EFFECT OF SOURCE TERM COMPOSITION ON OFFSITE DOSES

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Presented at
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ABSTRACT

The development of new realistic accident source terms has identified the need to establish a basis for comparing the impact of such source terms. This paper attempts to develop a generalized basis of comparison by investigating contributions to offsite acute whole body doses from each group of radionuclides being released to the atmosphere, using CRAC2. The paper also investigates the effect of important parameters such as regional meteorology, sheltering, and duration of release. Finally, the paper focuses on significant changes in the relative importance of individual radionuclide groups in PWR2, SST1, and a revision of the Stone & Webster proposed interim source term.

FOREWORD

The safety of nuclear power plants has been assessed generally on the basis of risk: the probability that a major accident will occur combined with the consequences that such an accident would have on the general public. That the probability, and hence the risk, is very low has been generally accepted since the Reactor Safety Study (1). Current work indicates that not only are probabilities low, but consequences of a severe accident are also far less than previous analyses had shown, although absolute reductions in consequences remain to be determined.

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The most important parameter needed to evaluate the consequences is the amount and kind of radioactive material postulated to be released to the environment following an accident: taken collectively, these are known as the "Source Term" because they describe the source of radioactivity for the consequence calculations.

One of the interesting observations of the Three Mile Island accident was that the amount of radioactive iodine released was much less than the analytical models in use at the time would have predicted (2).

Subsequent analyses have indicated that source terms used to evaluate potential risks in the past have been overestimated (3,4,5,6,7) by large factors. This overestimation was appropriate years ago because scientists had to make conservative and limiting assumptions about complex and poorly understood phenomena to avoid underestimating the risk from severe accidents.

Prompted by these findings, the task of developing realistic accident source terms has been undertaken by several groups including Stone & Webster Engineering Corporation (SWEC). SWEC's investigation includes assessing the impact of revised source terms on offsite consequences and evaluating such consequences for realistic accident source terms (8,9).

INTRODUCTION

As there are many groups independently developing new source terms for various plants, it is both conceivable and very likely that the compositions of such source terms will be different, making the establishment of generic offsite consequences very difficult. This difficulty arises from the fact that, in general, health consequences are population distribution dependent and are evaluated using response functions with threshold levels. Furthermore, comparisons of source terms based on early fatalities tend to be meaningless because such fatalities are calculated to be zero for a wide range of reduced source term magnitudes. Offsite doses, rather than fatalities, is a more meaningful way of comparing various source terms.

An investigation of the effect of source term composition on offsite doses, taking into account variations of parameters such as weather conditions, duration of release to the environment, timing of the release, sheltering, and duration of exposure to ground contamination is reported in this paper.

PARAMETERS CONSIDERED

Table 1 presents a comparison of the fission product group composition for Regulatory source terms (PWR2, SST1) and the proposed initial and revised SWEC Interim Source Terms (IST and RIST, respectively) (8).

As can be seen from Table 1, it is assumed in all cases that all of the noble gases would be released in a postulated major nuclear accident. Percentages of other radionuclide groups, however, differ markedly by up to a factor of 70.

TABLE 1

COMPARISON OF SOURCE TERMS
(Percent of Core Inventory Released to the Atmosphere)

Fission Product Group	WASH-1400 PWR2 (1)	SANDIA SST1(11)	SWEC Proposed Interim Source Term (IST)	Revised Interim Source Term (RIST)	Base Case
Noble Gases	90	100	100	100	100
Iodine	70	45	1.0	1.0	1.0
Cs-Rb	50	67	1.0	1.0	1.0
Te-Sb	30	64	1.0	1.0	1.0
Ba-Sr	6	7	1.0	0.4	1.0
Ru	2	5	1.0	0.03	1.0
La	0.4	0.9	0.4	0.02	1.0

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Offsite doses following the release of radioactive materials depend on a number of factors, including the following:

- Amount of radioactive material released

  Provided all other accident conditions are relatively constant, larger amounts of radioactive materials released would result in proportionately larger offsite doses.

- Specific nuclides being released

  Decay characteristics (e.g., radioactive half-lives and energies) make some radionuclides more important than others.

- Distance from the release point

  With the exception of very extraordinary weather conditions, doses will decrease as distances from the release point are increased.

