RISK ANALYSIS OF POSTULATED PLUTONIUM RELEASES FROM THE EXXON NUCLEAR MIXED OXIDE FUEL PLANT AS A RESULT OF HIGH WINDS AND EARTHQUAKES

INTRODUCTION

The Nuclear Regulatory Commission has sponsored a program to estimate the potential hazard to the general population as a result of the impact of high winds and earthquakes on the Exxon Nuclear Mixed Oxide Fuel Plant at Richland, Washington. This paper outlines the procedures used in combining the results of various increments of analysis obtained in this study to produce a measure of risk. The risk measure presented in this paper is the probability per year that a high wind or earthquake will result in doses above specific levels (complementary cumulative distributions). The two organs, lungs and bone, were chosen for the dose exceedance probability calculations since these organs are significant and generally dominate the 50-year committed dose equivalents from inhalation. The doses were calculated for the population within an 80 km (50-mile) radius of the plant and for the nearest residence located within 150 meters NE of the plant. Three tornado wind speeds, 150 mph, 190 mph, and 250 mph, and one earthquake event, 1.0g were evaluated for the analysis. Two earthquake events were reduced to one event since no significant plant damage was assessed for earthquakes of magnitude less than 1.0g peak ground acceleration.

TORNADO WIND SPEEDS

The estimated probabilities for the postulated tornado wind speeds were obtained from T. T. Fujita (Ref. 1). The frequency, F-scale, and associated wind speeds of historical tornadoes (1950-1975) were also obtained from Ref. 1 and are listed in Table 1 below.

TABLE 1

TORNADO FREQUEN.:Y, F-SCALE, AND ASSOCIATED \'IND SPEEDS (1950-1978)

Number of Tornadoes	F-Scale	Wind-Speed Range-mph	Reference Point Wind Speed-mph
8	0	40 - 72	59
5	1	73 - 112	92
9	2	113 - 157	131
0	3	158 - 206	177
0	4	207 - 260	277
0	5	261 - 318	276

To obtain confidence bounds on the probabilities of postulated wind speeds, an error factor of 10 was used throughout the analysis. Assuming that the postulated tornado wind speeds occur in accordance with a Poisson process, the error factor of 10 will, to an order of magnitude accuracy, provide conservative 90% confidence bounds for wind speed occurrence probabilities within the wind speed range of the observed data with one or more points.* Estimates of complementary cumulative tornado wind speed probabilities and associated confidence bounds are provided in Table 2.

EARTHQUAKES

Two earthquake events were considered in this analyses. Each earthquake event consisted of a discrete range of peak ground acceleration levels

*These 90% confidence bounds will in 90% of the cases cover the true wind speed probability if the assumed model and distributions are correct.

and a point value used to characterize the range. No significant damage was assessed for any earthquake less than 1.0g peak ground acceleration. Probabilities vs. peak acceleration with estimated standard deviations (σ) are provided in Ref. 2 and reproduced here as Figure 1. Table 2 presents peak ground acceleration levels vs. cc probabilities and associated uncertainty bounds for the significant earthquake events. For the accompanying risk analyses, the bounds on the probability estimates were modified to a factor of 10 for an earthquake of greater than 1.0g. These modified factor of 10 bounds, in general, include more than 2σ variations from the best estimate probability and are conservative (>90%) if the σ estimates and rounding uncertainties introduced in the gener‘tion of the cc curves for the risk analyses. The exact confidence represented by the bounds is not critical to the subsequent risk analysis.

