaptable to the ALRR. ISOGEN was therefore used in the development of the present program.

Atmospheric Diffusion

Most of the early atmospheric diffusion calculations in the nuclear industry were based on the Sutton equations (13), as are the diffusion calculations in the ALRR safety analysis report. Many computer codes were written incorporating them such as codes by Kenfield, et al. (9), Duncan (14), and Houston, et al. (15).

A very exhaustive study of atmospheric dispersion processes was undertaken by the United States Atomic Energy Commission. A compilation of the findings, edited by Slade (16), has gained wide acceptance throughout the nuclear industry. The study recommends the use of the Gaussian plume diffusion model with the vertical and horizontal standard deviations of the plume being based on work originally done by Pasquill (17) and Meade (18). It further recommends that the actual values of the standard deviations be based on Pasquill's categories as modified by Hilsmeier and Gifford (19).

Several computer codes have been written using many of these recommendations. Among them are codes by Blain and Bramblett (8), Stallmann and Kam (10), Houston, et al. (15), Binford, et al. (20), and Strenge, et al. (21). The models and assumptions used by the different codes are not the same in many cases which makes comparison between codes difficult.

To help remedy this and similar situations in the industry, the United States Nuclear Regulatory Commission has published a set of guides to be used by the power reactor industry in evaluating specific problems or postulated accidents (2). In recommendations to be used following release of radionuclides to the atmosphere, the Nuclear Regulatory Commission makes reference to the use of Appendix A of reference 16 in the determination of atmospheric diffusion parameters. The tables and graphs in Appendix A of reference 16 will therefore be used in the present program as they pertain to atmospheric diffusion following a radiation release at the ALRR.

Human Radiation Dose

Much of the work on the human radiation dose in the ALRR safety analysis report was based on an early AEC publication, WASH-740 (22). Much of the data in WASH-740 quickly became obsolete, however, as more recent information was accumulated. Another early publication on the effects of radiation on the human body was a very comprehensive and well-accepted study by ICRP 2 (23). A code by Killough, et al. (24) was one of several codes to use these models as a basis for calculation of organ dose. As more information became available, the models were revised and new models were formulated. Again this lead to the situation that different dose calcu-

lations were not comparable. The models and equations used in the present program are those recommended by the NRC guides referring to external and internal dose to the whole body and the thyroid.

In reviewing the large number of computer codes which calculated fission product buildup, atmospheric diffusion, and radiation dose, many used models and assumptions consistent with the NRC Regulatory Guides. Some, however, used only portions of the recommendations or used values which were not consistent with the Guides (14,15,20,21,24). Others were written specifically for power reactors or were not applicable to the ALRR in other ways. For example, a code under development by the NRC (25) and under trial use by the Omaha Public Power District uses the equations recommended by the NRC Regulatory Guides for diffusion and dose calculations. However, the code is best suited for long-term dose estimates at power reactors and is not readily adaptable to the ALRR. Considering that there is no single code which adequately represents the situations encountered in an ALRR fuel meltdown accident, it was decided to write a computer program specifically for the ALRR which could be used in a simple manner to estimate the dose to the surrounding population following a fuel meltdown accident at the ALRR.

DEVELOPMENT OF THE COMPUTER PROGRAM

Introduction

In the development of a computer program to estimate the population dose following a fuel meltdown accident at the ALER, conservative assumptions and predictions will be used when the data needed are not yet available or are uncertain. For example, it is very difficult to accurately predict the behavior of fission products upon fuel melting. Quantitative data on the release of fission products from fuel under accident conditions are being evaluated, but of course the physical environment surrounding the fuel will be somewhat different for each type of reactor and each accident. Therefore an attempt will be made to qualitatively predict conditions and reactions and ensure that the predictions are conservative.

Once it has been determined which fission product isotopes are likely to escape from the fuel and in what amounts, the dispersion within the containment and eventual release to the environment must be estimated. This also involves some qualitative predictions but quantitative data on ventilation system fan pumping rates, containment building structural leak rates, and efficiencies of the air filters are available.

The behavior of fission product isotopes after their release to the atmosphere has been a subject under continuous investigation, and the models developed have been tested quite extensively through diffusion studies. For many years, atmospheric diffusion calculations pertaining to reactor safety analyses were most often based on the well-known Sutton equations (13). It has been shown, however, that there are some theoretical difficulties in the Sutton model (26). The general theory on which Sutton based his model may not apply to the region of the atmosphere which was modeled, namely the lower few meters. Good verifications of diffusion predictions by the Sutton model have also been difficult, except in some cases for very long distances under specific atmospheric conditions. More useful mathematical models describing atmospheric diffusion were therefore sought.

The effect of fission product isotopes on the human body has also been extensively studied, and several different methods are used to arrive at an estimate of the dose to the human body.

In an effort to arrive at a good approximation to the dose that the population would receive in the event of an accidental fission product release, the Nuclear Regulatory Commission has compiled a set of models and assumptions to be used by the power reactor industry for this purpose. The models and assumptions that apply to the ALRR will be used in the following development of the computer program.

Selection of Major Equations

It will be assumed that following a fuel meltdown accident, twenty-five percent of the radioactive iodine inventory and one hundred percent of the noble gas inventory developed from full power operation of the ALRR core will be immediately released from the reactor primary containment and evenly dispersed throughout the containment room. All of the iodine released will be in a form not likely to deposit on the ground, therefore no correction will be made for depletion of the effluent plume of radioactive iodine due to deposition on the ground. Also no correction will be made for radiological decay of iodine in transit (27).

External whole body doses will be calculated using "infinite cloud" assumptions. In the case of beta radiation, the receptor is assumed to be exposed to an infinite cloud at the maximum ground level concentration at that distance from the reactor. The dose will be (28)

$$D_{\beta} = 0.457 \cdot E_{\beta} \cdot \Psi \quad \{1\}$$

where

D_{β} = external beta dose from an infinite cloud (rad)

E_{β} = average beta energy per disintegration (Mev/dis)

Ψ = the concentration time integral of each radioisotope (curie s/m³).

In the case of gamma radiation, the receptor is assumed to be

exposed to only one-half the cloud owing to the presence of the ground. The gamma dose will be

$$D_{\gamma} = 0.25 \cdot E_{\gamma} \cdot \Psi \quad \{2\}$$

where

D_{γ} = external gamma dose from an infinite cloud (rad)

E_{γ} = average gamma energy per disintegration (Mev/dis).

The dose from inhalation of the radioiodine isotopes is dependent on the age and breathing rate of the recipient, as well as the concentration of radioiodine in the surrounding air. The inhalation dose will be (29)

$$D(j,a) = R(a) \cdot \Psi \cdot \text{DFA}(j,a) \cdot 10^9 \quad \{3\}$$

where

$D(j,a)$ = dose to organ (j) of an individual in age group (a) due to inhalation of each radionuclide (rem)

$R(a)$ = breathing rate of age group (a) (m^3/s)

$\text{DFA}(j,a)$ = the inhalation dose factor for organ (j) and age group (a) (mrem/picocurie).

The concentration time integral, Ψ , of a radionuclide is defined as

$$\Psi = \int_{t_a}^{t_a+t} X dt \quad \{4\}$$

where

t_a = time of arrival of the plume (s)

t = time of exposure to the plume (s)

χ = concentration of each radionuclide at the location of the receptor (curies/m³).

If the dimensions of a plume are relatively small, then it can be assumed that the concentration of radionuclides in the plume does not appreciably change during the period of exposure to the plume. In this case, the concentration time integral can be approximated by

$$\Psi = \chi \cdot t \quad \{5\}$$

Equation {5} will be used in the dose calculation for the relatively short puff release.

The concentration of each radionuclide at the location of the receptor can be found by (30)

$$\chi = \frac{C'}{\pi \cdot \sigma_y \cdot \sigma_z \cdot S} \cdot \text{EXP} \left[- \frac{Y^2}{2\sigma_y^2} - \frac{H^2}{2\sigma_z^2} \right] \quad \{6\}$$

where

C' = rate of release of radioactive material (curies/s)

σ_y = horizontal standard deviation of the plume (meters)

σ_z = vertical standard deviation of the plume (meters)

S = wind speed at the point of release (meters/s)

Y = crosswind distance from the line of wind direction
(meters)

H = effective stack height (meters)

Equations {1} through {6} are the major equations to be used in the estimation of the population dose following an accidental fission product release at the ALRR.

Description of Final Package

The computer code described below begins with the determination of the activity in the fuel at the time of the accident, and proceeds to calculate the release of activity from the containment, its dispersal in the atmosphere, and the eventual dose to the human body.

The activity in the fuel is calculated using an existing radioisotope generation and decay computer program which is modified somewhat for use in ALRRDOSE. The release of activity from the containment is calculated by first making conservative assumptions about the release and dispersal of fission products within the containment, and then by dividing the atmospheric release into three separate parts. Two release periods will be of short duration, one being an unfiltered release and the other being a filtered release, and the third release period will be a long-term filtered

release. Within each release period, atmospheric diffusion is described by using equation {6} with the diffusion parameters σ_y and σ_z being dependent upon the atmospheric conditions input at execution time and the distance of the receptor from the reactor. The thyroid dose and total body dose to a receptor located at different distances from the reactor are then calculated for each age group by using equations {1} through {3}. Finally the results of the calculations are printed in tables or on graphs from which one can determine the dose to a person standing at a specified distance from the reactor for a specific time period following a fuel meltdown accident.

In describing the final package, reference will be made to the program listings contained in Appendix A. The reference numbers of applicable statements will be listed in brackets following the description of each segment of the program. The final package will be described as it relates to the printing of the results in tables and not to the production of graphs. The differences between these two options will be described in later sections.

The first segment of ALRRDOSE is space allocation and assignment of initial values to variables to be used later, followed by the reading and writing out of the input parameters [1-74]. Subroutine isogn2 is then called [75].

Subroutine isogn2

Subroutine isogn2 is a modified version of the computer code ISOGEN. ISOGEN, described in Appendix B, is a radioisotope generation and decay program. It is used to calculate and print out all the fission product isotopes contained in the core after the specified time period which could contribute to the whole body dose or the thyroid dose.

The input to subroutine isogn2 consists of three major groups. The first group is basic nuclear data for the isotopes of interest. Included in the data are half-life, disintegration energy, cross section, fission yield, and daughter product information for each isotope. Reference 4 lists all the radioisotopes which contribute to the whole body or thyroid dose. ISOGEN was run using parameters from a typical ALRR core life as input. It was found that the only fission product isotopes produced in significant quantities which contribute to the total body or thyroid dose are 4 isotopes of krypton, 7 isotopes of iodine, and 6 isotopes of xenon. Of these 17 isotopes, all contribute to the total body dose, but only iodine isotopes contribute to the thyroid dose.

The 753-member ISOGEN library was then surveyed and it was found that eight additional isotopes have decay or absorption products which form one of the 17 contributing

isotopes. Data on these 25 isotopes plus that of U235 and U238 are shown in Table 1.

The second group of input data required by subroutine isogn2 includes the time, neutron flux, and resonance to thermal neutron flux ratio to be used for each of up to 30 time steps. The length of a time step and the reactor power during that time step are input at execution time. Neither the neutron flux in the fuel over core life nor the resonance to thermal neutron flux ratio is known accurately for the ALRR. An option is available in ISOGEN in which the power level and resonance to thermal neutron flux ratio are input and the code calculates the flux required to maintain the desired power level. Thus if one can determine the resonance to thermal neutron flux ratio, the flux can be calculated. The thermal flux in the ALRR fuel has been experimentally determined by the xenon transient technique (31). ISOGEN was run with the input parameters duplicating those at the time of the experiment. The resonance to thermal neutron flux ratio was then varied until the thermal flux in the fuel calculated by ISOGEN equalled that experimentally determined. The ratio was determined to be 0.05 and is assumed to remain constant throughout core life.

The third group of input data includes the library index numbers of the fission product isotopes of interest plus the index numbers and amounts of U235 and U238 present at the

Table 1. Nuclide library information used in isogn2

Nuclide	Half-life	At. No.	Natural Abundance	Minor Branch	Fission Yield, %
KR 84	1.000E 30 Y	36	5.69E 01	0.0	9.53E-01
KR 85M	4.400E 00 H	36	0.0	2.30E-01	1.31E 00
KR 85	1.140E 01 Y	36	0.0	0.0	0.0
KR 86	1.000E 30 Y	36	1.74E 01	0.0	1.84E 00
KR 87	7.800E 01 M	36	0.0	0.0	2.50E 00
KR 88	2.800E 00 H	36	0.0	0.0	3.58E 00
TE129M	3.300E 01 D	52	0.0	3.20E-01	3.60E-01
TE131M	1.200E 00 D	52	0.0	2.20E-01	4.35E-01
TE132	7.800E 01 H	52	0.0	0.0	4.22E 00
TE133M	5.000E 01 M	52	0.0	0.0	4.77E 00
TE134	4.200E 01 M	52	0.0	0.0	7.74E 00
I 129	1.600E 07 Y	53	0.0	0.0	6.40E-01
I 130	1.250E 01 H	53	0.0	0.0	0.0
I 131	8.050E 00 D	53	0.0	1.00E-02	2.47E 00
I 132	2.300E 00 H	53	0.0	0.0	0.0
I 133	2.100E 01 H	53	0.0	2.40E-02	1.85E 00
I 134	5.300E 01 M	53	0.0	0.0	0.0
I 135	6.700E 00 H	53	0.0	2.70E-01	6.45E 00
XE131M	1.200E 01 D	54	0.0	0.0	0.0
XE133M	2.300E 00 D	54	0.0	0.0	1.60E-01
XE133	5.270E 00 D	54	0.0	0.0	6.46E 00
XE134	1.000E 30 Y	54	1.04E 01	0.0	7.74E 00
XE135M	1.600E 01 M	54	0.0	0.0	0.0
XE135	9.200E 00 H	54	0.0	0.0	6.45E 00
XE138	1.400E 01 M	54	0.0	0.0	6.68E 00
U235	7.130E 08 Y	92	7.2 E-01	0.0	0.0
U238	4.510E 09 Y	92	9.93E 01	0.0	0.0

Table 1. continued

Nuclide	Decay daughters		Reaction daughters		Mev per decay	
	Major	Minor	Major	Minor	Beta	Gamma
KR 84	0	0	KR 85M	KR 85	0.0	0.0
KR 85M	RB 85	KR 85	0	0	0.220	0.186
KR 85	RB 85	0	KR 86	0	0.250	0.005
KR 86	0	0	KR 87	0	0.0	0.0
KR 87	RB 87	0	0	0	1.350	1.100
KR 88	RB 88	0	0	0	0.390	1.890
TE129M	TE129	I129	0	0	0.270	0.0
TE131M	I131	TE131	0	0	0.160	1.500
TE132	I132	0	0	0	0.161	0.230
TE133M	I133	0	0	0	0.800	2.100
TE134	I134	0	0	0	0.500	0.120
I129	XE129	0	I130	0	0.080	0.0
I130	XE130	0	I131	0	0.260	2.200
I131	XE131	XE131M	I132	0	0.340	0.380
I132	XE132	0	0	0	0.450	2.360
I133	XE133	XE133M	0	0	0.440	0.580
I134	XE134	0	0	0	1.600	0.380
I135	XE135	XE135M	0	0	0.320	1.770
XE131M	XE131	0	0	0	0.159	0.005
XE133M	XE133	0	0	0	0.190	0.040
XE133	CS133	0	XE134	0	0.150	0.030
XE134	0	0	XE135	0	0.0	0.0
XE135M	XE135	0	0	0	0.080	0.450
XE135	CS135	0	XE136	0	0.300	0.260
XE138	CS138	0	0	0	0.0	0.690
U235	TH231	0	U236	0	4.490	0.150
U238	TH234	0	U239	0	4.270	0.0

Table 1. continued

Nuclide	Total cross section		Partial cross section	
	Thermal	Resonance	Thermal	Resonance
KR 84	1.40E-01	4.90E 00	4.00E-02	0.0
KR 85M	0.0	0.0	0.0	0.0
KR 85	7.00E 00	2.60E 01	0.0	0.0
KR 86	6.00E-02	2.00E-02	0.0	0.0
KR 87	0.0	0.0	0.0	0.0
KR 88	0.0	0.0	0.0	0.0
TE129M	0.0	0.0	0.0	0.0
TE131M	0.0	0.0	0.0	0.0
TE132	0.0	0.0	0.0	0.0
TE133M	0.0	0.0	0.0	0.0
TE134	0.0	0.0	0.0	0.0
I 129	2.80E 01	2.40E 01	0.0	0.0
I 130	1.80E 01	0.0	0.0	0.0
I 131	5.00E 01	0.0	0.0	0.0
I 132	0.0	0.0	0.0	0.0
I 133	0.0	0.0	0.0	0.0
I 134	0.0	0.0	0.0	0.0
I 135	0.0	0.0	0.0	0.0
XE131M	0.0	0.0	0.0	0.0
XE133M	0.0	0.0	0.0	0.0
XE133	1.90E 02	0.0	0.0	0.0
XE134	2.00E-01	5.00E 01	0.0	0.0
XE135M	0.0	0.0	0.0	0.0
XE135	3.22E 06	2.14E 06	0.0	0.0
XE138	0.0	0.0	0.0	0.0
U235	6.33E 02	6.00E 01	5.30E 02	8.00E 00
U238	2.74E 00	2.81E 02	2.50E-01	0.0

beginning of the first time step. The amount of U235 is input at execution time and the amount of U238 is calculated using the fact that the fuel is enriched to 93.2% with U235.

$$U238 = U235 \cdot 0.068 / 0.932 \quad \{8\}$$

The main body of the program begins with the determination of the atmospheric stability category [79-84]. This is dependent on the wind speed, incoming solar radiation (insolation), and the time of day and does not change during the calculation. The guidelines followed are based on work done by Pasquill (17) and Meade (18), and the values used by the program are shown in Table 2.

A set of dose calculations will be performed once for each age group at each distance. The first calculation will be made at the exclusion boundary distance directly downwind of the point of release. From this point the distance is incremented in both the downwind direction and crosswind direction with the incremental distances increasing exponentially.

Each set of dose calculations consists of three separate parts, as shown in Table 3. Within each part, a separate calculation will be performed for each of the 17 contributing radioisotopes. The first part of a set estimates the dose to the total body and thyroid resulting from a ground level unfiltered puff release occurring during the time that the

Table 2. Pasquill's stability categories¹

Period	Wind speed (m/s)	Clear	Slightly cloudy	≤3/8 cloudiness	≥4/8 cloudiness	Heavily overcast
day	<2	1	1	2	2	4
	2-3	1	2	2	3	4
	3-5	2	2	3	3	4
	5-6	3	3	4	4	4
	>6	3	4	4	4	4
night	<2	6	6	6	6	4
	2-3	6	6	6	5	4
	3-5	5	5	5	4	4
	5-6	4	4	4	4	4
	>6	4	4	4	4	4

¹Stability category 1 corresponds to Pasquill's category A, 2 to B, 3 to C, 4 to D, 5 to E, and 6 to F.