- Timing of the release

  The time between the initiation of the accident and the initiation and duration of the release are important to offsite dose assessment, because radioactive half-lives for the significant nuclides can range from less than an hour (I-134) to tens of thousands of years (Pu-239); further, time is an important factor in fission product aerosol behavior during an accident.

- Physical form of released materials

  The physical form of the released radioactive materials can significantly affect offsite doses. Materials in particulate form would deposit on the ground becoming long-term dose contributors, whereas gaseous materials would contribute only to short-term doses.

- Weather condition at the time of the release

  Weather characteristics at the time of the release (wind speed, stability class, and/or rain, etc) and conditions during subsequent hours determine the dispersion of radioactivity in the atmosphere which, in turn, directly impacts offsite doses.

- Natural and active protection factors

  Depending on the time that the accident occurs, people may be outdoors, which would tend to increase doses, or indoors which would tend to reduce doses. In addition, active sheltering might be sought by the general public following a major accident or even temporary relocation once the magnitude of the ground contamination was evaluated.

ANALYTICAL APPROACH

The approach used in the analyses presented in this paper was first to determine the importance of each radionuclide group to offsite doses, secondly to study the effect of each parameter identified in the previous section, and finally to study the effect of certain combinations of those parameters.

Offsite dose assessments were performed using the computer code CRAC2 (Calculations of Reactor Accident Consequences, Version 2), developed by Sandia National Laboratories (10).

CRAC2 calculates doses versus distance from the reactor based on the amount of radioactive material released and random samples of sequences of hourly meteorological conditions following the release. After all the random meteorological conditions and their associated probabilities are processed, frequency distributions of doses at each user-specified distance are generated.

The meteorological data input to the code consisted of 8760 hourly measurements (1 year) of wind direction, wind speed, stability class, and rain intensity. The hourly data were sorted initially into 29 priority weather categories called bins. Dose calculations were then performed using a user-specified number of sequences from each bin.

Using a base case, described in Table 2, contributions to the acute whole body doses were calculated for each release group listed in Table 1. This identified the relative importance of each group to offsite doses. In addition, the effects, or importance, of other parameters used in offsite dose assessments were investigated, as described in the following sections of this paper.

TABLE 2

BASE CASE DESCRIPTION

- 2 Hours Decay Prior to Release
- 2 Hours Duration of Release
- 10-Meter Release Height (Ground Release)
- No Heat Associated With the Release
- 24 Hours Exposure to Ground Contamination
- Maximum Individual Doses (No Sheltering)
- 3412 MW_t PWR End of Core Life Inventory
- 100 Percent Noble Gases Released
- 1 Percent of All Other Nuclides Released
- Miami Typical Meteorological Year Data
- 4 Samples Per Bin in CRAC2

The meteorological data employed were Typical Meteorological Years (TMY), which are based on approximately 25 years of hourly weather observations at National Weather Service stations in Chicago, Miami, Phoenix, and New York. These four areas were chosen on the basis of having meteorological conditions fairly representative of the continental U.S., in terms of the meteorological prioritization in CRAC2 (11).

The core fission product inventory used in the analyses was that of a 3412 MW_t PWR at the end of core life and was taken from the Sandia Siting Study (11).

In the cases where protective sheltering action was assumed, the sheltering factors used were those corresponding to the Northeastern region of the U.S (11) (typically substantial houses with basements), i.e., a cloud shielding factor of 0.5 and a ground shielding factor of 0.08 were assumed. Also, when active sheltering was assumed, the breathing rate was reduced from 2.66×10^{-4} m^3/sec to 1.33×10^{-4} m^3/sec, accounting for the reduced concentration indoors (12).

Except where specific protective sheltering was assumed, the simple but conservative case of continuous total exposure for the full time on an infinite smooth plane was used.

Whole body doses versus distance were chosen as the basis for comparison in these analyses. Further, because the purpose of the analyses was to establish relative effects of various source term compositions and other parameters, and to avoid threshold effects which result from interdiction criteria built into CRAC2, only the acute whole body doses were considered. Avoiding the threshold effects also allows scaling of the results to reflect doses for source terms consisting of any combination of radionuclide group release fractions.