TABLE 2

A. COMPLEMENTARY CUMULATIVE (cc) PROBABILITIES OF TORNADO WIND SPEEDS AND ASSOCIATED CONFIDENCE LIMITS

Tornado Wind Speed	cc Probability per year	Conservative 90% Confidence Bounds on the Probability
150 mph	3.0E-7	(3.0E-8, 3.0E-6)
190 mph	6.0E-8	(6.0E-9, 6.0E-7)
250 mph	3.0E-9	(3.0E-10, 3.0E-8)

TABLE 3

B. EARTHQUAKE PROBABILITY AND ASSOCIATED UNCERTAINTY

Peak Ground Acceleration	Probability per year	Approximate 90% Bounds on the Probability
1.0g	1.0E-5	(1.0E-6, 1.0E-4)

CC CURVES FOR CONSEQUENCES FROM ACCIDENTAL RELEASES

The 50-year committed dose equivalents from inhalation following a natural phenomena event of tornadoes or earthquakes were calculated by Watson and McPherson (Ref. 2) and presented in Table 3 below. Table 3 provides the dose to the nearest residence and to the population within an 80 km (50-mile) radius of the plant from tornadoes and earthquakes. The table provides calculations of doses using more likely estimates and conservative estimates for the source releases and dispersion (meteorological) which were treated as random variables. The most likely estimates were computed using the median (50%) values for source releases and dispersions and were assigned a probability of .95. (The median value was used as the approximate midpoint of the probability interval from 0 to 0.95.) The conservative estimates were calculated using 95% values and were assigned a probability of 0.05. The probabilities of possible sources and the probabilities of possible dispersions were thus discretized into two intervals, 0 to 0.95 represented by the median value and .95 to 1.0 represented by the 95th percentile. This breakdown of probabilities is gross, and care should be taken in interpreting any subsequent risk results to no more than an order of magnitude type of precision.

Figures 2 and 3 give the step function cc curves of doses to lungs and bones for the population within an 80 km (50-mile) radius of the plant due to damage from tornadoes. These complementary cumulative distributions give the probability per year that tornado-induced damage will result in doses greater than various values shown in the figures. Figures 4 and 5 provide the corresponding cc distributions of nearest resident doses for high winds. Figures 6 through 9 contain the corresponding step function cc distributions for earthquakes. These cc step functions and associated approximate confidence bounds have a similar interpretation as those presented for tornadoes.