Table 3. Parts of a set of dose calculations

Part	Type of release	Pressure range (mb)	Volume released (m ³)	Release rate (m ³ /s)
1	Ground level unfiltered puff	1030.7-1013.3	2.03	0.03
2	Elevated filtered puff	1030.7-1017.0	193.	3.78
		1017.0-1013.3	51.3	3.02
		1013.3-1005.8	103.	1.25
3	Elevated filtered continuous	below 1013.3	--	.236

containment is above atmospheric pressure. The second calculation is made for the period of time that the high capacity exhaust fan is in operation and estimates the dose from the resulting elevated filtered puff release. The third calculation estimates the dose from an elevated filtered continuous release occurring when the low capacity exhaust fan is the only means by which containment air is exhausted from the containment building.

Ground level unfiltered puff release

Calculation of the dose from a ground level unfiltered puff release begins with the determination of the amount of each radioisotope that will leak from the containment during overpressure [126-129]. This will depend upon the amount of the radioisotope produced in the core (Q_0 , calculated in subroutine isogn2), the fraction of each nuclide which escapes from the core to the containment, and the containment pressure at the time of the accident. The effect of radiological decay of noble gas isotopes from the time they are released from the containment until they reach the receptor will be accounted for by making an adjustment to Q_0 [109-123],

$$Q = Q_0 \cdot \text{EXP}(-\lambda \cdot X/S) \quad \{9\}$$

where

Q = the quantity of the radioisotope produced, corrected for radiological decay (curies)

λ = decay constant of isotope of interest (s^{-1})

X = downwind distance (meters)

S = wind speed (m/s).

Unfiltered containment air will leak to the atmosphere only in the event that containment air pressure is greater than atmospheric pressure. The ALRR Operating Limits (32) require that at a building overpressure of 1030.7mb (7" H₂O), no more than 2.03m³ (71.8ft³) of unfiltered air will leak from the containment during pressure reduction. Therefore, making the conservative assumption that the leak rate is a linear function of containment overpressure, the number of curies of each isotope that will leak during overpressure can be found by multiplying the actual containment overpressure, as compared to the maximum, by the fraction of the total containment air that escapes from the building; then multiplying the result by the fractional amount of each radioisotope produced that escapes from the core to the containment. The equation is [127-129]

$$C = \left[\frac{XPRESS - 1013.25}{1030.7 - 1013.25} \right] \cdot \left[\frac{2.03}{1.42 \cdot 10^4} \right] \cdot Q \cdot F \quad \{10\}$$

where

C = leakage from the containment (curies)

XPRESS = the containment pressure at the time of the
accident (mb)

F = the fraction of each radioisotope that escapes
the core.

The subscripts on C and Q in the program listing are KR for krypton, II for iodine, and XE for xenon. 100% of the noble gases and 25% of the iodine produced in the core are released to the containment.

The next segment of the program [133-144] calculates the horizontal and vertical standard deviations of the plume (σ_y and σ_z , respectively), with the methods of interpolation being similar to that used in reference 15.

For ground level releases additional dispersion will be produced in the plume by the turbulent wake of the reactor building. This will increase the value of the standard deviations by a factor ranging from one to a maximum of 1.732 (3).

$$\sigma_y' = (\sigma_y^2 + K \cdot A / \pi)^{1/2} \quad \{11\}$$

$$\sigma_z' = (\sigma_z^2 + K \cdot A / \pi)^{1/2} \quad \{12\}$$

where

K = the shape factor

A = the minimum cross sectional area of the reactor
building (m²).

The shape factor in this case is 1/2 (33) and the minimum cross sectional area of the reactor building is 401.7m². The standard deviations become

$$\sigma_y' = (\sigma_y^2 + 63.93)^{1/2} \quad \{13\}$$

$$\sigma_z' = (\sigma_z^2 + 63.93)^{1/2} \quad \{14\}.$$

For a cloud containing radioisotopes, if one assumes that diffusion in the line of the wind direction is small compared to the wind speed, then the total time that a receptor will receive a dose from this cloud is the total time that the cloud is being produced. Therefore, the exposure time to an unfiltered puff release will be the time period that the containment pressure is above atmospheric.

The concentration time integral of radionuclides in the atmosphere following a ground level unfiltered puff release (CH in the program listing) can be calculated at different distances by combining equations {5} and {6} and noting that $C = C' \cdot t$ [147-152],

$$\Psi = \frac{C}{\pi \cdot \sigma_y \cdot \sigma_z \cdot S} \cdot \text{EXP} \left[- \frac{Y^2}{2\sigma_y^2} - \frac{H^2}{2\sigma_z^2} \right] \quad \{15\}$$

The external dose (eqns. {1}, {2}, and {5}), and the internal total body dose (eqns. {3} and {5}) are added to obtain the total body dose [154-158,161],

$$D_{\beta} = 0.457 \cdot [(E_{\beta} \cdot \Psi)_{KR} + (E_{\beta} \cdot \Psi)_{XE}] \quad \{16\}$$

$$D_{\gamma} = 0.250 \cdot [(E_{\gamma} \cdot \Psi)_{KR} + (E_{\gamma} \cdot \Psi)_{XE}] \quad \{17\}$$

$$D_{EX} = D_{\beta} + D_{\gamma} \quad \{18\}$$

$$D_{IN} = R(a) \cdot DFA(j, a)_{TB} \cdot \Psi \cdot 10^9 \quad \{19\}$$

$$D_{TB} = D_{EX} + D_{IN} \quad \{20\}$$

where

D_{β} = external beta dose (rem)

D_{γ} = external gamma dose (rem)

D_{EX} = total external total body dose (rem)

D_{IN} = internal total body dose (rem)

D_{TB} = total dose to the total body (rem)

and all other variables are as defined above.

The thyroid dose is calculated using equations {3} and {5} [159, 164],

$$D_{THY} = R(a) \cdot DFA(j, a)_{THY} \cdot \Psi \cdot 10^9 \quad \{21\}$$

where

D_{THY} = the total dose to the thyroid (rem).

Values for the average beta and gamma energy per disintegration (E_{β}, E_{γ}) are those shown in Table 1. The inhalation dose factors ($DFA(j, a)$) for the total body and thyroid are shown for the different age groups in Table 4. The breathing rates of different age groups ($R(a)$) are taken as 1.5 times the breathing rates recommended in reference (34) and are as follows:

Table 4. Inhalation dose factors (mrem/picocurie)

	Nuclide	Adult	Teenager	Child	Infant
	I 129	6.91E-06	9.81E-06	2.86E-05	5.82E-05
	I 130	6.61E-07	0.0	0.0	0.0
	I 131	2.56E-06	3.52E-06	9.47E-06	1.79E-05
TOTAL BODY	I 132	1.45E-07	0.0	0.0	0.0
	I 133	5.67E-07	7.93E-07	2.17E-06	4.19E-06
	I 134	7.70E-08	0.0	0.0	0.0
	I 135	3.22E-07	0.0	0.0	0.0
	I 129	5.55E-03	7.32E-03	2.14E-02	5.21E-02
	I 130	2.18E-04	0.0	0.0	0.0
	I 131	1.49E-03	1.74E-03	4.16E-03	1.01E-02
THYROID	I 132	5.48E-05	0.0	0.0	0.0
	I 133	3.66E-04	4.79E-04	1.36E-03	3.33E-03
	I 134	2.87E-05	0.0	0.0	0.0
	I 135	1.17E-04	0.0	0.0	0.0

ADULT - $3.47 \times 10^{-4} \text{ m}^3/\text{s}$

TEENAGER - $2.34 \times 10^{-4} \text{ m}^3/\text{s}$

CHILD - $1.22 \times 10^{-4} \text{ m}^3/\text{s}$

INFANT - $9.72 \times 10^{-5} \text{ m}^3/\text{s}$

This completes the calculation of the total body and thyroid doses from the ground level unfiltered puff release.

Elevated filtered puff release

The calculation of the total body and thyroid doses from an elevated filtered puff release begins with initialization of variables and conversion of units [166-170]. Then the amount of each radioisotope which is discharged through the stack during overpressure reduction is calculated [173-192]. This is dependent on the containment pressure at the time of the accident, the exhaust rate through the emergency air filters, and the filter efficiencies.

Using the manufacturer's fan curves for the exhaust fans in operation during overpressure, it can be shown that the time required to reduce the containment pressure from 1030.7mb to 1013.25mb (atmospheric) is a total of 68 seconds (8). It will take 51 seconds to reduce the pressure from 1030.7mb to 1017.0mb (1.5 in H_2O) and 17 seconds from 1017.0mb to 1013.25mb. At containment pressures greater than 1017.0mb choking flow of $3.78 \text{ m}^3/\text{s}$ through the exhaust fans

is attained. As the pressure decreases from 1017.0mb to 1013.25mb (atmospheric), the exhaust rate decreases from 3.78m³/s to 2.26m³/s. It will be assumed that the flow rate during this period is the linear average, 3.02m³/s. During overpressure reduction, high and low capacity exhaust fans will pump containment air through high efficiency filters and then out the stack. The exhaust fans will continue reducing containment air pressure below atmospheric at an average flow rate of 1.25m³/s until the pressure reaches 1005.8mb (-3 in. H₂O). At that time a high capacity fan shuts off and the remaining low capacity fan will keep the containment air pressure below atmospheric. There are, therefore, three separate release periods in the elevated filtered puff release, as shown in Table 3. The total volume of air released during each period is calculated by multiplying the flow rate by the duration of the release period.

If the stack velocity is less than 1.5 times the wind speed, a correction for downwash must be made to the stack height [175, 176] (36).

$$H_d = 3 \cdot [1.5 - (S_v / S)] \cdot I \quad \{22\}$$

where

H_d = the downwash correction

S_v = the vertical stack exit velocity (m/s)

S = the mean wind speed at the height of release (m/s)

I = the inside diameter of the stack (m)

The verticle exit velocity is the exhaust rate divided by the stack cross sectional area, and the inside stack diameter is 1.22m. At the maximum exhaust rate of $3.78\text{m}^3/\text{s}$, S_v is $3.24\text{m}/\text{s}$.

At containment pressures above 1017.0mb, the amount of each isotope that is exhausted through the stack can be calculated in a manner similar to that used in the ground level unfiltered puff release, with an additional factor for filter efficiency [177-179],

$$C = \left[\frac{XPRESS-1017.0}{1030.7-1017.0} \right] \cdot \left[\frac{193}{1.42 \cdot 10^4} \right] \cdot Q \cdot F \cdot \epsilon \quad \{23\}$$

where

ϵ = filter efficiency.

The high efficiency filters have no effect on the noble gases, of course, but they are limited to a minimum of 99.9% efficient for iodine (32).

When the containment pressure is between 1017.0mb and 1013.25mb, C is [183-185]

$$C = \left[\frac{XPRESS-1013.25}{1017.0-1013.25} \right] \cdot \left[\frac{51.3}{1.42 \cdot 10^4} \right] \cdot Q \cdot F \cdot \epsilon \quad \{24\}$$

When the containment pressure is at atmospheric or below, the volume of air released is no longer pressure dependent, so C is simply [190-192]

$$C = \frac{103}{1.42 \cdot 10^4} \cdot Q \cdot F \cdot e \quad \{25\}$$

Since release from the stack is an elevated release, the standard deviations of the plume must be recalculated neglecting the correction for the turbulent wake of the reactor building. The concentration time integral, Ψ , is calculated for each period of release using equation {5}, and the total body and thyroid doses are then calculated as before and added to the previous doses from the ground level unfiltered puff release [133-162].

This completes the calculation of the dose from the elevated filtered puff release.

Elevated filtered continuous release

The elevated filtered continuous release is derived from a low capacity exhaust fan used to maintain the containment pressure below atmospheric to prevent outward leakage of radioisotopes. The fan operates at a constant rate of $0.236 \text{ m}^3/\text{s}$. However, the activity of the air inside the containment is continuously changing due both to radioactive decay and decreasing isotopic concentration in the containment air as outside air replaces the air being ejected through the stack.

The rate of change of isotopic activity in the containment room air is (1)

$$Q_c' = -\lambda \cdot Q_c - (L/V) \cdot Q_c \quad [26]$$

where

Q_c' = rate of change of activity of each isotope in the containment air (curies/s)

λ = the decay constant of the nuclide of interest (s^{-1})

L = exhaust rate of the air (m^3/s)

V = volume of the containment building (m^3)

Q_c = the activity in the containment air (curies)

Solving for Q_c ,

$$Q_c = Q_o \cdot \text{EXP}[-(\lambda + L/V) \cdot t] \quad [27]$$

where

Q_o = initial activity of each isotope released to the containment air (curies).

The rate at which activity is emitted from the building is

$$C' = (L/V) \cdot Q_c \cdot \epsilon \quad [28]$$

where

ϵ = filter efficiency

Substituting,

$$C' = (L/V) \cdot Q_o \cdot \epsilon \cdot \text{EXP}[-(\lambda + L/V) \cdot t] \quad [29]$$

Knowing the rate at which activity is released from the building, C' , the concentration, χ , at a point outside the reactor exclusion boundary can be calculated using equation {6}. The concentration time integral is then calculated by using equation {4}. Substituting equation {29} and {6} into equation {4},

$$\Psi = \int_{t_a}^{t_a+t} \frac{\epsilon \cdot L \cdot Q_0}{V \cdot \pi \cdot \sigma_y \cdot \sigma_z \cdot S} \cdot \text{EXP} \left[-\frac{Y^2}{2\sigma_y^2} - \frac{H^2}{2\sigma_z^2} \right] \cdot \text{EXP} [-(\lambda + L/V) \cdot t] dt \quad \{30\}$$

where

t = time of exposure to the plume (s).

A receptor located some distance from the reactor will be exposed to a plume whose leading edge contains the radioisotopes that were emitted at the time of the accident. The activity in the leading edge of the plume is decreased only by radiological decay and diffusion, and is not affected by dilution of the air in the containment room. To properly account for this fact, the time of arrival of the plume is assumed to be zero and the decay of the radioisotopes in transit is included by adjusting Q_0 , as is done in equation {9}. Integrating equation {30}, the concentration time integral becomes

$$\Psi = \frac{1}{\lambda + L/V} \cdot \frac{\epsilon \cdot L \cdot Q_0}{V \cdot \pi \cdot \sigma_y \cdot \sigma_z \cdot S} \cdot \text{EXP} \left[-\frac{Y^2}{2\sigma_y^2} - \frac{H^2}{2\sigma_z^2} \right] \cdot \{1 - \text{EXP} [-(\lambda + L/V) \cdot t]\} \quad \{31\}$$

The time of exposure to the cloud is calculated by subtracting the time it takes for the plume to reach the receptor from the time of interest after the accident [201-203]. The concentration time integral is then calculated [207-209, 147-152], and the total body dose and thyroid dose are calculated and added to the doses from all other types of releases previously calculated [154-162]. This completes the calculation of the total body dose and thyroid dose from an elevated filtered continuous release.

The program then repeats all of the above calculations at the same distance until the doses from all 17 contributing isotopes have been totaled. The dose at this point in the program represents the total dose to the total body and thyroid that a receptor would receive if he were standing at the point where the calculations were performed for the duration of the time of interest after the accident.

The next portion of the program compares the doses calculated by the program with the dose limits as specified in 10CFR100 (37) [219-228]. If the dose rises above 25 rem to the total body, or 300 rem to the thyroid, asterisks will be printed in the output instead of the value of the dose. If the dose to either the total body or thyroid falls below 1 mrem, the dose is considered insignificant and is printed as zero in the output.

The crosswind distance is then incremented and the calculation of the total body and thyroid doses from the 17 radioisotopes is repeated. The doses are compared with the limits as before and the crosswind distance is incremented again. If the crosswind distance is ever greater than the width of the plume, the crosswind distance is set to zero, the downwind distance is incremented by one increment, and the dose calculation is started from the beginning. The width of the plume is calculated by assuming that the edge of the plume is the point where the concentration has decreased to 5% of its maximum value (38) [232,233],

$$Y_p = [2 \cdot \sigma_y^2 \cdot \ln(100/p)]^{1/2} \quad \{32\}$$

where

Y_p = crosswind distance where the concentration has dropped to p% of its value on the plume axis.

If $p = 5$,

$$Y_p = 2.45 \cdot \sigma_y \quad \{33\}$$

This process is continued until all points that can potentially receive a significant population dose for that age group have been checked.

The final segment of the program [306-346] prints the results of the calculations in a table. The next age group is then selected and the entire calculation described above is repeated for each age group specified.

Input Description

The first data input to ALRRDOSE will determine whether the results will be printed in tables or drawn on graphs. If a table of dose versus downwind distance and crosswind distance is desired, enter a zero in column 10 of the first card (see Table 5). In this case only one set of cards described below will be needed. If a graph of dose versus distance directly downwind of the reactor is desired, enter a 1 in column 10 of the first card and in column 20 enter the number of different cases for which the results are to be superimposed onto one graph. For this option, one set of cards described below will be needed for each case considered.

Each set of input cards to ALRRDOSE consists of four groups. The units of the input parameters are those in common use at the ALRR. In this way, a person not familiar with the code can more easily run it.

As shown in Table 5, the first group of input data in a set (card 1) includes the degree of cloudiness of the sky, whether the calculation is made during the day or at night, the age groups for which the calculation is to be done, and the number of time steps in the calculation. If tables are desired, the calculations will be performed for all age groups of that option. For example, if 3 were the input

Table 5. Input for ALRRDOSE

Group	No.	Information	Units	Format
0	1	Output option desired 0 - Graphs (limited output) 1 - Tables (full output)		2I10
	2	Number of different cases 1-6 - The number of cases		
1	1	The degree of cloudiness of the sky 1 - Clear 2 - Slightly cloudy 3 - $\leq 3/8$ Cloudiness 4 - $\geq 4/8$ Cloudiness 5 - Heavily overcast		4I10
	2	The time of day 1 - During daylight hours 2 - Not during daylight hours		
	3	The age group for which the calculation is to be done 1 - Adult 2 - (Adult)+teenager 3 - (Adult+teenager+) child 4 - (Adult+teenager+child+) infant		
	4	The number of time steps in the calculation (up to 30)		
2	1	The ground wind speed at the time of the accident	knots	4E10.4
	2	The mass of U235 in the core at the beginning of core life	grams	
	3	The pressure in the containment at the time of the accident	inches H ₂ O	
	4	The time of interest after the accident	seconds	
3	1-30	The duration of each time step	seconds	8E10.4
4	1-30	The power level during each time step	megawatts	8E10.4

parameter for the age groups, the dose would be estimated for the adult, the teenager, and the child. If a graph is desired, however, only one age group is considered for each case. In this case, if the input parameter for age groups were 3, only the child dose would be calculated and plotted.

The second group (card 2) consists of the ground wind speed at the time of the accident (knots), the mass of U235 in the core at the beginning of core life (grams), the pressure in the containment at the time of the accident (≥ 0) (inches H₂O), and the time of interest after the accident (seconds).