RESULTS - SOURCE TERM COMPOSITION

Figure 1 presents mean acute whole body doses versus distance from the reactor for a number of the source terms presented in Table 1 and the fractional contribution from each radionuclide group. The parameters used to calculate these doses are the base case parameters with the exception, of course, of the source term composition. Doses due to noble gases only are presented in this figure as a limiting case, because there is general agreement that in a major release to the atmosphere, all of the noble gases will be included. It is striking that even though the PWR-2 and SST1 compositions are not similar, the calculated doses are almost identical. Reducing the source terms to the base case level reduced doses by approximately a factor of 15, and further reducing the source term to the IST and RIST levels reduced the doses by an additional factor of about 2 for an overall reduction factor of approximately 30.

The dose from each release group changes for different composition source terms. For example, the dose contribution due to iodine, for PWR-2, is approximately 15 times higher than that due to the Cs-Rb group and 80 times higher than that due to the La group. For the base case, the iodine doses are again higher by approximately a factor of 10 compared to the Cs-Rb group, but are lower by a factor of 1.5 compared to the La group. Noble gases vary from being the least contributor at distances less than 1 mile, to being the third least contributor at greater distances in PWR-2, whereas for the SST1 source term they are the least contributor to the dose at all distances.

For the IST and RIST source terms, the noble gases dominate doses at distances greater than 3 miles and the Cs-Rb group is the least contributor at all distances where it was the third most important contributor for PWR-2 and SST1.

Figure 2 presents the dose contribution to acute whole body doses from each group of radionuclides for the base case described in Table 2. Note that dose patterns for any source term can be constructed by multiplying the contributions shown (which are based on 100 percent of the noble gases and 1 percent of every other group being released) by the percentage release being considered.

RESULTS OF PARAMETRIC STUDY

The number of samples per bin used in the analyses was determined by executing the base case with 1, 4, and 8 samples per bin and comparing the acute whole body doses at distances up to 10 miles.

As indicated earlier in this paper, CRAC2 calculates frequency distributions of doses at each specified distance based on the probabilities of the selected random weather sequence samples. The doses compared in this paper are:

a) Mean Dose, $Dm = \sum_i P_i \cdot D_i$; where:

D_i = dose calculated using random weather sequence sample i

P_i = probability of random weather sequence sample i

b) Ninety-Five Percentile Dose - dose that will be exceeded only 5 percent of the time based on weather sequences sampled.

Figure 3 depicts the mean and 95 percentile doses as a function of distance from the reactor, using 1, 4, and 8 random weather samples per bin for the IST. It is evident from this figure that increasing the number of samples per bin from 1 to 4 to 8 has very little effect on either the mean or the 95 percentile doses at the distances considered. The maximum variation was observed at 10 miles from the reactor where the 8 samples per bin mean dose was approximately 26 percent higher than that of 1 sample per bin and 14 percent higher than that of 4 samples per bin. The variations at other distances were generally substantially less than 10 percent, with variations between 4 and 8 samples per bin being the smallest.

Based on these observations, 4 samples per bin was chosen as the appropriate number to be used for the rest of the analyses.

Figure 3 also presents mean and 95 percentile doses at distances up to 10 miles using four sets of meteorological data. These results indicate that there is a variation of less than a factor of 2 at both mean and 95 percentile levels between the 4 sets of meteorological data and approximately a factor of 3 between mean and 95 percentile doses. As Miami meteorology seemed to be the most representative of the four areas, it was used for the remainder of the analyses.

Figure 4 presents the results of the parametric analyses of duration of exposure to ground contamination, sheltering, and duration of release.

It can be seen that increasing the duration of exposure from 1 to 2 days increases the calculated dose by less than a factor of 2 (~1.5) at any distance for both the mean and 95 percentile levels. Reducing the exposure to 12 hours reduces the calculated dose by about the same factor, which seems to indicate that acute whole body doses for the base case are dominated by exposure to ground contamination.

Comparison of the sheltered versus unsheltered doses indicates that protective sheltering can reduce mean acute whole body doses by factors of 4 to 7.5 depending on the distance from the reactor, and it can reduce 95 percentile doses by factors of 5 to 6.5 depending on distance. It should be noted that these reduction factors are obtained from comparisons to unrealistically conservative doses (exposure on an infinite smooth plane). The sheltering factors presented in Figure 4, however, are needed to adjust the base case doses for sheltering. If comparisons were made to doses for a more realistic rough terrain case, sheltering factors would appear to be smaller by up to a factor of 2; at these levels, protective sheltering can significantly reduce offsite doses.