The third group (as many cards as are needed) consists of the duration of each time step (seconds) and the fourth group consists of the power level during each time step (megawatts). There can be as many as 30 time steps in this calculation. This will permit modeling a change in power level during core life or multiple startups and shutdowns. The time that the reactor is shut down can be included by entering zero for power level during that time step. Use several time steps of short duration to model long periods at constant power in order to properly account for fission product buildup.

Output Description

The output from both of the output options of ALRRDOSE is divided into three sections. The first two sections are the same for both options for each case considered. The first section is a list of the input parameters and the second section is a table of the fission product inventory of the fuel which contributes to the total body dose or thyroid dose.

If the "tables" option is specified, the third section will consist of two tables for each age group specified; a table of total dose to the total body as a function of distance directly downwind of the point of release and the crosswind distance from the centerline of the plume, and a similar table of total dose to the thyroid. Using this option, one obtains the most complete set of results. The dose estimate is printed for all distances downwind which could potentially receive a dose and all crosswind distances which could potentially receive a dose.

If the "graphs" option is requested, the dose is estimated for distances directly downwind of the reactor only and for only one age group. In this case, the third section of the output will consist of two plots of dose versus downwind distance; one plot for the total body dose, and one plot for the thyroid dose. As many as six plots (each requiring

different input parameters) can be superimposed onto one graph. Examples of each type of output are given in the sample problems.

LIMITATIONS OF THE COMPUTER PROGRAM

If one examines the input requirements and calculational procedures of ALRRDOSE, certain restrictions on the applicability of the code become apparent.

For example, two of the input parameters are the degree of cloudiness of the sky and the ground wind speed. Each of these parameters describes conditions existing at the time of the accident and both are likely to change as time increases. Another input parameter describes whether or not the accident takes place during daylight hours. Obviously, this will also change as time passes. Thus, these three input parameters set an upper limit on the time of interest after the accident.

This restriction is not severe, however, because it is assumed that in the event of an accidental fuel meltdown, the population which could be exposed to any radionuclides released would be evacuated within a reasonable time. Eight hours is therefore set as a practical upper limit to the time of interest after the accident.

If conditions change soon after the accident, a rough approximation to the dose can be obtained by running ALRRDOSE once for each set of conditions. This will yield approximate upper and lower bounds to the dose received.

The lower limit to the time of interest after the accident is set by the program to be the time it takes for the radioisotopes to reach the receptor. It is the distance of interest divided by the wind speed.

Another limitation on ALRRDOSE is that the dose estimate is not accurate for very low wind speeds. Diffusion experiments have shown that at wind speeds below 2 m/s, diffusion category assignment is unreliable (39). The diffusion estimates at low wind speeds, however, result in a lower dose than calculated in many cases (40). If the wind speed falls below 2 m/s, ALRRDOSE will print a message cautioning the user that the dose estimate may be unreliable. ALRRDOSE is applicable only to the ALRR and only for a fuel meltdown accident. Application of the code to another reactor or for another type of accident would require extensive modification.

RESULTS

Design Basis Accident for the ALRR

One of the primary objectives of writing the present code is to evaluate the consequences following the design basis accident (DBA) for the ALRR. This must be known to determine whether the reactor facility complies with conditions on site boundaries set forth in 10CFR100 (37). The DBA can be modeled by specifying the "worst possible case" for the input parameters. The worst case for this code is a wind speed of 2m/s, a combination of wind speed, sky condition, and time of day which results in Pasquill's diffusion category being F (6 in Table 2), a containment pressure of 7 inches H₂O, and the reactor being at the end of core life.

Description of the DBA for the ALRR

The design basis accident for the Ames Laboratory Research Reactor is the slow meltdown and destruction of the reactor core resulting from the complete loss of primary D₂O coolant, along with the failure of all of the emergency cooling systems (or the failure of the operator to initiate emergency cooling when necessary), and a coincident positive containment pressure of 7 inches H₂O.

The primary coolant may be lost by a rupture of the core inlet pipe, heat exchanger, associated plumbing, or the reactor tank itself (see Figure 1). If a leak should occur and the coolant drops more than four inches below its normal level, the reactor automatically shuts down, isolation valves A and B in the inlet and outlet lines close, and bypass valve C opens. The automatic operation of these valves, located immediately beneath the reactor, sets up a natural convection loop which will effectively cool the fuel elements for a minimum of 14 hours, adequate time for corrective measures to be taken.

If this first line emergency system fails or is too slow to prevent major damage, or if the rupture occurs between the bypass valves and the core, then other fuel cooling measures can be utilized. The design of the room below the core is such that all lost coolant will flow into a sump equipped with a sump pump. The operator can energize an external recirculation system which pumps the lost D_2O to a header from which it flows by gravity through the fuel elements and back through the leak to the sump. If this system fails or is inadequate, the final emergency cooling system can be initiated. Light water from a 75,000 gallon elevated storage tank can be released into the header that supplies coolant to the elements.

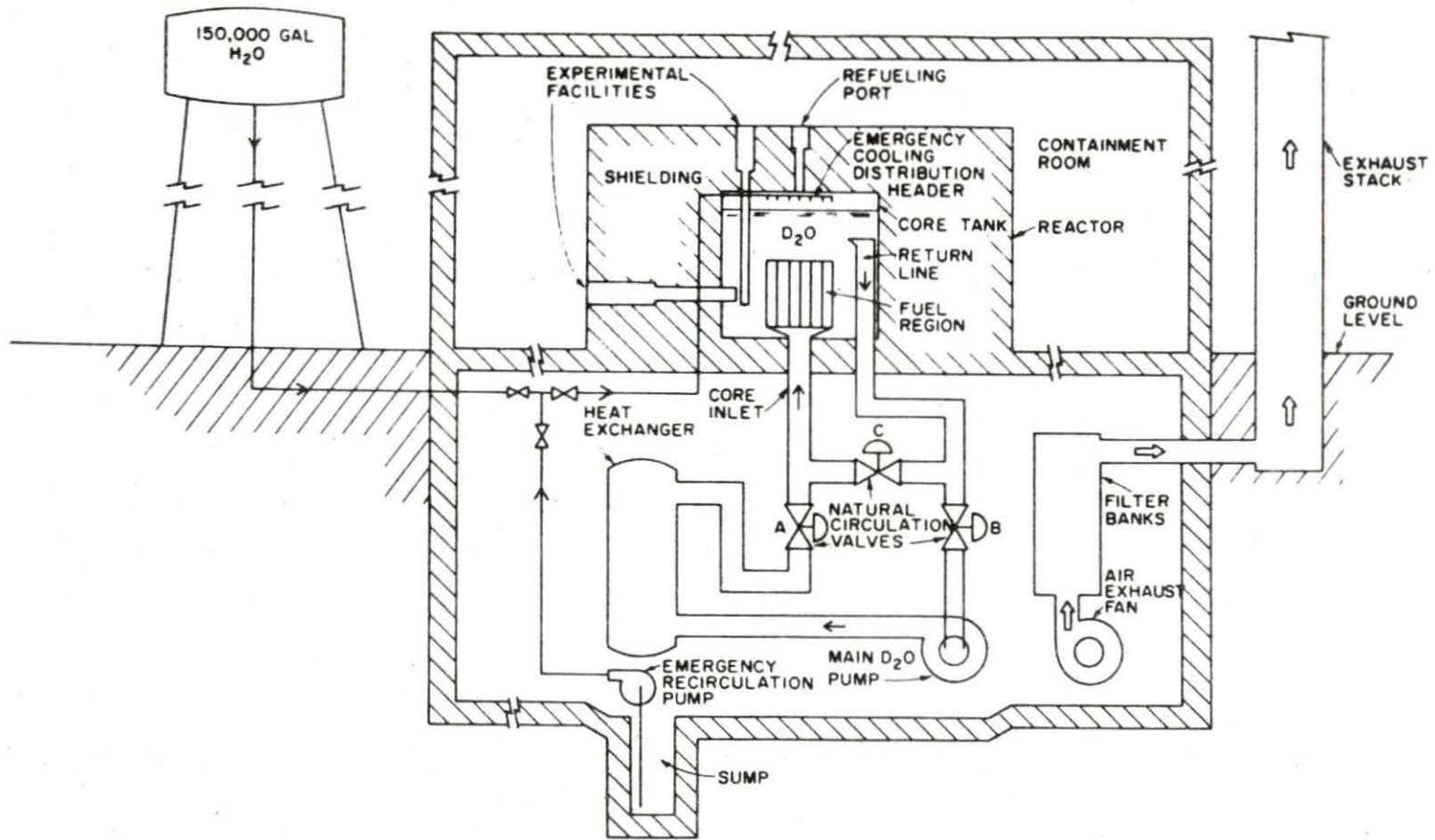


Figure 1. Schematic of ALRR

Only the failure of all of these emergency cooling systems will result in fuel meltdown and the design basis accident.

Results of ALRRDOSE

ALRRDOSE was run to estimate the dose from the DBA by specifying the "worst possible case" parameters for the input. Output from both output options is included beginning with the "tables" option. The first section of the output, the input listing, is shown in Figure 2. The next section, the fission product inventory in the fuel at the time of the accident, is shown in Figure 3. Figures 4 and 5 are tables of dose versus downwind and crosswind distance. Although only the adult dose is shown, ALRRDOSE produces similar tables for the other age groups.

The output from the "graphs" option begins with Figure 6 and is a comparison between two different age groups of the dose from the DBA. A portion of the input listing of each case is shown in Figures 6 and 7. The remainder of the input listing and the list of the fission product inventory are the same as those in Figures 2 and 3. Plots of the dose to the total body and thyroid from the DBA versus distance are shown in Figures 8 and 9.


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*****
***** INPUT FOR CASE NO. 1 *****
*****

WIND SPEED= 0.3886E 01 KACTS
MASS OF U235= 0.5000E 04 GRAMS
CONTAINMENT PRESSURE= 0.7000E 01 INCHES H2O
TIME OF INTEREST AFTER THE ACCIDENT= 0.7200E 04 SECONDS
SKY CCNDITION= 3
TIME OF DAY= 2
NO. OF AGE GROUPS= 4

TIME STEP ( 1)= 0.677E 06 SECONDS    POWER LEVEL ( 1)= 0.500E 01 MEGAWATTS
TIME STEP ( 2)= 0.677E 06 SECONDS    POWER LEVEL ( 2)= 0.500E 01 MEGAWATTS
TIME STEP ( 3)= 0.677E 06 SECONDS    POWER LEVEL ( 3)= 0.500E 01 MEGAWATTS
TIME STEP ( 4)= 0.677E 06 SECONDS    POWER LEVEL ( 4)= 0.500E 01 MEGAWATTS
TIME STEP ( 5)= 0.677E 06 SECONDS    POWER LEVEL ( 5)= 0.500E 01 MEGAWATTS
TIME STEP ( 6)= 0.677E 06 SECONDS    POWER LEVEL ( 6)= 0.500E 01 MEGAWATTS
TIME STEP ( 7)= 0.677E 06 SECONDS    POWER LEVEL ( 7)= 0.500E 01 MEGAWATTS
TIME STEP ( 8)= 0.677E 06 SECONDS    POWER LEVEL ( 8)= 0.500E 01 MEGAWATTS
TIME STEP ( 9)= 0.677E 06 SECONDS    POWER LEVEL ( 9)= 0.500E 01 MEGAWATTS
TIME STEP (10)= 0.677E 06 SECONDS    POWER LEVEL (10)= 0.500E 01 MEGAWATTS
TIME STEP (11)= 0.677E 06 SECONDS    POWER LEVEL (11)= 0.500E 01 MEGAWATTS
TIME STEP (12)= 0.677E 06 SECONDS    POWER LEVEL (12)= 0.500E 01 MEGAWATTS
TIME STEP (13)= 0.677E 06 SECONDS    POWER LEVEL (13)= 0.500E 01 MEGAWATTS
TIME STEP (14)= 0.677E 06 SECONDS    POWER LEVEL (14)= 0.500E 01 MEGAWATTS
TIME STEP (15)= 0.677E 06 SECONDS    POWER LEVEL (15)= 0.500E 01 MEGAWATTS
TIME STEP (16)= 0.677E 06 SECONDS    POWER LEVEL (16)= 0.500E 01 MEGAWATTS
TIME STEP (17)= 0.677E 06 SECONDS    POWER LEVEL (17)= 0.500E 01 MEGAWATTS
TIME STEP (18)= 0.677E 06 SECONDS    POWER LEVEL (18)= 0.500E 01 MEGAWATTS
TIME STEP (19)= 0.677E 06 SECONDS    POWER LEVEL (19)= 0.500E 01 MEGAWATTS
TIME STEP (20)= 0.677E 06 SECONDS    POWER LEVEL (20)= 0.500E 01 MEGAWATTS

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Figure 2. Input listing for the DBA for all age groups

TIME STEP (21)=	0.677E 06 SECONDS	POWER LEVEL (21)=	0.500E 01 MEGAWATTS
TIME STEP (22)=	0.677E 06 SECONDS	POWER LEVEL (22)=	0.500E 01 MEGAWATTS
TIME STEP (23)=	0.677E 06 SECONDS	POWER LEVEL (23)=	0.500E 01 MEGAWATTS
TIME STEP (24)=	0.677E 06 SECONDS	POWER LEVEL (24)=	0.500E 01 MEGAWATTS
TIME STEP (25)=	0.677E 06 SECONDS	POWER LEVEL (25)=	0.500E 01 MEGAWATTS
TIME STEP (26)=	0.677E 06 SECONDS	POWER LEVEL (26)=	0.500E 01 MEGAWATTS
TIME STEP (27)=	0.677E 06 SECONDS	POWER LEVEL (27)=	0.500E 01 MEGAWATTS
TIME STEP (28)=	0.677E 06 SECONDS	POWER LEVEL (28)=	0.500E 01 MEGAWATTS
TIME STEP (29)=	0.677E 06 SECONDS	POWER LEVEL (29)=	0.500E 01 MEGAWATTS
TIME STEP (30)=	0.667E 06 SECONDS	POWER LEVEL (30)=	0.500E 01 MEGAWATTS

Figure 2. continued

 CORE INVENTORY OF FISSION PRODUCTS THAT CONTRIBUTE TO THE TOTAL BODY DOSE
 AND THYROID DOSE AFTER 0.203E 08 SECONDS FROM THE BEGINNING OF CORE LIFE.

ELEMENT	CURIES	BETA MEV/DIS	GAMMA MEV/DIS	HALF-LIFE (SEC)
XE138	0.280E 06	0.0	0.690E 00	0.840E 03
XE135	0.929E 05	0.300E 00	0.260E 00	0.331E 05
XE135M	0.730E 05	0.800E-01	0.450E 00	0.960E 03
XE133	0.556E 06	0.150E 00	0.300E-01	0.455E 06
XF133M	0.134E 05	0.190E 00	0.400E-01	0.199E 06
XE131M	0.118E 04	0.159E 00	0.500E-02	0.104E 07
I135	0.270E 06	0.320E 00	0.177E 01	0.241E 05
I134	0.324E 06	0.160E 01	0.380E 00	0.318E 04
I133	0.278E 06	0.440E 00	0.580E 00	0.756E 05
I132	0.178E 06	0.450E 00	0.236E 01	0.628E 04
I131	0.118E 06	0.340E 00	0.380E 00	0.696E 06
I130	0.586E 03	0.260E 00	0.220E 01	0.450E 05
I129	0.853E-03	0.800E-01	0.0	0.505E 15
KR 88	0.150E 06	0.390E 00	0.189E 01	0.101E 05
KR 87	0.105E 06	0.135E 01	0.110E 01	0.468E 04
KR 85	0.531E 03	0.250E 00	0.500E-02	0.328E 09
KR 85M	0.549E 05	0.220E 00	0.186E 00	0.158E 05

Figure 3. Fission product inventory for the DBA

***** ADULT TOT BODY DOSE (REM) *****									
*CROSSWIND	0	20	42	67	94	124	157	194	234
*DISTANCE									
*(METERS)									

*DOWNWIND									
*DISTANCE									
*(METERS)									
* 215.	0.130	0.024	0.0	0.0	0.0	0.0	0.0	0.0	0.0
* 235.	0.109	0.025	0.0	0.0	0.0	0.0	0.0	0.0	0.0
* 257.	0.094	0.026	0.0	0.0	0.0	0.0	0.0	0.0	0.0
* 282.	0.086	0.027	0.0	0.0	0.0	0.0	0.0	0.0	0.0
* 309.	0.079	0.028	0.0	0.0	0.0	0.0	0.0	0.0	0.0
* 339.	0.071	0.028	0.0	0.0	0.0	0.0	0.0	0.0	0.0
* 372.	0.064	0.029	0.0	0.0	0.0	0.0	0.0	0.0	0.0
* 409.	0.058	0.028	0.0	0.0	0.0	0.0	0.0	0.0	0.0
* 449.	0.053	0.029	0.004	0.0	0.0	0.0	0.0	0.0	0.0
* 494.	0.052	0.031	0.005	0.0	0.0	0.0	0.0	0.0	0.0
* 543.	0.056	0.036	0.007	0.0	0.0	0.0	0.0	0.0	0.0
* 598.	0.067	0.045	0.012	0.0	0.0	0.0	0.0	0.0	0.0
* 658.	0.087	0.063	0.020	0.0	0.0	0.0	0.0	0.0	0.0
* 725.	0.119	0.090	0.035	0.0	0.0	0.0	0.0	0.0	0.0
* 798.	0.166	0.131	0.059	0.012	0.0	0.0	0.0	0.0	0.0
* 880.	0.219	0.180	0.092	0.025	0.0	0.0	0.0	0.0	0.0
* 970.	0.274	0.232	0.132	0.044	0.0	0.0	0.0	0.0	0.0
* 1069.	0.294	0.258	0.165	0.070	0.017	0.0	0.0	0.0	0.0
* 1179.	0.297	0.268	0.190	0.097	0.032	0.0	0.0	0.0	0.0
* 1301.	0.296	0.273	0.208	0.123	0.052	0.0	0.0	0.0	0.0
* 1435.	0.290	0.273	0.220	0.146	0.074	0.027	0.0	0.0	0.0
* 1584.	0.285	0.271	0.227	0.161	0.093	0.040	0.0	0.0	0.0
* 1748.	0.280	0.268	0.230	0.172	0.107	0.052	0.019	0.0	0.0
* 1929.	0.271	0.261	0.229	0.179	0.119	0.065	0.027	0.0	0.0
* 2129.	0.258	0.250	0.224	0.181	0.128	0.077	0.037	0.013	0.0
* 2351.	0.242	0.235	0.215	0.179	0.134	0.086	0.046	0.020	0.0
* 2595.	0.224	0.219	0.202	0.174	0.135	0.093	0.055	0.027	0.0
* 2866.	0.205	0.201	0.188	0.165	0.134	0.097	0.062	0.033	0.014
* 3165.	0.186	0.183	0.173	0.155	0.129	0.099	0.068	0.040	0.020
* 3495.	0.167	0.165	0.157	0.143	0.123	0.098	0.071	0.045	0.025
* 3860.	0.154	0.152	0.145	0.134	0.117	0.096	0.072	0.048	0.028
* 4263.	0.140	0.135	0.134	0.124	0.110	0.092	0.071	0.050	0.031
* 4709.	0.127	0.126	0.122	0.114	0.103	0.088	0.070	0.052	0.034
* 5202.	0.113	0.112	0.109	0.103	0.094	0.082	0.068	0.052	0.037
* 5747.	0.098	0.097	0.095	0.091	0.084	0.076	0.065	0.052	0.039
* 6348.	0.084	0.084	0.082	0.079	0.075	0.068	0.060	0.050	0.040
* 7014.	0.073	0.072	0.071	0.069	0.066	0.061	0.055	0.047	0.039
* 7749.	0.063	0.062	0.061	0.060	0.058	0.054	0.050	0.044	0.038
* 8561.	0.054	0.054	0.053	0.052	0.050	0.048	0.045	0.040	0.035
* 9459.	0.046	0.046	0.045	0.045	0.043	0.042	0.039	0.036	0.033
* 10451.	0.040	0.040	0.040	0.039	0.038	0.037	0.035	0.033	0.030
* 11548.	0.037	0.036	0.036	0.036	0.035	0.034	0.032	0.030	0.028
* 12760.	0.033	0.033	0.033	0.032	0.032	0.031	0.029	0.028	0.026
* 14095.	0.029	0.029	0.029	0.029	0.028	0.028	0.026	0.025	0.023
* 14404.	0.029	0.029	0.029	0.028	0.028	0.027	0.026	0.025	0.023

Figure 4. Adult total body dose from the DBA

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*****
*
*CROSSWIND
*DISTANCE      275|    328|    383|    443|    510|    583|    665|    755|    854
*(METERS)
*
-----
*DOWNWIND
*DISTANCE
*(METERS)
*
*  215.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*  235.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*  257.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*  282.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*  309.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*  339.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*  372.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*  409.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*  449.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*  494.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*  543.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*  598.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*  658.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*  725.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*  798.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*  880.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
*  970.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
* 1069.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
* 1179.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
* 1301.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
* 1435.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
* 1584.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
* 1748.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
* 1929.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
* 2129.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
* 2351.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
* 2595.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
* 2866.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
* 3165.  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
* 3495.  0.011| 0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
* 3860.  0.014| 0.0  0.0  0.0  0.0  0.0  0.0  0.0  0.0
* 4263.  0.017| 0.007| 0.0  0.0  0.0  0.0  0.0  0.0  0.0
* 4709.  0.020| 0.010| 0.0  0.0  0.0  0.0  0.0  0.0  0.0
* 5202.  0.023| 0.012| 0.0  0.0  0.0  0.0  0.0  0.0  0.0
* 5747.  0.026| 0.016| 0.008| 0.0  0.0  0.0  0.0  0.0  0.0
* 6348.  0.029| 0.019| 0.011| 0.006| 0.0  0.0  0.0  0.0  0.0
* 7014.  0.030| 0.021| 0.014| 0.008| 0.004| 0.0  0.0  0.0  0.0
* 7749.  0.030| 0.023| 0.016| 0.010| 0.006| 0.0  0.0  0.0  0.0
* 8561.  0.030| 0.024| 0.018| 0.012| 0.007| 0.004| 0.0  0.0  0.0
* 9459.  0.028| 0.024| 0.018| 0.014| 0.009| 0.006| 0.003| 0.0  0.0
* 10451. 0.026| 0.023| 0.018| 0.014| 0.010| 0.006| 0.004| 0.0  0.0
* 11548. 0.025| 0.021| 0.018| 0.014| 0.010| 0.007| 0.004| 0.002| 0.0
* 12760. 0.023| 0.020| 0.017| 0.013| 0.010| 0.007| 0.004| 0.002| 0.0
* 14099. 0.021| 0.019| 0.016| 0.013| 0.010| 0.007| 0.004| 0.003| 0.0
* 14404. 0.021| 0.018| 0.015| 0.013| 0.010| 0.007| 0.004| 0.003| 0.0

```

Figure 4. continued

***** ADULT THYROID DCSE (REM) *****										
	0	20	42	67	94	124	157	194	234	
*CROSSWIND										
*DISTANCE										
*(METERS)										
*DOWNWIND										
*DISTANCE										
*(METERS)										
* 215.	10.106	1.852	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
* 235.	8.521	1.978	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
* 257.	7.333	2.054	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
* 282.	6.756	2.141	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
* 309.	6.180	2.204	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
* 339.	5.612	2.238	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
* 372.	5.049	2.251	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
* 405.	4.508	2.233	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
* 449.	4.009	2.162	0.271	0.0	0.0	0.0	0.0	0.0	0.0	0.0
* 494.	3.561	2.109	0.350	0.0	0.0	0.0	0.0	0.0	0.0	0.0
* 543.	3.175	2.034	0.440	0.0	0.0	0.0	0.0	0.0	0.0	0.0
* 598.	2.855	1.956	0.534	0.0	0.0	0.0	0.0	0.0	0.0	0.0
* 658.	2.531	1.882	0.629	0.0	0.0	0.0	0.0	0.0	0.0	0.0
* 725.	2.384	1.820	0.720	0.0	0.0	0.0	0.0	0.0	0.0	0.0
* 799.	2.230	1.774	0.810	0.178	0.0	0.0	0.0	0.0	0.0	0.0
* 880.	2.104	1.735	0.896	0.249	0.0	0.0	0.0	0.0	0.0	0.0
* 970.	1.990	1.693	0.971	0.331	0.0	0.0	0.0	0.0	0.0	0.0
* 1069.	1.812	1.593	1.024	0.436	0.108	0.0	0.0	0.0	0.0	0.0
* 1179.	1.624	1.469	1.040	0.534	0.180	0.0	0.0	0.0	0.0	0.0
* 1301.	1.453	1.343	1.025	0.608	0.260	0.0	0.0	0.0	0.0	0.0
* 1435.	1.297	1.219	0.986	0.653	0.334	0.122	0.0	0.0	0.0	0.0
* 1584.	1.179	1.120	0.940	0.669	0.384	0.168	0.0	0.0	0.0	0.0
* 1748.	1.084	1.038	0.892	0.667	0.415	0.204	0.074	0.0	0.0	0.0
* 1929.	0.989	0.952	0.837	0.653	0.436	0.238	0.100	0.0	0.0	0.0
* 2129.	0.894	0.866	0.776	0.629	0.446	0.266	0.128	0.046	0.0	0.0
* 2351.	0.801	0.780	0.711	0.594	0.444	0.287	0.154	0.065	0.0	0.0
* 2595.	0.715	0.699	0.646	0.555	0.433	0.299	0.176	0.085	0.0	0.0
* 2866.	0.638	0.626	0.586	0.514	0.417	0.304	0.194	0.104	0.045	0.0
* 3155.	0.566	0.556	0.526	0.471	0.394	0.301	0.206	0.121	0.060	0.0
* 3495.	0.498	0.491	0.468	0.426	0.366	0.292	0.211	0.135	0.074	0.0
* 3860.	0.450	0.444	0.426	0.392	0.343	0.280	0.210	0.141	0.083	0.0
* 4263.	0.404	0.399	0.385	0.357	0.317	0.266	0.206	0.145	0.090	0.0
* 4709.	0.359	0.356	0.344	0.323	0.291	0.249	0.199	0.146	0.096	0.0
* 5202.	0.313	0.311	0.302	0.286	0.261	0.229	0.189	0.145	0.102	0.0
* 5747.	0.266	0.264	0.258	0.247	0.229	0.205	0.176	0.142	0.106	0.0
* 6348.	0.224	0.223	0.218	0.210	0.198	0.181	0.159	0.134	0.105	0.0
* 7014.	0.187	0.186	0.183	0.177	0.169	0.157	0.141	0.122	0.101	0.0
* 7749.	0.156	0.155	0.153	0.150	0.144	0.135	0.124	0.110	0.094	0.0
* 8561.	0.128	0.128	0.127	0.124	0.120	0.114	0.107	0.097	0.085	0.0
* 9459.	0.104	0.104	0.103	0.101	0.099	0.095	0.089	0.083	0.074	0.0
* 10451.	0.086	0.085	0.085	0.084	0.082	0.079	0.075	0.070	0.064	0.0
* 11548.	0.071	0.071	0.071	0.070	0.068	0.066	0.063	0.059	0.054	0.0
* 12760.	0.057	0.057	0.056	0.056	0.055	0.053	0.051	0.048	0.044	0.0
* 14099.	0.043	0.043	0.043	0.042	0.041	0.040	0.039	0.036	0.034	0.0
* 14404.	0.040	0.040	0.040	0.039	0.038	0.037	0.036	0.034	0.032	0.0

Figure 5. Adult thyroid dose from the DBA


```

*****
*
*CROSSWIND
*DISTANCE
*(METERS)
*
*DOWNWIND
*DISTANCE
*(METERS)
*
* 215. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 235. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 257. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 292. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 309. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 339. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 372. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 409. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 449. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 494. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 543. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 598. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 658. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 725. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 798. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 880. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 970. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 1069. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 1179. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 1301. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 1435. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 1584. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 1748. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 1929. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 2129. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 2351. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 2595. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 2866. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 3165. | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 3495. | 0.033 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 3860. | 0.041 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 4263. | 0.048 | 0.021 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 4709. | 0.056 | 0.027 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 5202. | 0.064 | 0.034 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 5747. | 0.072 | 0.043 | 0.023 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 6348. | 0.077 | 0.051 | 0.030 | 0.015 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0
* 7014. | 0.078 | 0.055 | 0.036 | 0.020 | 0.010 | 0.0 | 0.0 | 0.0 | 0.0
* 7749. | 0.076 | 0.058 | 0.040 | 0.025 | 0.014 | 0.0 | 0.0 | 0.0 | 0.0
* 8561. | 0.071 | 0.057 | 0.042 | 0.029 | 0.018 | 0.010 | 0.0 | 0.0 | 0.0
* 9459. | 0.064 | 0.053 | 0.042 | 0.031 | 0.021 | 0.013 | 0.007 | 0.0 | 0.0
* 10451. | 0.056 | 0.048 | 0.039 | 0.030 | 0.021 | 0.014 | 0.008 | 0.0 | 0.0
* 11548. | 0.048 | 0.041 | 0.034 | 0.027 | 0.019 | 0.013 | 0.008 | 0.004 | 0.0
* 12760. | 0.040 | 0.034 | 0.029 | 0.023 | 0.017 | 0.012 | 0.007 | 0.004 | 0.0
* 14099. | 0.031 | 0.027 | 0.023 | 0.018 | 0.014 | 0.010 | 0.006 | 0.004 | 0.0
* 14404. | 0.029 | 0.025 | 0.021 | 0.017 | 0.013 | 0.009 | 0.006 | 0.004 | 0.0

```

Figure 5. continued

```

*****
***** INPUT FOR CASE NO. 1 *****
*****

WIND SPEED= 0.3886E 01 KNOTS
MASS OF U235= 0.5000E 04 GRAMS
CONTAINMENT PRESSURE= 0.7000E 01 INCHES H2O
TIME OF INTEREST AFTER THE ACCIDENT= 0.7200E 04 SECONDS
SKY CONDITION=      3
TIME OF DAY=        2
NO. OF AGE GROUPS=   1

TIME STEP ( 1)= 0.677E 06 SECONDS      POWER LEVEL ( 1)= 0.500E 01 MEGAWATTS
TIME STEP ( 2)= 0.677E 06 SECONDS      POWER LEVEL ( 2)= 0.500E 01 MEGAWATTS
TIME STEP ( 3)= 0.677E 06 SECONDS      POWER LEVEL ( 3)= 0.500E 01 MEGAWATTS
TIME STEP ( 4)= 0.677E 06 SECONDS      POWER LEVEL ( 4)= 0.500E 01 MEGAWATTS
TIME STEP ( 5)= 0.677E 06 SECONDS      POWER LEVEL ( 5)= 0.500E 01 MEGAWATTS

```

Figure 6. Input listing for the DBA for the adult

```

*****
***** INPUT FOR CASE NO. 2 *****
*****

WIND SPEED= 0.3886E 01 KNOTS

MASS OF U235= 0.5000E 04 GRAMS

CONTAINMENT PRESSURE= 0.7000E 01 INCHES H2O

TIME OF INTEREST AFTER THE ACCIDENT= 0.7200E 04 SECONDS

SKY CONDITION=      3

TIME OF DAY=       2

NO. OF AGE GROUPS=      4

TIME STEP ( 1 )=  0.677E 06 SECONDS      POWER LEVEL ( 1 )=  0.500E 01 MEGAWATTS
TIME STEP ( 2 )=  0.677E 06 SECONDS      POWER LEVEL ( 2 )=  0.500E 01 MEGAWATTS
TIME STEP ( 3 )=  0.677E 06 SECONDS      POWER LEVEL ( 3 )=  0.500E 01 MEGAWATTS
TIME STEP ( 4 )=  0.677E 06 SECONDS      POWER LEVEL ( 4 )=  0.500E 01 MEGAWATTS
TIME STEP ( 5 )=  0.677E 06 SECONDS      POWER LEVEL ( 5 )=  0.500E 01 MEGAWATTS

```

Figure 7. Input listing for the DBA for the infant

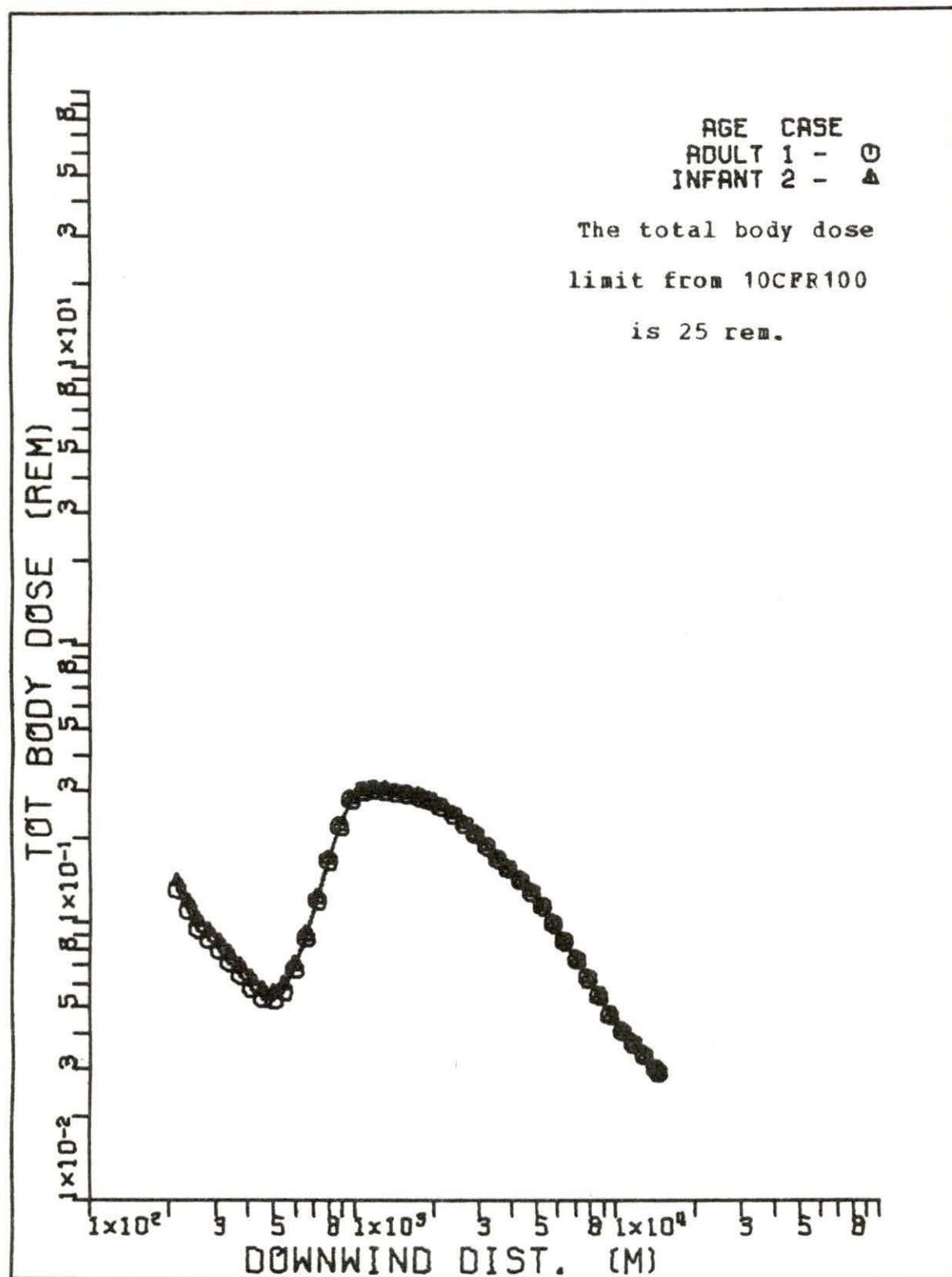


Figure 8. Adult and infant total body dose from DBA

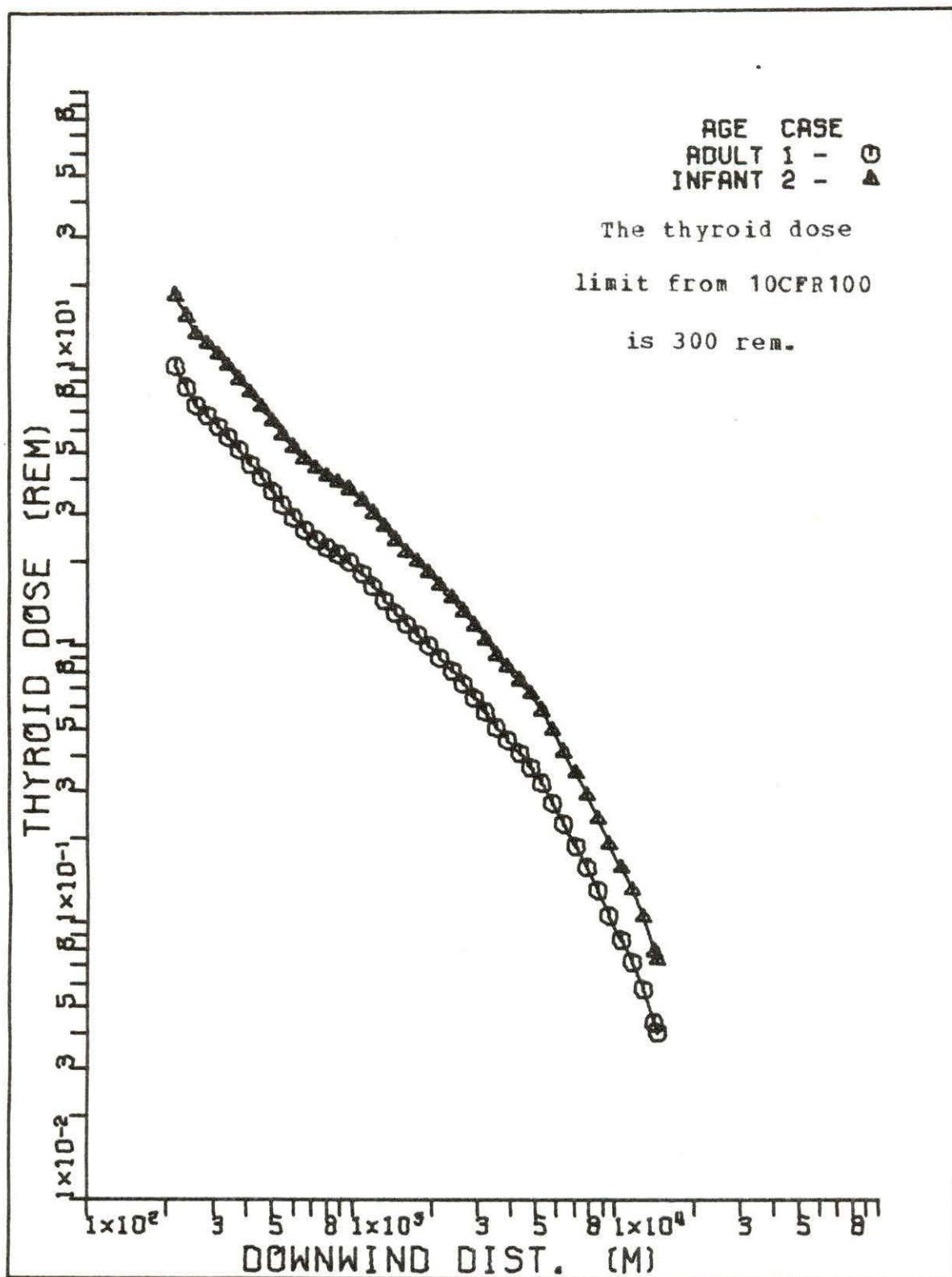


Figure 9. Adult and infant thyroid dose from DBA

Figure 8 shows that the total body dose to an adult is nearly equal to that to an infant. This is due to the fact that the internal total body dose is the only portion of the total body dose that is age dependent and its contribution to the total dose is very small. The thyroid dose to an infant, however, is larger than that to an adult, as shown in Figure 9. The infant dose is the largest of all the age groups followed by the adult dose, the child dose, and the teenage dose. The maximum values of the doses from the DBA for the different age groups is shown in Table 6. These doses are considerably below the maximum values imposed by 10CFR100 of 25 rem to the total body and 300 rem to the thyroid in two hours.

Table 6. Maximum dose from the DBA at the ALRR

Age group	Maximum total body dose (rem)	Distance (m)	Maximum thyroid dose (rem)	Distance (m)
Adult	0.297	1179	10.106	215
Teenager	0.296	1179	7.025	215
Child	0.297	1179	9.403	215
Infant	0.299	1179	18.255	215

Other Fuel Meltdown Accidents

The dose estimate from the design basis accident is necessarily a very conservative estimate. At the time the DBA takes place, all parameters affecting the dose to the population must have values resulting in the largest dose estimate. A more realistic case, however, is that at the time of the postulated fuel meltdown accident, one or more of the parameters affecting the dose will be different than the "worst possible case." ALBRDOSE was run with different values for the input parameters to estimate the population dose from fuel meltdown accidents other than the DBA.

The wind speed, the time of day and the degree of cloudiness were varied to determine the effect of the atmospheric stability category on the dose estimate, and the containment pressure was varied to determine the contribution of the ground level unfiltered puff release to the dose estimate. The time of interest after the accident was also varied to determine the effect of the evacuation time on the total dose. The results for four different sets of conditions are shown in the following sections. The input parameters are listed first followed by the plots of the results. Except for the parameter under study, all parameters are kept the same as the DBA parameters in each case with the exception of the number of time steps, which was changed to one to conserve computer time.

Effect of changes in wind speed

The effect of changes in wind speed on the dose can be observed by selecting conditions such that the atmospheric stability category remains constant at different wind speeds. The stability category remains at 4 at all wind speeds if the sky is heavily overcast. This condition was selected and the dose was calculated at six different wind speeds. The input parameters are listed for each case in Figures 10 through 15. The wind speeds used are 1.5 m/s, 2.0 m/s, 3.0 m/s, 5.0 m/s, 7.0 m/s, and 10.0 m/s. The results of the dose calculations, plotted in Figures 16 and 17, show that the overall effect of an increase in the wind speed within one stability category is a decrease in the dose estimate. This is due to increased diffusion at higher wind speeds. The wind speed appears in the denominator of the equation for calculating the air concentration of each nuclide. Therefore, the curves should exhibit an approximate $1/S$ relationship, where S is the wind speed, which is the case.