The effect of duration of release on offsite doses was investigated by executing CRAC2 with the base case and increasing the release duration to 6 and 10 hours (10 hours is the highest duration of release allowed by CRAC2). The ratios of the doses to those calculated for the base case show a reduction of less than a factor of 1.5 for mean doses and less than a factor of 1.8 for 95 percentile doses.

CONCLUSIONS

- Based on the fractional dose contributions evaluated in this paper, radionuclide groups that were deemed insignificant contributors in the past might become the controlling factors in consequence analyses when new realistic source terms are established. This, combined with the fact that radionuclide groups deliver doses through different exposure pathways (13), calls for a reexamination of radionuclide importance and a reevaluation of protective measures that should be taken in case of an accident.

- Because of the consistency observed in the effects of the studied parameters, the mean unsheltered dose seems to be a reasonable measure of the relative consequences of different source terms, especially noting that, for reduced source terms, fatality thresholds are only exceeded at very short distances from the reactor.

Based on the consistency of ratio curves 3c, 4a, and 4b, it appears that valid comparisons of source terms of different compositions can be made over the ranges of the parameters tested using Figure 2. As sheltering characteristics at any given site are essentially constant, dose-based comparisons are valid for a site, but comparisons between sites should be approached with caution. Further, it will be found that sheltering is more effective with some source term compositions than with others.

Several additional conclusions can be drawn relative to the effect of source term composition and other parameters on offsite doses following an accident at a nuclear power plant, these are presented below and summarized in Table 3.

- Based on the sampling technique used for meteorological conditions with CRAC2, 95 percentile doses are a fairly consistent factor of 3 higher than the mean doses at all distances.

- Use of meteorological data for different regions of the country only introduces variations less than 1.8 for mean doses and less than 1.6 for 95 percentile doses regardless of the assumptions of duration of exposure, sheltering, etc.

- Protective sheltering can reduce doses by a factor of 7.0 or more near the reactor and factors of 4 or more at distances greater than 5 miles at both the mean and the 95 percentile dose levels.

- Increasing the duration of exposure to ground contamination by a factor of 2 (24 to 48 hours) increases the doses by approximately a factor of 1.6.

- Variations in duration of release from 2 to 10 hours decrease both mean and 95 percentile doses by less than a factor of 2.

TABLE 3

DOSE EFFECT RATIOS FOR CRAC2 PARAMETRIC ANALYSES

Case Examined	Mean Dose Ratios to Base Case(b)	Mean Dose Ratios(a)		
		Chicago	Phoenix	New York
Base Case	1.0	1.31-1.36(c)	0.84-0.90	1.22-1.45
48 Hour Ground Exposure	1.6-1.7	1.31-1.35	0.84-0.90	1.20-1.43
Sheltering	4.8-7.3	1.26-1.40	0.77-0.87	1.26-1.51
SST1 (d)	14.-16.	1.30-1.33	0.86-0.94	1.18-1.41

Case Examined	95 Percentile Dose Ratios to Base Case	95 Percentile Dose Ratios(a)		
		Chicago	Phoenix	New York
Base Case	1.0	1.09-1.44	0.91-1.05	1.15-1.42
48 Hour Ground Exposure	1.7-2.0	1.10-1.59	0.89-1.21	1.16-1.44
Sheltering	4.7-6.6	1.18-1.82	0.74-1.26	1.66-1.73
SST1 (d)	11.-19.	1.09-1.70	0.74-1.21	1.12-1.66

NOTES: (a) Ratios of doses obtained using given meteorology and indicated variations to those obtained using Miami meteorology.

(b) Ratios of doses calculated with Miami meteorology and variations in the indicated parameters.

(c) Ranges indicate variations of ratios versus distance.

(d) Ratios of doses calculated for SST1, to those calculated for the base case.