```
*****
***** INPUT FOR CASE NO. 1 *****
*****
WIND SPEED= 0.1943E 01 KNOTS
MASS OF U235= 0.5000E 04 GRAMS
CONTAINMENT PRESSURE= 0.7000E 01 INCHES H2O
TIME OF INTEREST AFTER THE ACCIDENT= 0.2880E 05 SECONDS
SKY CONDITION=      5
TIME OF DAY=      1
NO. OF AGE GROUPS=      1
TIME STEP ( 1)= 0.203E 08 SECONDS      POWER LEVEL ( 1)= 0.500E 01 MEGAWATTS
```

```
*****
*****
```

WARNING

WIND SPEED IS LESS THAN 2 M/S.

DOSE ESTIMATES MAY BE UNRELIABLE.

Figure 10. Input listing for a wind speed of 1.5 m/s

```

*****
***** INPUT FOR CASE NO. 2 *****
*****
WIND SPEED= 0.3886E 01 KNOTS
MASS OF U235= 0.5000E 04 GRAMS
CONTAINMENT PRESSURE= 0.7000E 01 INCHES H2O
TIME OF INTEREST AFTER THE ACCIDENT= 0.2880E 05 SECONDS
SKY CONDITION=      5
TIME OF DAY=      1
NO. OF AGE GROUPS=      1
TIME STEP ( 1)= 0.203E 08 SECONDS      POWER LEVEL ( 1)= 0.500E 01 MEGAWATTS
*****
*****

```

Figure 11. Input listing for a wind speed of 2.0 m/s


```
*****
***** INPUT FOR CASE NO. 3 *****
*****

WIND SPEED= 0.5828E 01 KNOTS

MASS OF U235= 0.5000E 04 GRAMS

CONTAINMENT PRESSURE= 0.7000E 01 INCHES H2O

TIME OF INTEREST AFTER THE ACCIDENT= 0.2880E 05 SECONDS

SKY CONDITION=      5

TIME OF DAY=      1

NO. OF AGE GROUPS=      1

TIME STEP ( 1)= 0.203E 08 SECONDS      POWER LEVEL ( 1)= 0.500E 01 MEGAWATTS

*****
*****
```

Figure 12. Input listing for a wind speed of 3.0 m/s

```
*****
***** INPUT FOR CASE NO. 4 *****
*****

WIND SPEED= 0.9713E 01 KNOTS
MASS OF U235= 0.5000E 04 GRAMS
CONTAINMENT PRESSURE= 0.7000E 01 INCHES H2O
TIME OF INTEREST AFTER THE ACCIDENT= 0.2880E 05 SECONDS
SKY CONDITION=      5
TIME OF DAY=      1
NO. OF AGE GROUPS=      1
TIME STEP ( 1)= 0.203E 08 SECONDS      POWER LEVEL ( 1)= 0.500E 01 MEGAWATTS

*****
*****
```

Figure 13. Input listing for a wind speed of 5.0 m/s

```

*****
***** INPUT FOR CASE NO. 5 *****
*****
WIND SPEED= 0.1360E 02 KNOTS
MASS OF U235= 0.5000E 04 GRAMS
CONTAINMENT PRESSURE= 0.7000E 01 INCHES H2O
TIME OF INTEREST AFTER THE ACCIDENT= 0.2880E 05 SECONDS
SKY CCNDITION= 5
TIME OF DAY= 1
NO. OF AGE GROUPS= 1
TIME STEP ( 1)= 0.203E 08 SECONDS      POWER LEVEL ( 1)= 0.500E 01 MEGAWATTS
*****
*****

```

Figure 14. Input listing for a wind speed of 7.0 m/s

```
*****
***** INPUT FOR CASE NO. 6 *****
*****
WIND SPEED= 0.1942E 02 KNCTS
MASS OF U235= 0.5000E 04 GRAMS
CONTAINMENT PRESSURE= 0.7000E 01 INCHES H2O
TIME OF INTEREST AFTER THE ACCIDENT= 0.2880E 05 SECONDS
SKY CONDITION=      5
TIME OF DAY=      1
NO. OF AGE GROUPS=      1
TIME STEP ( 1)= 0.203E 08 SECONDS      POWER LEVEL ( 1)= 0.500E 01 MEGAWATTS
*****
*****
```

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Figure 15. Input listing for a wind speed of 10.0 m/s

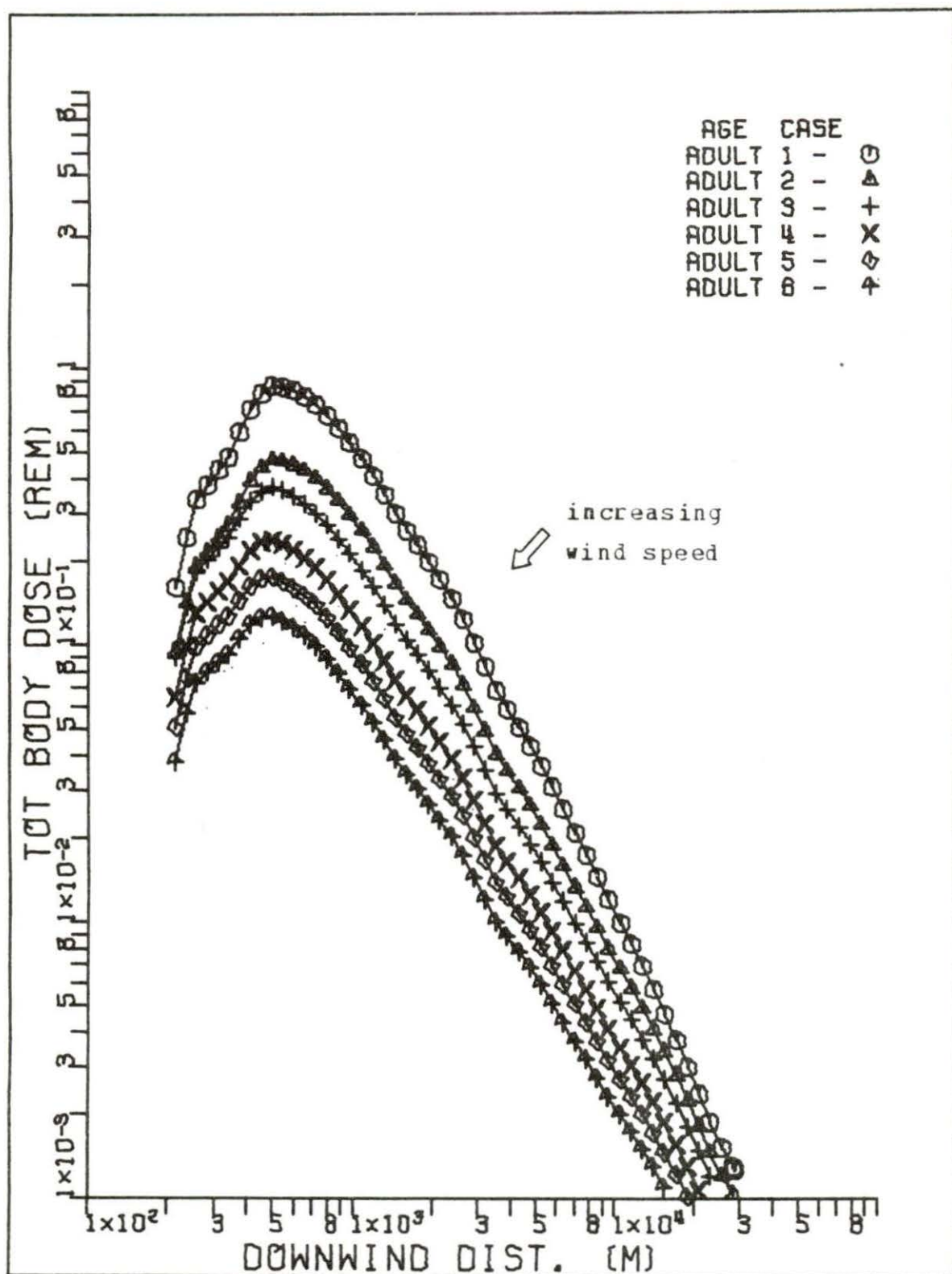


Figure 16. Adult total body dose for different wind speeds at a stability category of 4

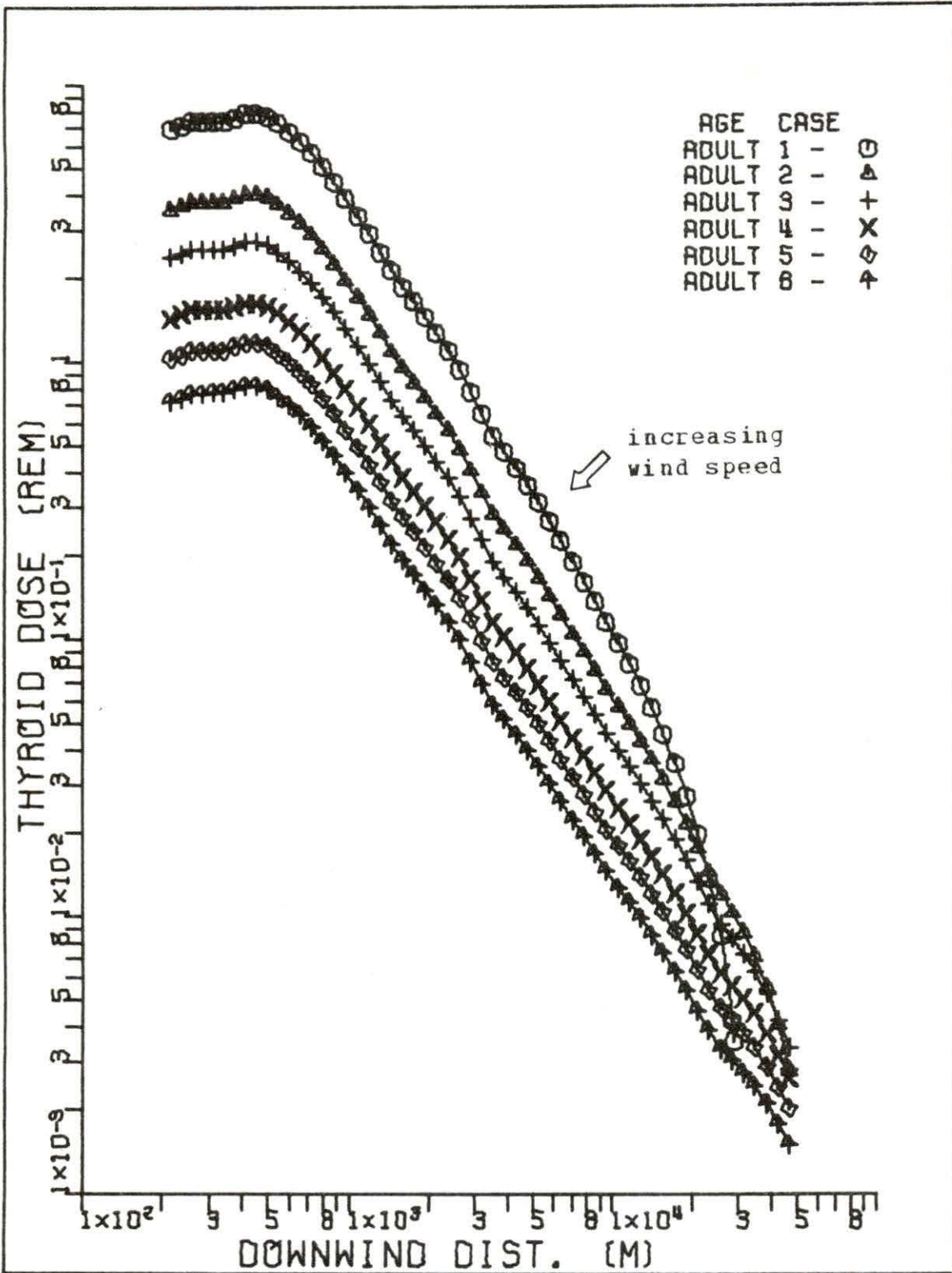


Figure 17. Adult thyroid dose for different wind speeds at a stability category of 4

Effect of changes in atmospheric stability

The effect of changes in the atmospheric stability category on the dose is determined by changing the sky condition and time of day while keeping the wind speed constant. Figures 18 through 23 list the input parameters for each stability category at a constant wind speed of 2 m/s. The results are shown in Figures 24 and 25. Case one calculated the dose for stability category one, case two for category two, and so on. The atmospheric diffusion increases as the stability category goes from six to one. This is the apparent reason for the shift in the maximum of the total body dose curve to shorter distances and higher doses as the diffusion increases. The activity released from the stack as an elevated filtered release diffuses to the ground at a much shorter distance when the stability category is one or two than when it is five or six. In addition, a receptor being exposed to the maximum concentration of a plume at very short distances will be exposed for a longer period of time than if he were at a greater distance from the reactor, resulting in a larger dose.