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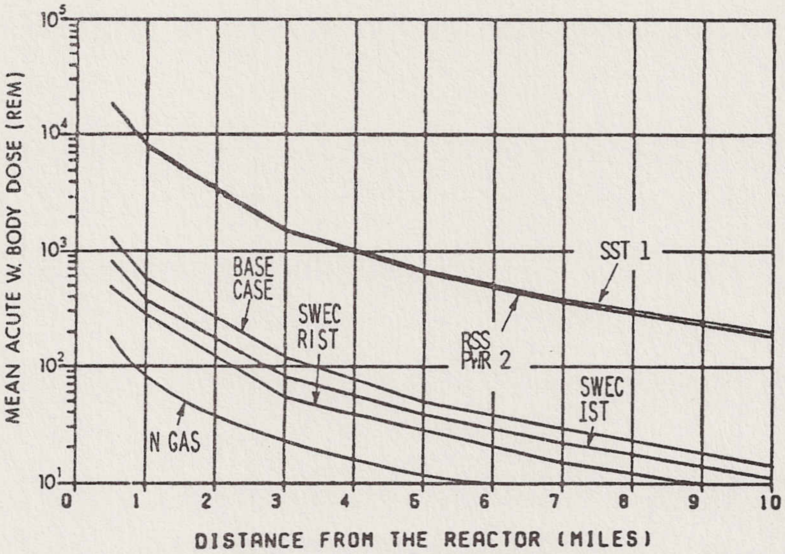

Figure 1A. Maximum Individual/24-Hour Ground (2-Hour Delay/2-Hour Release)