```
*****
***** INPUT FOR CASE NO. 1 *****
*****
WIND SPEED= 0.3886E 01 KNOTS
MASS OF U235= 0.5000E 04 GRAMS
CONTAINMENT PRESSURE= 0.7000E 01 INCHES H2O
TIME OF INTEREST AFTER THE ACCIDENT= 0.2880E 05 SECONDS
SKY CONDITION=      1
TIME OF DAY=      1
NO. OF AGE GROUPS=      1
TIME STEP ( 1)= 0.203E 08 SECONDS      POWER LEVEL ( 1)= 0.500E 01 MEGAWATTS
*****
*****
```

Figure 18. Input listing for stability category 1

```
*****
***** INPUT FOR CASE NO. 2 *****
*****
WIND SPEED= 0.3886E 01 KNCTS
MASS OF U235= 0.5000E 04 GRAMS
CONTAINMENT PRESSURE= 0.7000E 01 INCHES H2O
TIME OF INTEREST AFTER THE ACCIDENT= 0.2880E 05 SECONDS
SKY CONDITION=      2
TIME OF DAY=      1
NO. OF AGE GROUPS=      1
TIME STEP ( 1)= 0.203E 08 SECONDS      POWER LEVEL ( 1)= 0.500E 01 MEGAWATTS
*****
*****
```

74

Figure 19. Input listing for stability category 2

```
*****
***** INPUT FOR CASE NO. 3 *****
*****
WIND SPEED= 0.3886E 01 KNCTS
MASS OF U235= 0.5000E 04 GRAMS
CONTAINMENT PRESSURE= 0.7000E 01 INCHES H2O
TIME OF INTEREST AFTER THE ACCIDENT= 0.2880E 05 SECONDS
SKY CONDITION=      4
TIME OF DAY=        1
NO. OF AGE GROUPS=    1
TIME STEP ( 1)= 0.203E 08 SECONDS      POWER LEVEL ( 1)= 0.500E 01 MEGAWATTS
*****
*****
```

Figure 20. Input listing for stability category 3


```

*****
***** INPUT FOR CASE NO. 4 *****
*****
WIND SPEED= 0.3886E 01 KNOTS
MASS OF U235= 0.5000E 04 GRAMS
CONTAINMENT PRESSURE= 0.7000E 01 INCHES H2O
TIME OF INTEREST AFTER THE ACCIDENT= 0.2880E 05 SECONDS
SKY CONDITION=      5
TIME OF DAY=      1
NO. OF AGE GROUPS=      1
TIME STEP ( 1)= 0.203E 08 SECONDS      POWER LEVEL ( 1)= 0.500E 01 MEGAWATTS
*****
*****

```

Figure 21. Input listing for stability category 4

```
*****
***** INPUT FOR CASE NO. 5 *****
*****
WIND SPEED= 0.3886E 01 KNCTS
MASS OF U235= 0.5000E 04 GRAMS
CONTAINMENT PRESSURE= 0.7000E 01 INCHES H2O
TIME OF INTEREST AFTER THE ACCIDENT= 0.2880E 05 SECONDS
SKY CONDITION=      4
TIME OF DAY=      2
NO. OF AGE GROUPS=      1
TIME STEP ( 1)=  0.203E 08 SECONDS      POWER LEVEL ( 1)=  0.500E 01 MEGAWATTS
*****
*****
```

Figure 22. Input listing for stability category 5

```
*****
***** INPUT FOR CASE NO. 6 *****
*****

WIND SPEED= 0.3886E 01 KNCTS
MASS OF U235= 0.5000E 04 GRAMS
CONTAINMENT PRESSURE= 0.7000E 01 INCHES H2O
TIME OF INTEREST AFTER THE ACCIDENT= 0.2880E 05 SECONDS
SKY CONDITION=      3
TIME OF DAY=      2
NO. OF AGE GROUPS=      1
TIME STEP ( 1)= 0.203E 08 SECONDS      POWER LEVEL ( 1)= 0.500E 01 MEGAWATTS

*****
*****
```

Figure 23. Input listing for stability category 6

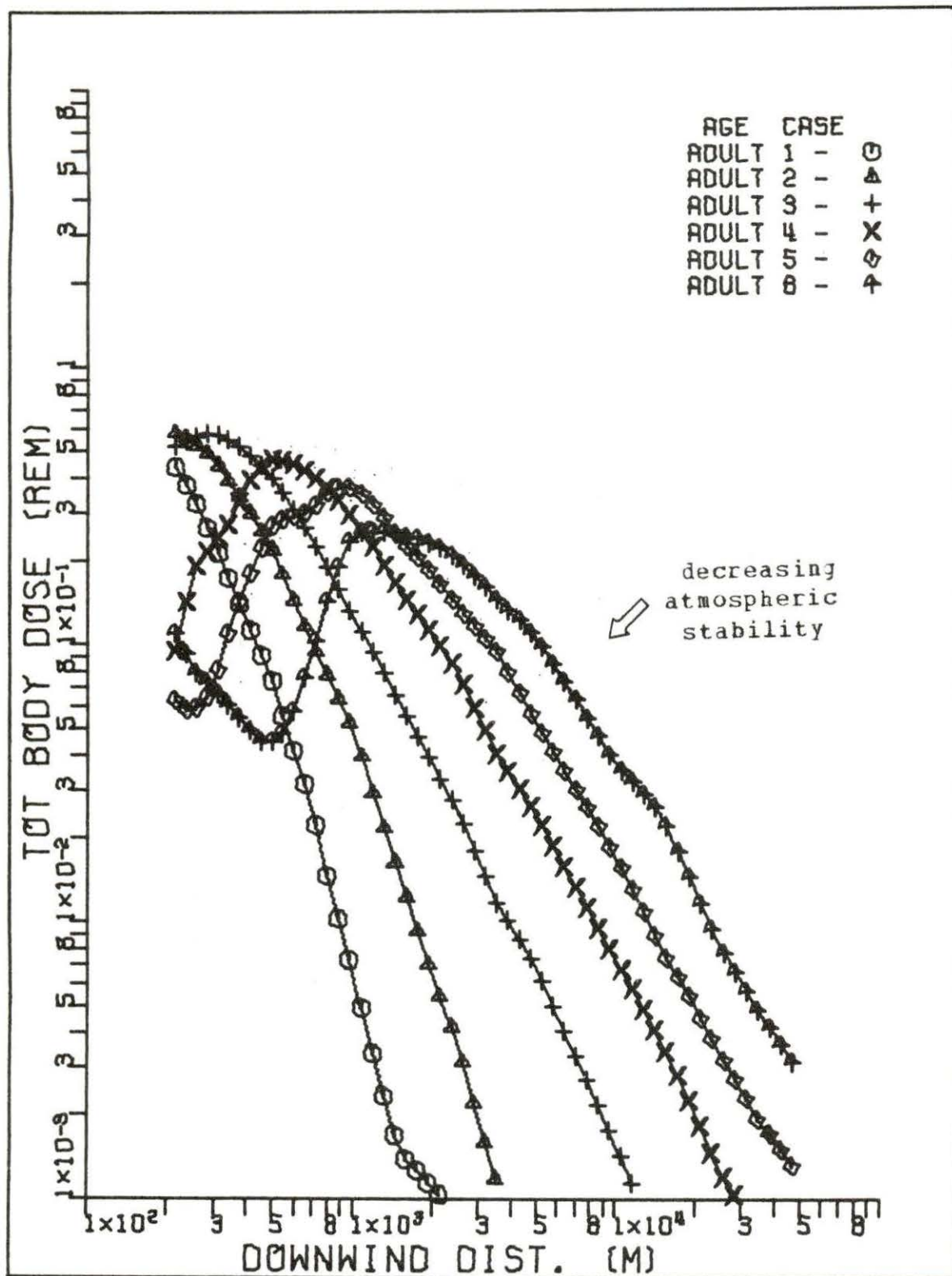


Figure 24. Adult total body dose for each stability category at a wind speed of 2 m/s

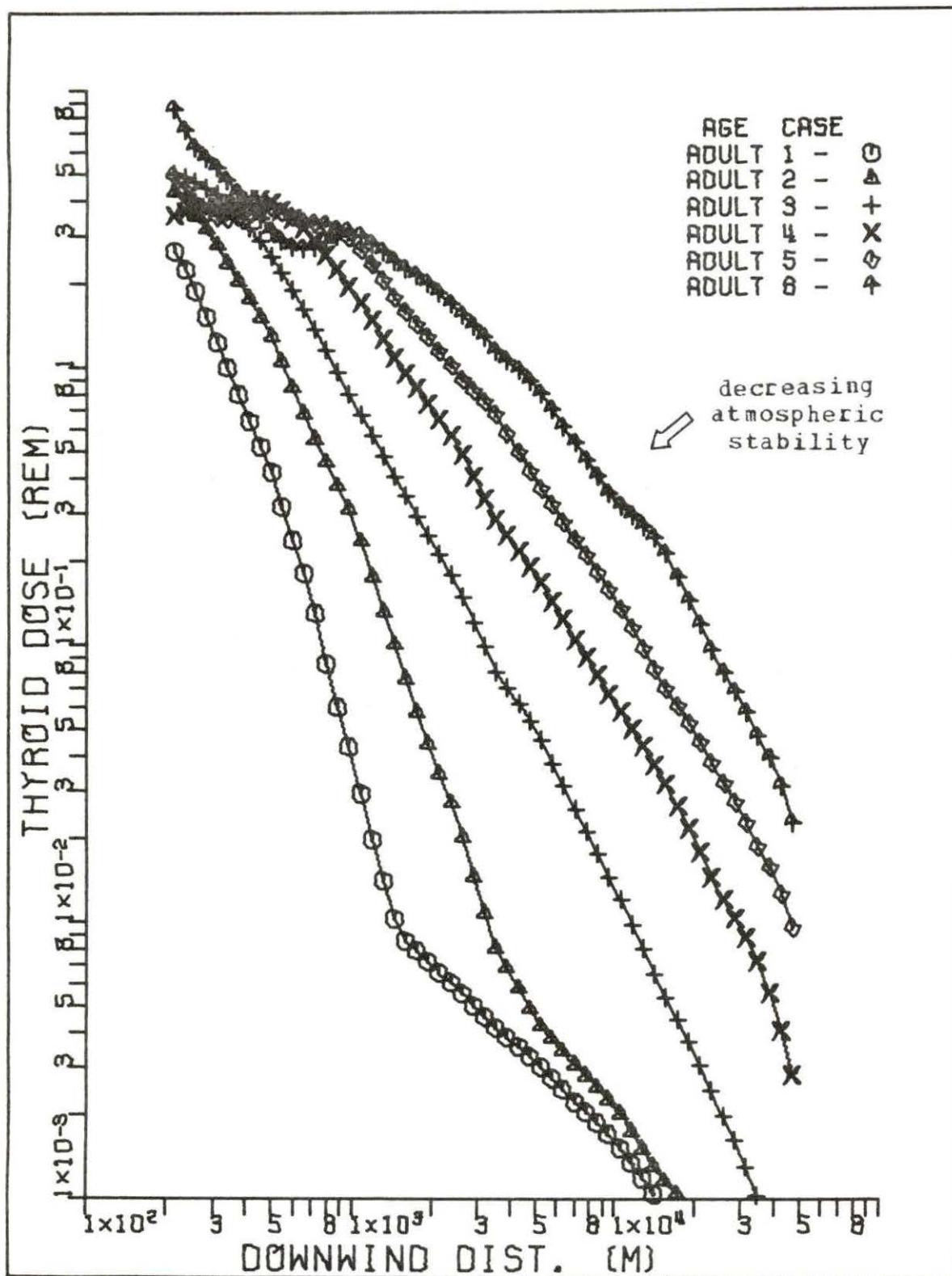


Figure 25. Adult thyroid dose for each stability category at a wind speed of 2 m/s

Effect of changes in containment air pressure

Unfiltered air will not leak from the containment building if the pressure inside the containment is at or below atmospheric pressure. Therefore, the contribution to the total dose from unfiltered containment air leakage can be determined by varying the pressure inside the containment at the time of the accident. The doses were estimated at three different containment pressures, the maximum pressure of 7 inches H_2O , 1.5 inches H_2O , and 0.0 inches H_2O or atmospheric. The input parameters are listed in Figures 26 through 28 and the results are plotted in Figures 29 and 30. When the containment pressure is above atmospheric, as it is in the first two cases, the contribution of the ground level unfiltered puff release to the total dose is seen to be the initial decreasing portion of the curves. The contribution of the elevated filtered continuous release plus the portion of the filtered puff release when the containment pressure is decreasing from 0.0 inches H_2O to -3 inches H_2O (see Table 3) is the area below the curve for 0.0 inches H_2O containment pressure, case 3. The contribution of the elevated filtered puff release when the containment is above atmospheric is then the difference between the curve of case three and the curves for positive containment pressure.

```

*****
***** INPUT FOR CASE NO. 1 *****
*****
WIND SPEED= 0.3886E 01 KNOTS
MASS OF U235= 0.5000E 04 GRAMS
CONTAINMENT PRESSURE= 0.7000E 01 INCHES H2O
TIME OF INTEREST AFTER THE ACCIDENT= 0.2880E 05 SECONDS
SKY CONDITION=      3
TIME OF DAY=      2
NO. OF AGE GROUPS=      1
TIME STEP ( 1)= 0.203E 08 SECONDS      POWER LEVEL ( 1)= 0.500E 01 MEGAWATTS
*****
*****

```

Figure 26. Input listing for a containment pressure of 7.0 inches H₂O

```
*****
***** INPUT FOR CASE NO. 2 *****
*****

WIND SPEED= 0.3886E 01 KNOTS
MASS OF U235= 0.5000E 04 GRAMS
CONTAINMENT PRESSURE= 0.1500E 01 INCHES H2O
TIME OF INTEREST AFTER THE ACCIDENT= 0.2880E 05 SECONDS
SKY CONDITION=      3
TIME OF DAY=      2
NO. OF AGE GROUPS=      1
TIME STEP ( 1)= 0.203E 08 SECONDS      POWER LEVEL ( 1)= 0.500E 01 MEGAWATTS

*****
*****
```

Figure 27. Input listing for a containment pressure of 1.5 inches H₂O

```
*****
***** INPUT FOR CASE NO. 3 *****
*****

WIND SPEED= 0.3886E 01 KNOTS
MASS OF U235= 0.5000E 04 GRAMS
CONTAINMENT PRESSURE= 0.0          INCHES H2O
TIME OF INTEREST AFTER THE ACCIDENT= 0.2880E 05 SECONDS
SKY CONDITION=      3
TIME OF DAY=        2
NO. OF AGE GROUPS=   1
TIME STEP ( 1)= 0.203E 08 SECONDS    POWER LEVEL ( 1)= 0.500E 01 MEGAWATTS

*****
*****
```

Figure 28. Input listing for a containment pressure of 0.0 inches H₂O

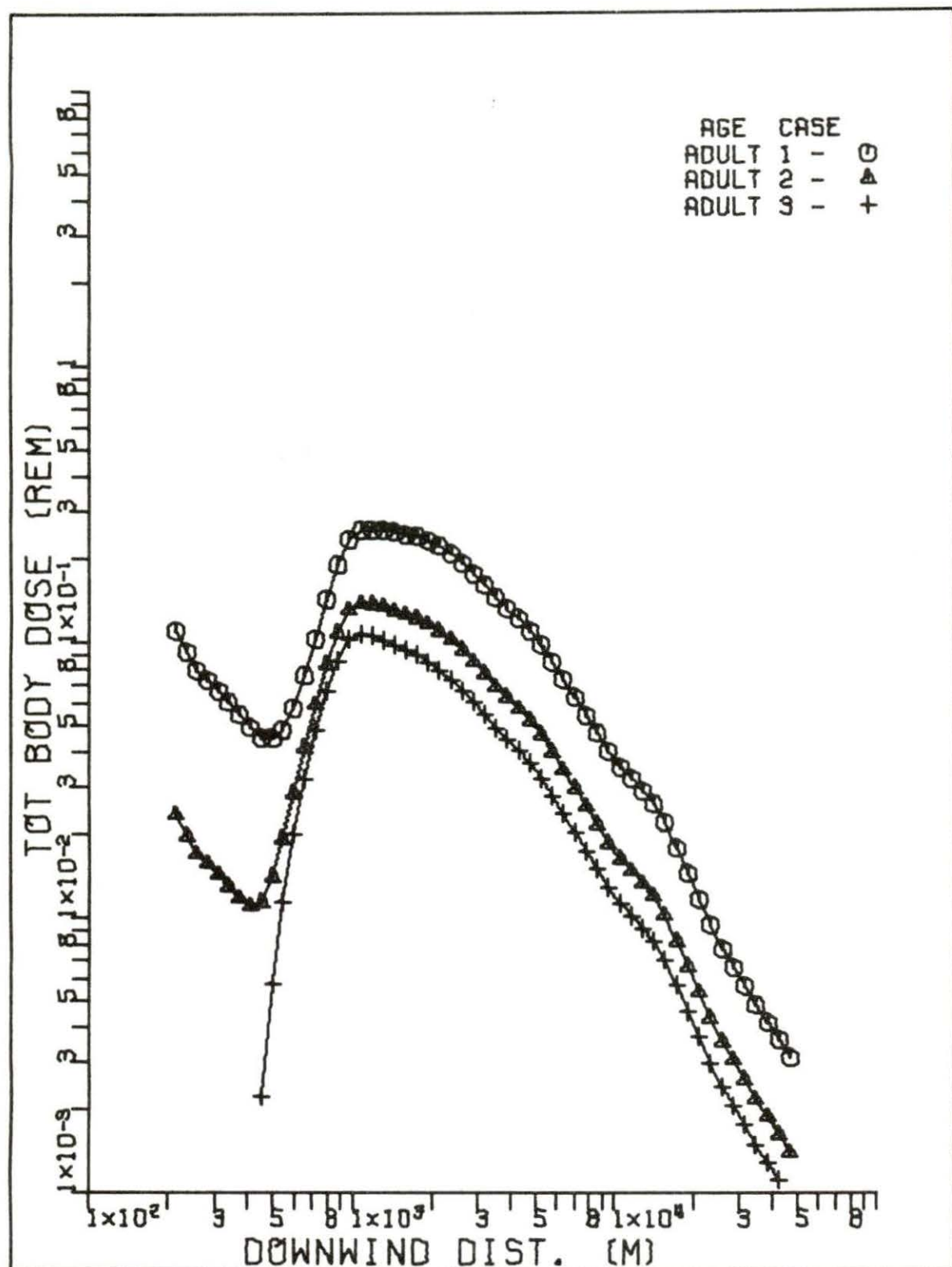


Figure 29. Adult total body dose at different containment pressures

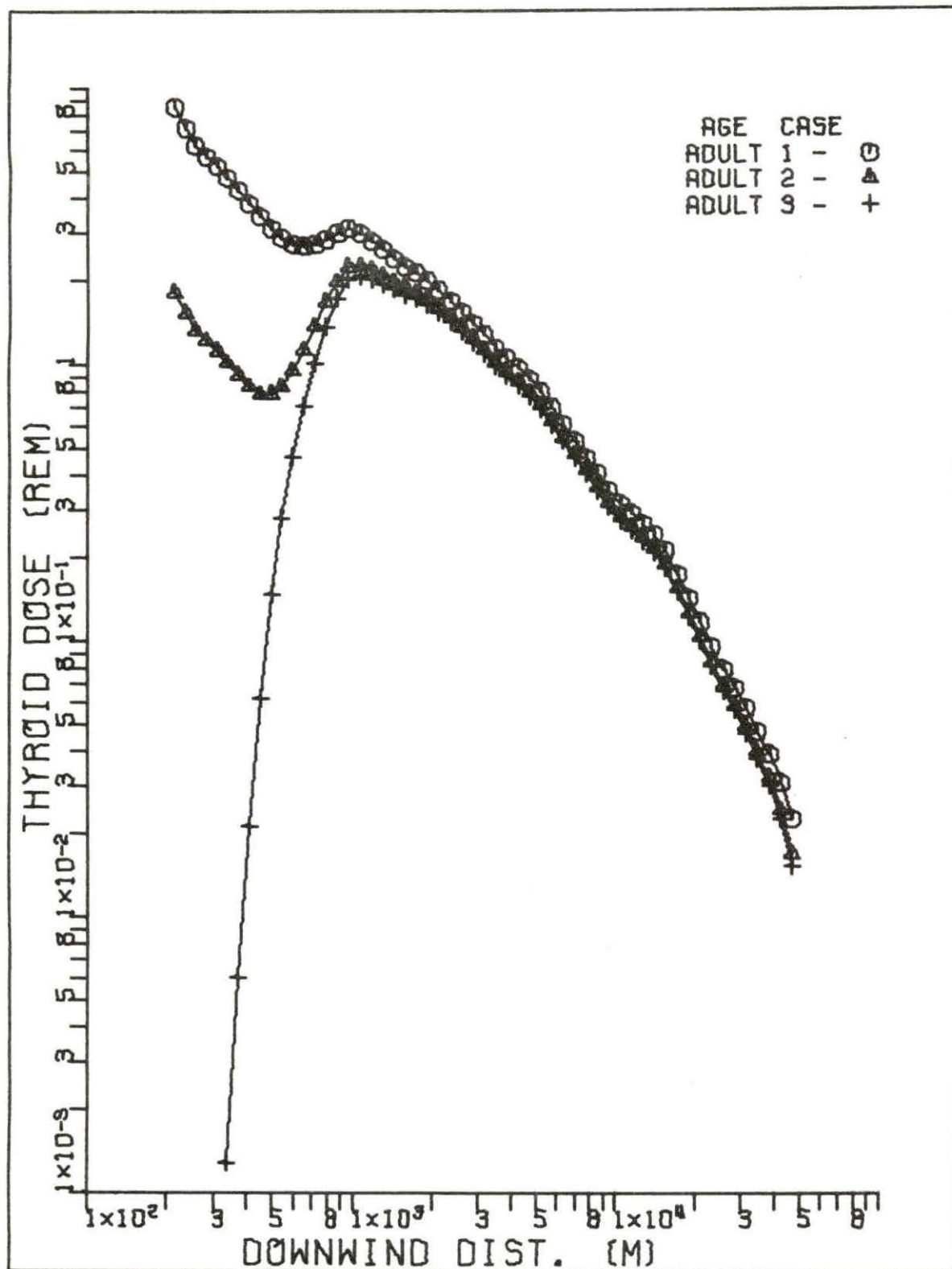


Figure 30. Adult thyroid dose at different containment pressures

Effect of changes in evacuation time

The effect of changes in evacuation time can be determined by varying the time of interest after the accident. Four evacuation times were considered, 10 minutes, 30 minutes, 2 hours, and 8 hours. The input parameters are listed in Figures 31 through 34 and the results are shown in Figures 35 and 36. The thyroid dose decreases for shorter evacuation times but the total body dose remains nearly constant. The apparent reason for this is that the total body dose is almost entirely comprised of the external dose received from the short-term puff releases and is affected very little by the elevated continuous release. The thyroid, however, receives a much higher dose from iodine than does the total body so the effect of the continuous release is seen in this case.