FRACTIONAL CONTRIBUTIONS

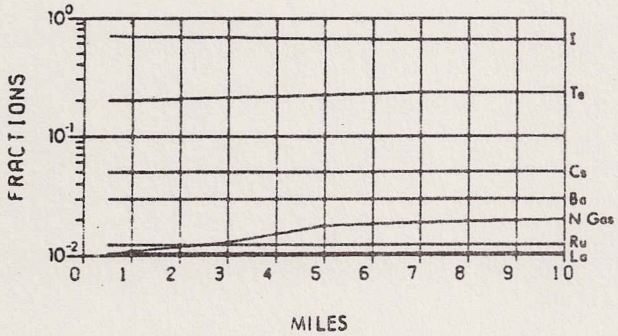

Figure 1B. RSS-PWR2

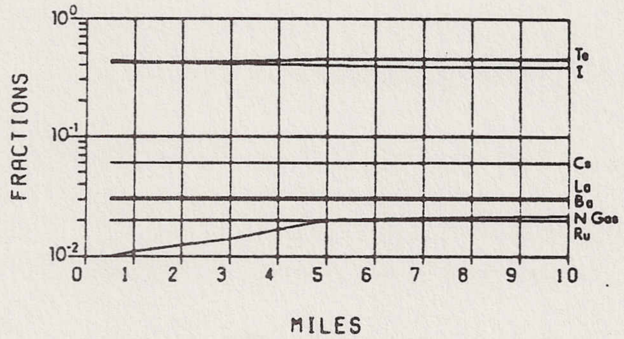

Figure 1C. SST1

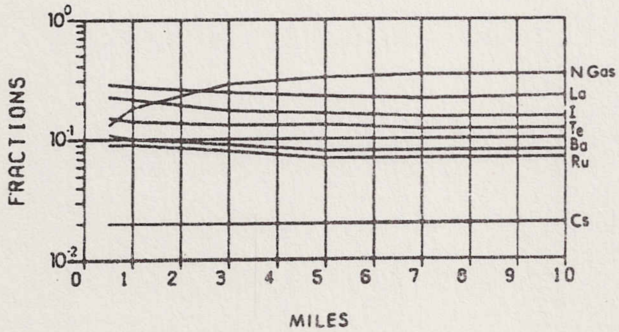

Figure 1D. IST

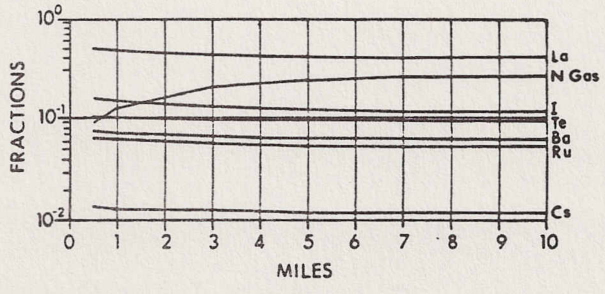

Figure 1E. Base Case

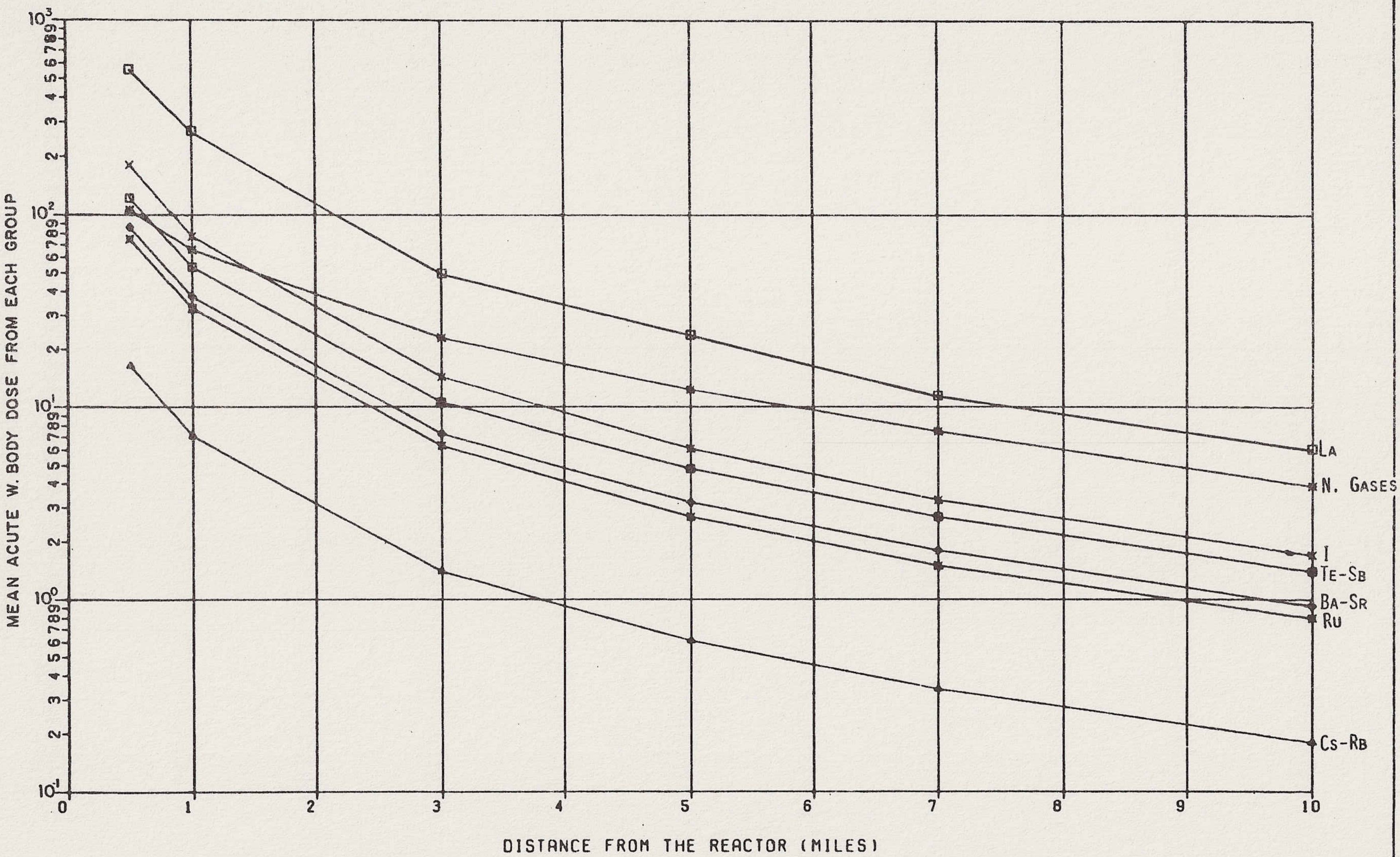

Figure 2. Dose Contribution From Each Release Group (Base Case)

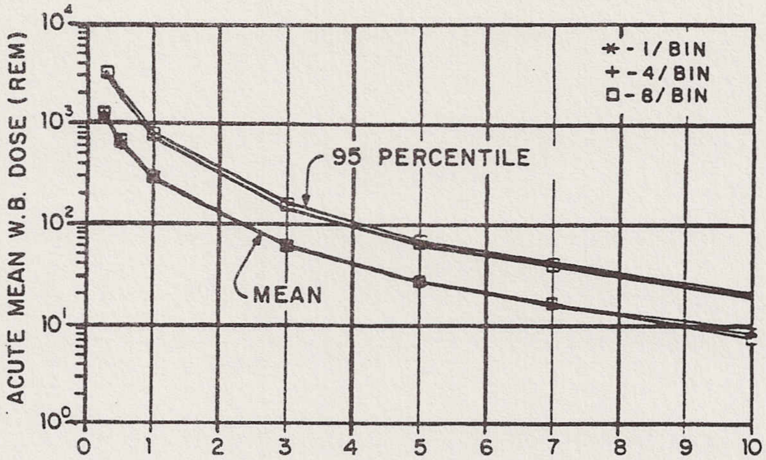

Figure 3A. Interim Source Term - Number of Samples/Bin

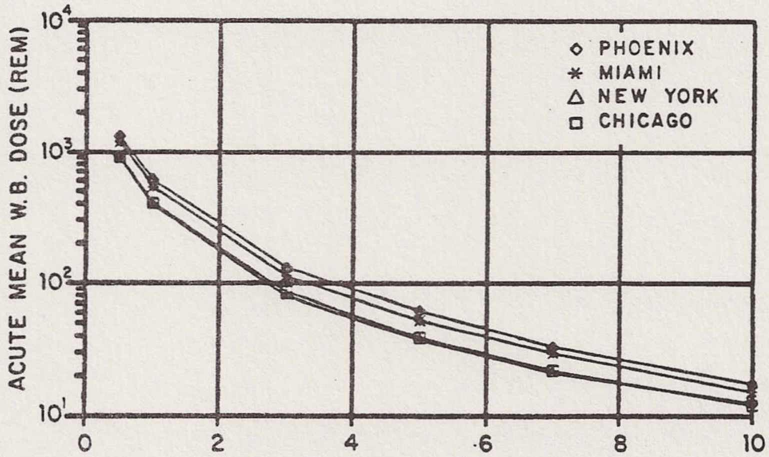

Figure 3B. Base Case - Mean Doses

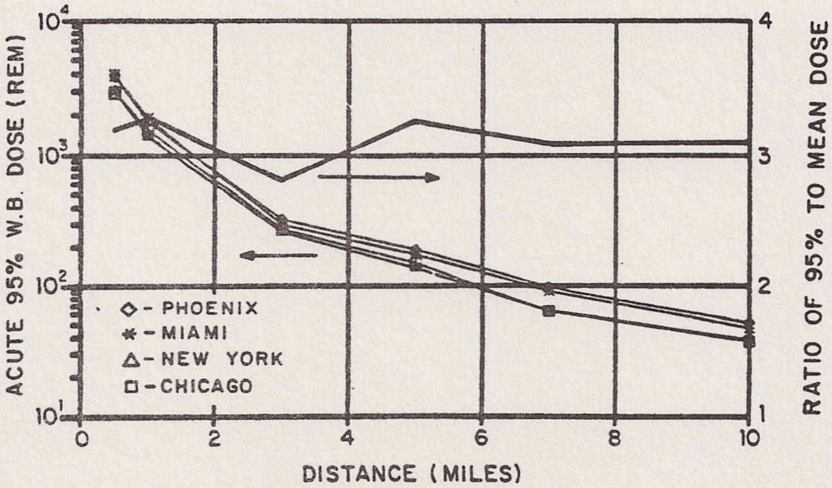

Figure 3C. Base Case - 95 Percentile Doses