```
*****
***** INPUT FOR CASE NO. 1 *****
*****
WIND SPEED= 0.3886E 01 KNOTS
MASS OF U235= 0.5000E 04 GRAMS
CONTAINMENT PRESSURE= 0.7000E 01 INCHES H2O
TIME OF INTEREST AFTER THE ACCIDENT= 0.2880E 05 SECONDS
SKY CONDITION=      3
TIME OF DAY=      2
NO. OF AGE GROUPS=      1
TIME STEP ( 1)= 0.203E 08 SECONDS      POWER LEVEL ( 1)= 0.500E 01 MEGAWATTS
*****
*****
```

Figure 31. Input listing for an evacuation time of 8 hours

```
*****
***** INPUT FOR CASE NO. 2 *****
*****
WIND SPEED= 0.3886E 01 KNOTS
MASS OF U235= 0.5000E 04 GRAMS
CONTAINMENT PRESSURE= 0.7000E 01 INCHES H2O
TIME OF INTEREST AFTER THE ACCIDENT= 0.7200E 04 SECONDS
SKY CONDITION= 3
TIME OF DAY= 2
NO. OF AGE GROUPS= 1
TIME STEP ( 1)= 0.203E 08 SECONDS POWER LEVEL ( 1)= 0.500E 01 MEGAWATTS
*****
*****
```

Figure 32. Input listing for an evacuation time of 2 hours

```
*****
***** INPUT FOR CASE NO. 3 *****
*****
WIND SPEED= 0.3886E 01 KNOTS
MASS OF U235= 0.5000E 04 GRAMS
CONTAINMENT PRESSURE= 0.7000E 01 INCHES H2O
TIME OF INTEREST AFTER THE ACCIDENT= 0.1800E 04 SECONDS
SKY CONDITION=      3
TIME OF DAY=      2
NO. OF AGE GROUPS=      1
TIME STEP ( 1)= 0.203E 08 SECONDS      POWER LEVEL ( 1)= 0.500E 01 MEGAWATTS
*****
*****
```

Figure 33. Input listing for an evacuation time of 30 minutes


```

*****
***** INPUT FOR CASE NO. 4 *****
*****
WIND SPEED= 0.3886E 01 KNCTS
MASS OF U235= 0.5000E 04 GRAMS
CONTAINMENT PRESSURE= 0.7000E 01 INCHES H2O
TIME OF INTEREST AFTER THE ACCIDENT= 0.6000E 03 SECONDS
SKY CONDITION=      3
TIME OF DAY=      2
NO. OF AGE GROUPS=      1
TIME STEP ( 1)= 0.203E 08 SECONDS      POWER LEVEL ( 1)= 0.500E 01 MEGAWATTS
*****
*****

```

Figure 34. Input listing for an evacuation time of 10 minutes

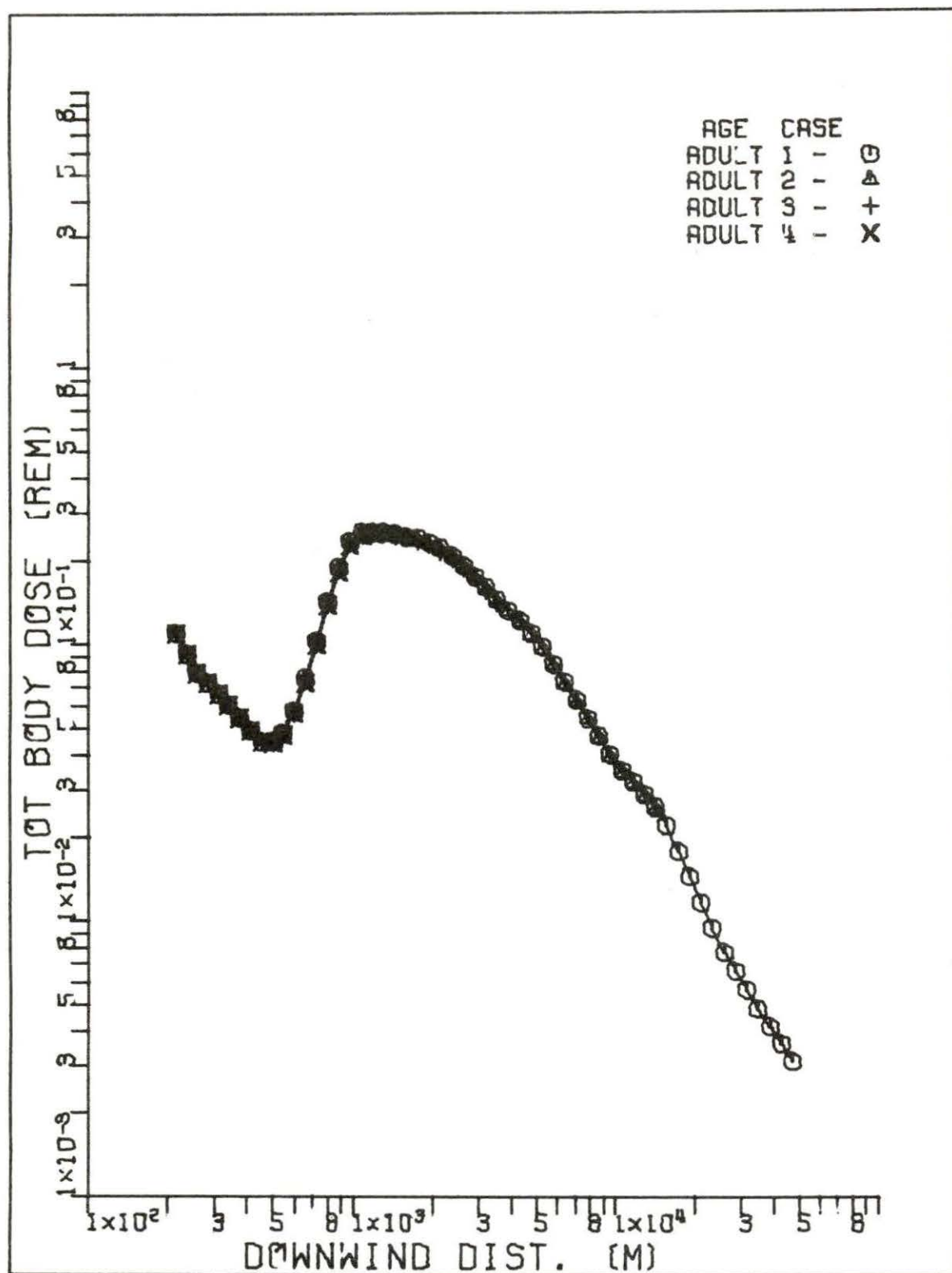


Figure 35. Adult total body dose for different evacuation times

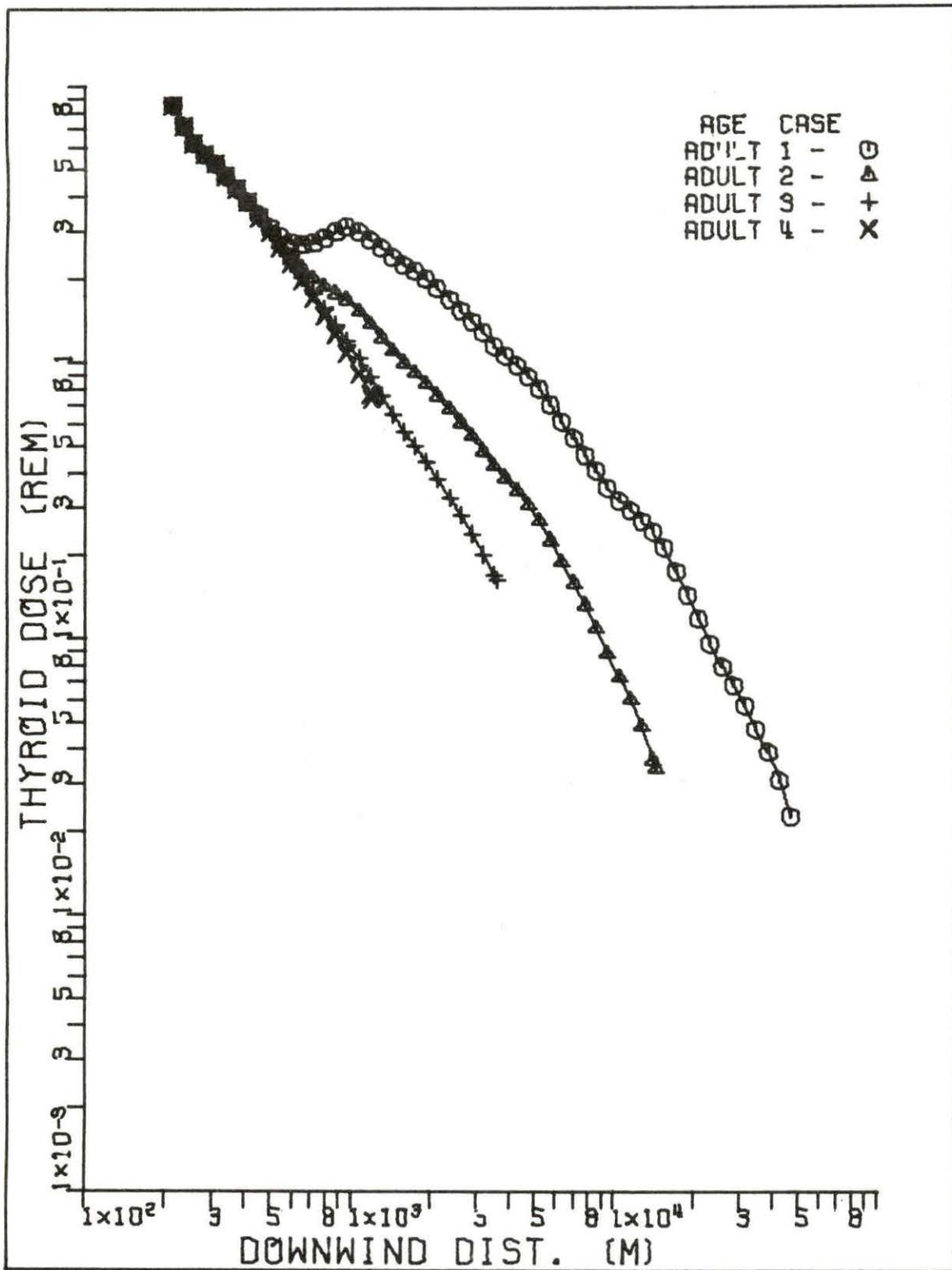


Figure 36. Adult thyroid dose for different evacuation times

SUMMARY AND CONCLUSIONS

ALRRDOSE is a useful tool which can be used to study the effects on the dose estimates of changes in atmospheric conditions, containment building parameters and core parameters. It can also be used to provide an estimate of the dose received in the event of a fuel meltdown accident at the ALRR.

The current safety analysis report for the ALRR estimated the doses from the DBA to be approximately ten times higher than those estimated by ALRRDOSE. The largest contributor to this difference seems to be that ALRRDOSE uses the Gaussian plume diffusion model instead of the Sutton model for atmospheric diffusion. At the exclusion boundary distance of 215 meters and a wind speed of 2.5 m/s, the Sutton model predicts the concentration of activity in the air to be $0.043 \cdot Q$ curie-s/m³ while the Gaussian plume diffusion model predicts $0.0047 \cdot Q$ curie-s/m³.

The dose estimates to the total body and thyroid calculated by ALRRDOSE for the design basis accident at the ALRR are far below the limits set forth by 10CFR100 and the estimates of doses from other accidents are lower than those of the DBA. Considering that most of the assumptions and approximations used in the code are conservative, the actual dose from a fuel meltdown accident at the ALRR would likely be lower than the estimates.

RECOMMENDATIONS FOR FUTURE WORK

ALRRDOSE was written specifically for the ALRR and applies only to a fuel meltdown accident. However, the portions of the program describing containment pressure reduction, release to the environment and dispersion in the atmosphere are equally valid for any type of instantaneous radioactivity release to the containment room. If the amount of radionuclides released to the containment can be determined, only moderate modification of the program would be required to determine the concentration in the air at different distances from the reactor.

With somewhat greater modification the code could be made to estimate the long-term dose from a radionuclide that is continuously released to the environment, such as tritium.

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APPENDIX A: LISTING OF ALRRDOSE

The following is a listing of ALRRDOSE. The reference numbers to the right of the statements are referenced in the description of the code beginning on page 15.


```

REAL*4 GLAB(5) / ' ' ' ' ' A ' ' GE ' ' CASE ' / 1
REAL*4 A1 / ' AD ' / B1 / ' ULT ' / A2 / ' TEEN ' / B2 / ' AGE ' / 2
1A3 / ' CH ' / B3 / ' ILD ' / A4 / ' INF ' / B4 / ' ANT ' / 3
REAL*4 YLAB(5) / ' TOT ' ' BOD ' ' Y DO ' ' SE ( ' ' REM ) ' / 4
REAL*4 BB1 / ' TH ' / BB2 / ' YROI ' / BB3 / ' D DO ' / 5
REAL*4 AB1 / ' TOT ' / AB2 / ' BOD ' / AB3 / ' Y DO ' / 6
REAL*4 DLAB(5) / ' ' ' ' ' ' ' / 7
REAL*4 AA(6) / ' 1 - ' ' 2 - ' ' 3 - ' ' 4 - ' ' 5 - ' ' 6 - ' / 8
DIMENSION DFA(7,2,4), IDCAT(5,5,2), TOTDOS(66,66), RA(4), PWR(30), 9
1D(66,6), TB(66,6), THY(66,6), XDOS(56), YDOS(56), NDIS(6), JAGE(6) 10
REAL LAKR, LAII, LAXE, LAMKR(7), LAMII(7), LANXE(7), THYDOS(66,66) 11
INTEGER TYPE, ICROS(66) 12
DATA DFA/6.19E-06,6.61E-07,2.56E-06,1.45E-07,5.67E-07,7.70E-08, 13
13.22E-07,5.55E-03,2.18E-04,1.49E-03,5.48E-05,3.66E-04,2.87E-05, 14
21.17E-04,9.81E-06,0.,3.52E-06,0.,7.93E-07,0.,0.,7.32E-03, 15
30.,1.74E-03,0.,4.79E-04,0.,0.,2.86E-05,0.,9.47E-06,0.,2.17E-06, 16
40.,0.,2.14E-02,0.,4.16E-03,0.,1.36E-03,0.,0.,5.82E-05,0., 17
51.79E-05,0.,4.19E-06,0.,0.,5.21E-02,0.,1.01E-02,0.,3.33E-03,2*0./ 18
DATA RA/3.47E-4,2.34E-4,1.22E-4,9.72E-5/ 19
COMMON/PETE/QXE(7), BETAXE(7), GAMAXE(7), QII(7), 20
1BETAI(7), GAMAI(7), QKR(7), BETAKR(7), GAMAKR(7), TIMEE(30), UMASS, 21
2LAMXE, LAMII, LAMKR, FLUXX(30), NTIM 22
REAL X(4) / 'TOT ' 'BODY' 'THYR' 'OID ' / 23
DATA IDCAT/1,1,2,3,3,1,2,2,3,4,2,2,3,4,4,2,3,3,4,4,4,4,4,4,4, 24
16,6,5,4,4,6,6,5,4,4,6,6,5,4,4,6,5,4,4,4,4,4,4,4,4/ 25
CALL ERRSET(208,256,-1,1) 26
DO 1 I=1,56 27
XDOS(I)=0. 28
1 YDOS(I)=0. 29
DO 2 I=1,6 30
DO 2 J=1,65 31
TB(J,I)=0. 32
THY(J,I)=0. 33
2 D(J,I)=0. 34
READ(2,209) IPLIT, NCASES 35
IF(IPLIT.NE.1) NCASES=1 36
DO 800 NCAS=1, NCASES 37
DO 4 JK=1,30 38
PWR(JK)=0. 39
TIMEE(JK)=0. 40
4 FLUXX(JK)=0. 41
DO 6 IJ=1,65 42
ICROS(IJ)=0 43
DO 6 IJIJ=1,65 44
TOTDOS(IJ,IJIJ)=0. 45
6 THYDOS(IJ,IJIJ)=0. 46
READ(2,209) ISKY, NDAY, IAGE, NTIM 47
READ(2,210) SPEED, UMASS, PRESS, TIMME 48
READ(2,210) (TIMEE(I), I=1, NTIM) 49
READ(2,210) (PWR(I), I=1, NTIM) 50
WRITE(6,211) NCAS, SPEED, UMASS, PRESS, TIMME 51
WRITE(6,212) ISKY, NDAY, IAGE 52
DO 3 KJ=1, NTIM 53
FLUXX(KJ)=PWR(KJ) 54
3 WRITE(6,213) KJ, TIMEE(KJ), KJ, PWR(KJ) 55
WRITE(6,214) 56
209 FORMAT(8I10) 57
210 FORMAT(8E10.4) 58
211 FORMAT('1',80(1H*)/'0',27(1H*),3X,'INPUT FOR CASE NO.',I2,3X, 59
127(1H*)/'0',80(1H*)/ 60
1'-','WIND SPEED=' ,E11.4, ' KNOTS'/'0', 'MASS OF U235=' ,E11.4, 61
2' GRAMS'/'0', 'CONTAINMENT PRESSURE=' ,E11.4, ' INCHES H2O' / 62
3'0', 'TIME OF INTEREST AFTER THE ACCIDENT=' ,E11.4, ' SECONDS' ) 63
212 FORMAT('0', 'SKY CONDITION=' ,I5/'0', 'TIME OF DAY=' ,I5/ 64