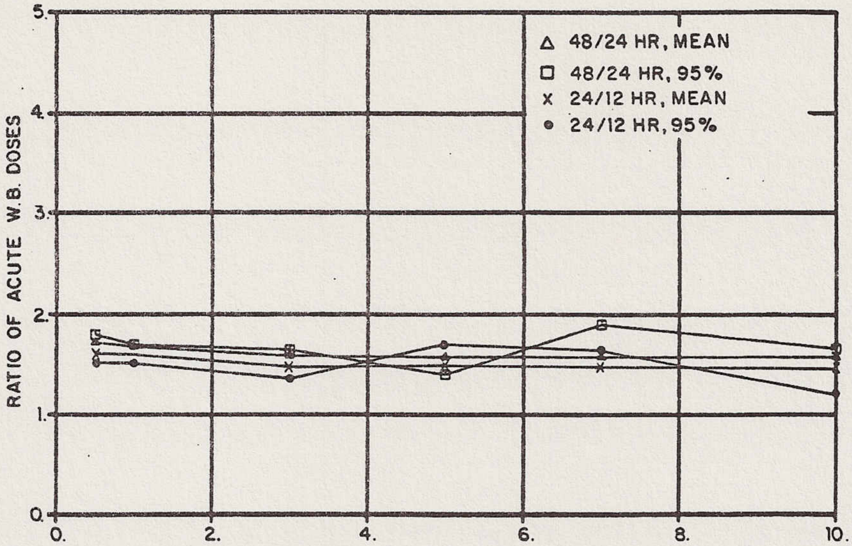

Figure 4A. Effect of Duration of Exposure to Ground Contamination

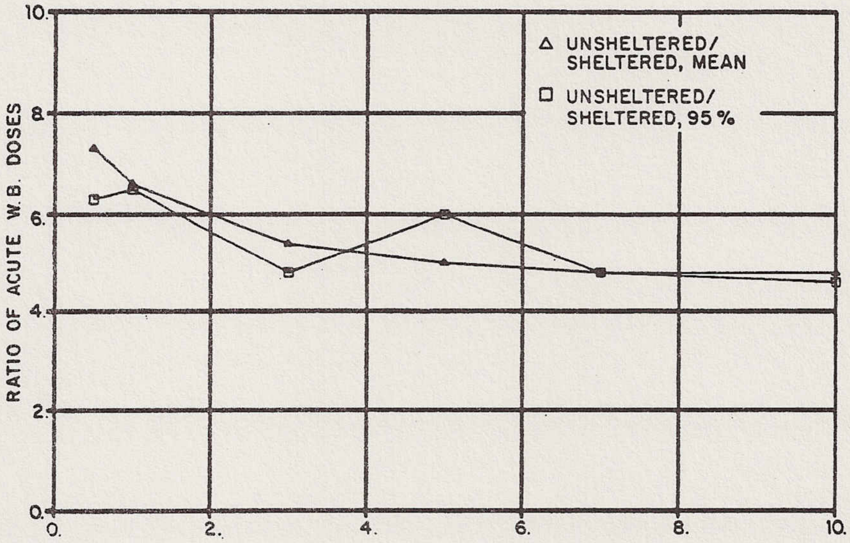

Figure 4B. Effect of Sheltering

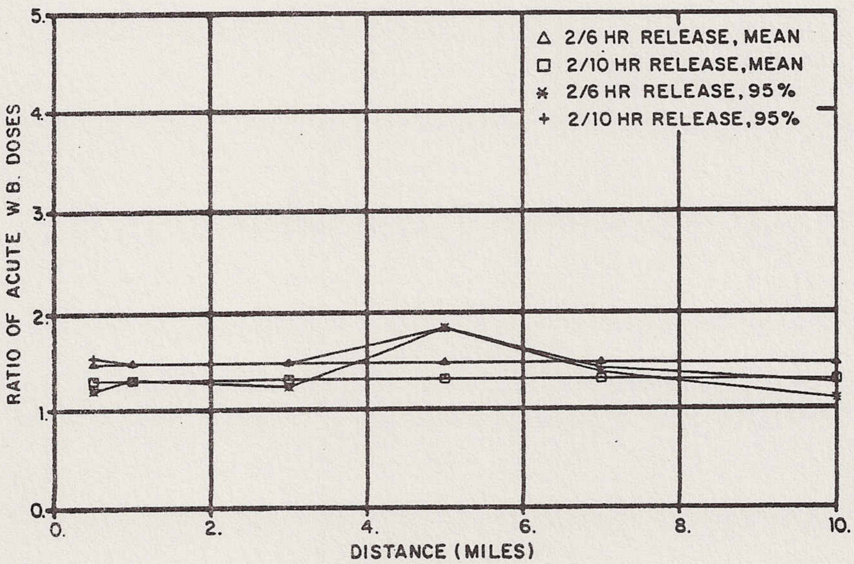

Figure 4C. Effect of Duration of Release