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1'0', 'NO. OF AGE GROUPS=' , I5)	65
213 FORMAT ('0', 'TIME STEP (' , I2, ')=' , E11.3, ' SECONDS' , 5X,	66
1'POWER LEVEL (' , I2, ')=' , E11.3, ' MEGAWATTS')	67
214 FORMAT ('-' , 80 (1H*) / '0' , 80 (1H*))	68
215 FORMAT ('1')	69
216 FORMAT ('-' , '***WARNING***' / '0' , ' WIND SPEED IS LESS THAN 2 M/S.'	70
1' '0' , ' DOSE ESTIMATES MAY BE UNRELIABLE.')	71
SPEED=SPEED*0.5148	72
IF (SPEED.GE.2.) GOTO 5	73
WRITE (6,216)	74
5 CALL ISOGN2	75
REWIND 5	76
C DETERMINE PASQUILL'S STABILITY CATEGORY FROM WIND SPEED (SPEED) ,	77
C DEGREE OF CLOUDINESS (ISKY) , AND TIME OF DAY (NDAY) .	78
NCLASS=5	79
IF (SPEED.LE.6.) NCLASS=4	80
IF (SPEED.LT.5.) NCLASS=3	81
IF (SPEED.LT.3.) NCLASS=2	82
IF (SPEED.LT.2.) NCLASS=1	83
TYPE=IDCAT (NCLASS, ISKY, NDAY)	84
JAGE (NCAS)=IAGE	85
DO 100 L=1, IAGE	86
NAGE=L	87
IF (I PLOT.EQ.1) NAGE=JAGE (NCAS)	88
ND=0	89
ICMAX=0	90
DIS=215.	91
DO 400 ID=10, 65	92
IF (DIS.LT.SPEED*TIMME) GOTO 31	93
DIS=SPEED*TIMME	94
ND=1	95
31 CROSS=0.	96
DO 500 IC=10, 65	97
C COMPUTE DOSE FROM EACH OF 17 NUCLIDES FOR GROUND LEVEL UNFILTERED PUFF	98
C RELEASE FIRST, THEN FOR ELEVATED FILTERED PUFF RELEASE, THEN FOR	99
C ELEVATED FILTERED CONTINUOUS RELEASE.	100
DOSTB=0.	101
DOSTHY=0.	102
DO 199 NUC=1, 7	103
I=NUC	104
H=0.	105
CKR=0.	106
CII=0.	107
CXE=0.	108
IF (LAMKR(I) .GT.0.) GOTO 24	109
LAKR=0.	110
GOTO 34	111
24 LAKR=0.693/LAMKR(I)	112
34 QPKR=QKR(I)*EXP(-LAKR*DIS/SPEED)	113
IF (LAMII(I) .GT.0.) GOTO 45	114
LAI=0.	115
GOTO 44	116
45 LAII=0.693/LAMII(I)	117
44 QPII=QII(I)	118
IF (LAMXE(I) .GT.0.) GOTO 54	119
LAXE=0.	120
GOTO 25	121
54 LAXE=0.693/LAMXE(I)	122
25 QPXE=QXE(I)*EXP(-LAXE*DIS/SPEED)	123
C COMPUTE THE PRESSURE-DEPENDENT LEAK RATE (CKR,CII,CXE) FROM	124
C THE CONTAINMENT BUILDING DURING OVERPRESSURE.	125
XPRESS=PRESS*2.4908	126
CKR=(XPRESS/17.4)*2.03/1.42E4*QPKR	127
CII=(XPRESS/17.4)*2.03/1.42E4*QPII*.25	128

```

CXE= (XPRESS/17.4) *2.03/1.42E4*QPXE      129
KK=1                                         130
C COMPUTE THE STANDARD DEVIATION OF THE PLUME AND INCLUDE THE      131
C CORRECTION FOR THE TURBULENT WAKE OF THE REACTOR BUILDING.     132
  41 SY=SIGMY(DIS,TYPE)                       133
    IF(H.NE.0.) GOTO 21                         134
    SSY=SQRT(SY**2+32.66)                       135
    SSSY=1.7321*SY                              136
    IF(SSY.GT.SSSY) SSY=SSSY                    137
    SY=SSY                                       138
  21 SZ=SIGMZ(DIS,TYPE)                       139
    IF(H.NE.0.) GOTO 51                         140
    SSZ=SQRT(SZ**2+32.66)                       141
    SSSZ=1.7321*SZ                              142
    IF(SSZ.GT.SSSZ) SSZ=SSSZ                    143
    SZ=SSZ                                       144
C COMPUTE THE CONCENTRATION OF THE RADIONUCLIDES (CHKR,CHII,CHXE) IN 145
C THE ATMOSPHERE AT THE DISTANCE OF INTEREST.                     146
  51 CX=CROSS**2/(2.*SY**2)                   147
    HX=CX+H**2/(2.*SZ**2)                       148
    IF (HX.GT.174.) HX=174.                     149
    CHKR=CKR/(3.1416*SPEED*SY*SZ)/EXP(HX)       150
    CHII=CII/(3.1416*SPEED*SY*SZ)/EXP(HX)       151
    CHXE=CXE/(3.1416*SPEED*SY*SZ)/EXP(HX)       152
C COMPUTE EXTERNAL DOSE AND INTERNAL DOSE                          153
  DOSBET=0.457* ((BETAKR(I)*CHKR)+(BETAXE(I)*CHXE)) 154
  DOSGAM=0.25* ((GAMAKR(I)*CHKR)+(GAMAXE(I)*CHXE)) 155
  DOSEX=DOSBET+DOSGAM                             156
  II=1-(I-7)                                       157
  DOSIN1=RA(NAGE)*CHII*DFA(II,1,NAGE)*1.0E9      158
  DOSIN2=RA(NAGE)*CHII*DFA(II,2,NAGE)*1.0E9      159
C COMPUTE TOTAL DOSE FOR TOTAL BODY AND THYROID                   160
  DOSTB=DOSTB+DOSEX+DOSIN1                       161
  DOSTHY=DOSTHY+DOSIN2                           162
  GOTO(32,42,52,200,199),KK                     163
C IF THE STACK VELOCITY IS LESS THAN 1.5 TIMES THE WIND SPEED, A 164
C CORRECTION FOR DOWNWASH MUST BE MADE TO THE STACK HEIGHT.     165
  32 H=30.2                                       166
    CKR=0.                                        167
    CII=0.                                        168
    CXE=0.                                        169
    SPD=1.5*SPEED                                170
C COMPUTE THE PRESSURE-DEPENDENT RATE OF DISCHARGE THROUGH THE 171
C STACK DURING OVERPRESSURE REDUCTION.                          172
  XPRESS=PRESS*2.4908                             173
  IF(PRESS.LE.1.5) GOTO 55                        174
  SV=3.24                                         175
  IF(SV.LE.SPD) H=24.69+(3.66*SV/SPD)           176
  CKR=(XPRESS-3.75)/13.7*193.*QPKR/1.42E4      177
  CII=(XPRESS-3.75)/13.7*193.*QPPII/1.42E7*0.25 178
  CXE=(XPRESS-3.75)/13.7*193.*QPXE/1.42E4      179
  KK=2                                           180
  GOTO 41                                         181
  42 XPRESS=3.75                                  182
  55 CKR=XPRESS/3.75*51.3/1.42E4*QPKR           183
    CII=XPRESS/3.75*51.3/1.42E7*QPPII*0.25     184
    CXE=XPRESS/3.75*51.3/1.42E4*QPXE           185
    SV=(XPRESS/3.75*1.30)+1.94                 186
    IF(SV.LE.SPD) H=24.69+(3.66*SV/SPD)       187
    KK=3                                         188
    GOTO 41                                       189
  52 CKR=103./1.42E4*QPKR                        190
    CII=103./1.42E7*QPPII*0.25                 191
    CXE=103./1.42E4*QPXE                       192

```


SV=1.07	193
IF (SV.LE.SPD) H=24.69+ (3.66*SV/SPD)	194
KK=4	195
GOTO 41	196
C COMPUTE THE CONCENTRATION TIME INTEGRAL OF EACH NUCLIDE AT THE	197
C DISTANCE OF INTEREST.	198
200 SV=.202	199
IF (SV.LE.SPD) H=24.69+ (3.66*SV/SPD)	200
TKR=TIMME-DIS/SPEED	201
TII=TIMME-DIS/SPEED	202
TXE=TIMME-DIS/SPEED	203
72 LAKR=LAKR+1.67E-5	204
82 LAII=LAII+1.67E-5	205
92 LAXE=LAXE+1.67E-5	206
62 CKR=QPKR/LAKR*1.67E-8*(1-EXP(-LAKR*TKR))	207
CII=QPPI/LAII*1.67E-8*(1-EXP(-LAII*TII))	208
CXE=QPXE/LAXE*1.67E-8*(1-EXP(-LAXE*TXE))	209
KK=5	210
GOTO 51	211
199 KK=1	212
C IF THE TOTAL BODY DOSE RISES ABOVE 25 REM	213
C OR IF THE THYROID DOSE RISES ABOVE 300 REM, PRINT ASTERISKS.	214
C IF THE TOTAL BODY DOSE OR THYROID DOSE FALLS BELOW 1 MREM,	215
C PROCEED TO THE NEXT DISTANCE INCREMENT.	216
C INCREMENT DOWNWIND DISTANCE EXPONENTIALLY. FOR EACH DOWNWIND	217
C DISTANCE INCREMENT CROSSWIND DISTANCE EXPONENTIALLY.	218
499 IF (DOSTHY.GT..001) GOTO 498	219
DOSTHY=0.	220
498 IF (DOSTHY.LE.300.) GOTO 497	221
DOSTHY=123456.	222
497 THYDOS (ID,IC) =DOSTHY	223
IF (DOSTB.GT..001) GOTO 496	224
DOSTB=0.	225
496 IF (DOSTB.LE.25.) GOTO 495	226
DOSTB=123456.	227
495 TOTDOS (ID,IC) =DOSTB	228
IF (IPLOT.EQ.1) GOTO 399	229
ICMAX=MAX0 (IC,ICMAX)	230
CROSS=CROSS+EXP (0.1*IC+2.)	231
YP=SQRT (5.99*SY**2)	232
IF (CROSS.GE.YP) GOTO 399	233
500 CONTINUE	234
399 D (ID-9,NCAS) =DIS	235
IF (ND.EQ.1) GOTO 122	236
400 DIS=DIS+EXP (-.1*ID+2.)	237
122 GO TO (691,692,693,694),NAGE	238
691 DLAB (3) =A1	239
DLAB (4) =B1	240
GOTO 695	241
692 DLAB (3) =A2	242
DLAB (4) =B2	243
GOTO 695	244
693 DLAB (3) =A3	245
DLAB (4) =B3	246
GOTO 695	247
694 DLAB (3) =A4	248
DLAB (4) =B4	249
695 IF (IPLOT.NE.1) GOTO 123	250
DO 700 N=1,56	251
TB (N,NCAS) =TOTDOS (N+9,10)	252
700 THY (N,NCAS) =THYDOS (N+9,10)	253
IF (NCAS.NE.NCASES) GOTO 800	254
ISYM=1	255
K=1	256

701	DO 702 J=1,NCASES	257
	DLAB(5)=AA(J)	258
	NAGE=JAGE(J)	259
	GO TO (791,792,793,794),NAGE	260
791	DLAB(3)=A1	261
	DLAB(4)=B1	262
	GOTO 795	263
792	DLAB(3)=A2	264
	DLAB(4)=B2	265
	GOTO 795	266
793	DLAB(3)=A3	267
	DLAB(4)=B3	268
	GOTO 795	269
794	DLAB(3)=A4	270
	DLAB(4)=B4	271
795	DO 703 I=1,56	272
	IF(D(I,J).LE.0.) GOTO 704	273
	XDOS(I)=ALOG(D(I,J))	274
704	IF(K.EQ.2) GOTO 707	275
	IF(TB(I,J).LE.0.) GOTO 703	276
	YDOS(I)=ALOG(TB(I,J))	277
	GOTO 703	278
707	IF(THY(I,J).LE.0.) GOTO 703	279
703	YDOS(I)=ALOG(THY(I,J))	280
	IF(J.LE.1) GOTO 690	281
	ISYM=ISYM+1	282
	MODE=-101	283
	CALL GRAPHS (56,XDOS,YDOS,ISYM,MODE,DLAB)	284
	GOTO 706	285
690	MODE=-101	286
	XSIZE=-7.0	287
	YSIZE=-10.0	288
	XSP=-3.0	289
	XMIN=2.0	290
	YSP=-5.0	291
	YMIN=-3.0	292
	CALL GRAPH (56,XDOS,YDOS,ISYM,MODE,XSIZE,YSIZE,XSP,XMIN,YSP,	293
	YMIN,'DOWNWIND DIST. (M);',YLAB,GLAB,DLAB)	294
706	DO 705 I=1,56	295
	IDOS(I)=0.	296
705	YDOS(I)=0.	297
702	CONTINUE	298
	IF(K.EQ.2) GOTO 131	299
	K=2	300
	ISYM=1	301
	YLAB(1)=BB1	302
	YLAB(2)=BB2	303
	YLAB(3)=BB3	304
	GOTO 701	305
123	DO 7 J=1,3,2	306
	IF(J.EQ.1) GOTO 124	307
	YLAB(1)=BB1	308
	YLAB(2)=BB2	309
	YLAB(3)=BB3	310
124	XJ=DLAB(3)	311
	XJJ=DLAB(4)	312
	WRITE(6,925) XJ,XJJ,(YLAB(I),I=1,5)	313
925	FORMAT ('1',84('*'),/,' ', '*',9X,7A4,T85,'*')	314
128	IIC=10	315
	CROSS=0.	316
	IID=65	317
	IF(ND.EQ.1) IID=ID	318
133	NIC=IIC+8	319
	DIS=215.	320


```

IF(NIC.GE.65) NIC=65 321
DO 129 ID=10,IID 322
137 IF(DIS.NE.215.) GOTO 120 323
DO 130 IC=IIC,NIC 324
ICROS(IC)=(CROSS+0.5) 325
130 CROSS=CROSS+EXP(0.1*IC+2.) 326
IF (IIC.EQ.10) GOTO 135 327
WRITE (6,215) 328
135 WRITE(6,930) (ICROS(I),I=IIC,NIC) 329
120 IF(ID.EQ.IID.AND.ND.EQ.1) DIS=SPEED*TIMME 330
132 IF(J.GT.1) GOTO 134 331
WRITE(6,931)DIS,(TOTDOS(ID,N),N=IIC,NIC) 332
GOTO 129 333
134 WRITE(6,931)DIS,(THYDOS(ID,N),N=IIC,NIC) 334
129 DIS=DIS+EXP(-.1*ID+2.) 335
136 IIC=NIC+1 336
IF(ICMAX.GE.IIC) GOTO 133 337
930 FORMAT(' ',84('*'),/ 338
3' ',**',9X,9('|',7X),' ',**',/' ', '*CROSSWIND',9('|',7X), 339
1' ',**',/' ', '*DISTANCE ',9('|',I7),' ',**',/' ', '* (METERS) ',9('|', 340
27X),' ',**',/' ',**',9X,9('|',7X),' ',**',/'+',1X,82('_'),/' ', 341
2' *DOWNWIND ',9('|',7X), 342
1' ',**',/' ', '*DISTANCE ',9('|',7X),' ',**',/' ', '* (METERS) ',9('|', 343
47X),' ',**',/'+',1X,9('_'),/' ',**',9X,9('|',7X),' ',**') 344
931 FORMAT(' ',**',F8.0,1X,9('|',F7.3),' ',**') 345
7 CONTINUE 346
799 YLAB(1)=AB1 347
YLAB(2)=AB2 348
YLAB(3)=AB3 349
100 CONTINUE 350
800 CONTINUE 351
131 STOP 352
END 353

```

APPENDIX B: ISOGEN

Summary

ISOGEN (12) (isotope generation) is an extremely fast computer program for calculating radioisotope generation and decay with chains containing up to 50 members each. Accuracy is ordinarily within 0.1% for each time step, although cumulative errors for many time steps may be somewhat larger. Branching may occur by radioactive decay, neutron capture, or fission at any chain member.

Much of the input is basic nuclear data in normal units. Output is expressed in atoms, grams, curies, beta mev/dis, and gamma mev/dis. Time, flux, and ratio of resonance to thermal neutrons is specified for up to 30 time steps. Decay chains are not given explicitly as input, but are generated by the program from basic nuclear data and initial parent nuclides. For the fission process, the identity of primary fission products of interest must be specified.

General Equations

A general solution to the differential equations of radioactive growth and decay was presented many years ago. These equations can be used easily to obtain the amount of a

daughter nuclide for short chains, especially when there are large differences in decay constants between chain members. However, application of the classical equation is difficult or impossible when two or more of the nuclides being considered have almost equal or equal total decay constants. The problem is usually most acute when more than one of the nuclides being considered has a product of decay constant and time of less than 0.1. The classical equation will then yield the answer as a small difference between two large numbers.

In the ISOGEN code, the integrated equations were rearranged to forms which yield accurate results more easily, and the form most easily applied to a particular set of data is used for the calculation. The details of the equations are explained in reference 41 and will not be discussed here.

Input Data

Input data are divided into three groups; basic nuclear data, time step information, and other data. The first group consists of half-life, energy, cross section, fission yield, and daughter product data stored in 500 member arrays, with an index number for each nuclide. The second group specifies the time, neutron flux, and power level to be used for each of up to 30 time steps. The third group includes index num-

bers and amounts of parents initially present at the beginning of the first time step.

Output Data

The output of ISOGEN includes the atoms grams, curies, beta mev/dis, and gamma mev/dis of the nuclides of interest at the specified times.