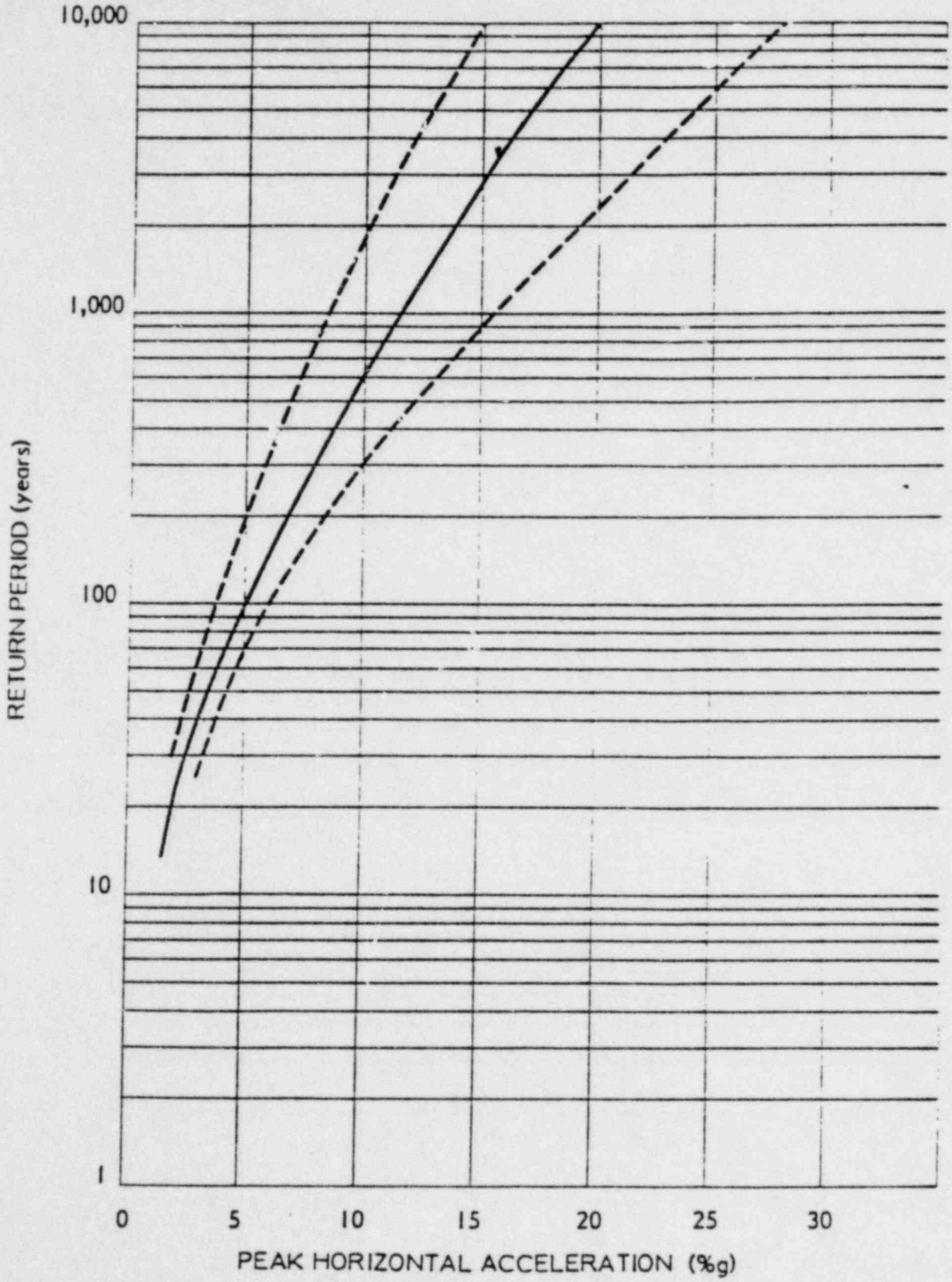


FIGURE 1

EARTHQUAKE RISK AT THE EXXON FACILITY

TABLE 3

FIFTY-YEAR COMMITTED DOSE EQUIVALENTS FROM INHALATION FOLLOWING NATURAL PHENOMENA EVENTS (CLASS Y MATERIAL)

		Population Dose (person-rem)				Dose at Nearest Residence (rem)			
Event	Organ	Case[a] I (0.90)	Case II (5E-2)	Case III (5E-2)	Case IV (3E-3)	Case I (0.90)	Case II (5E-2)	Case III (5E-2)	Case IV (3E-3)
Tornado wind Speeds									
150 mph	Lung	1.7E3	1.7E4	1.7E3	1.7E4	3.4E-2	3.4E-1	3.4E-2	3.4E-1
	Bone	2.5E3	2.5E4	2.5E3	2.5E4	5.0E-2	5.0E-1	5.0E-2	5.0E-1
190 mph	Lung	3.1E4	2.8E5	5.1E4	4.2E6	5.0E-1	5.0E0	7.8E-1	7.8E0
	Bone	4.5E4	4.1E5	7.4E4	6.1E6	7.3E-1	7.3E0	1.1E0	1.1E1
250 mph	Lung	1.9E4	1.3E5	2.6E4	1.2E6	3.7E0	3.7E1	4.1E0	4.1E1
	Bone	2.8E4	1.8E5	3.7E4	1.7E6	5.4E0	5.4E1	5.9E0	5.9E1
Earthquake Acceleration									
1.0g	Lung	1.6E4	1.1E5	2.2E4	3.6E5	2.4E0	2.8E1	2.7E0	3.1E1
	Bone	2.3E4	1.5E5	3.2E4	5.2E5	3.5E0	4.1E1	3.9E0	4.5E1

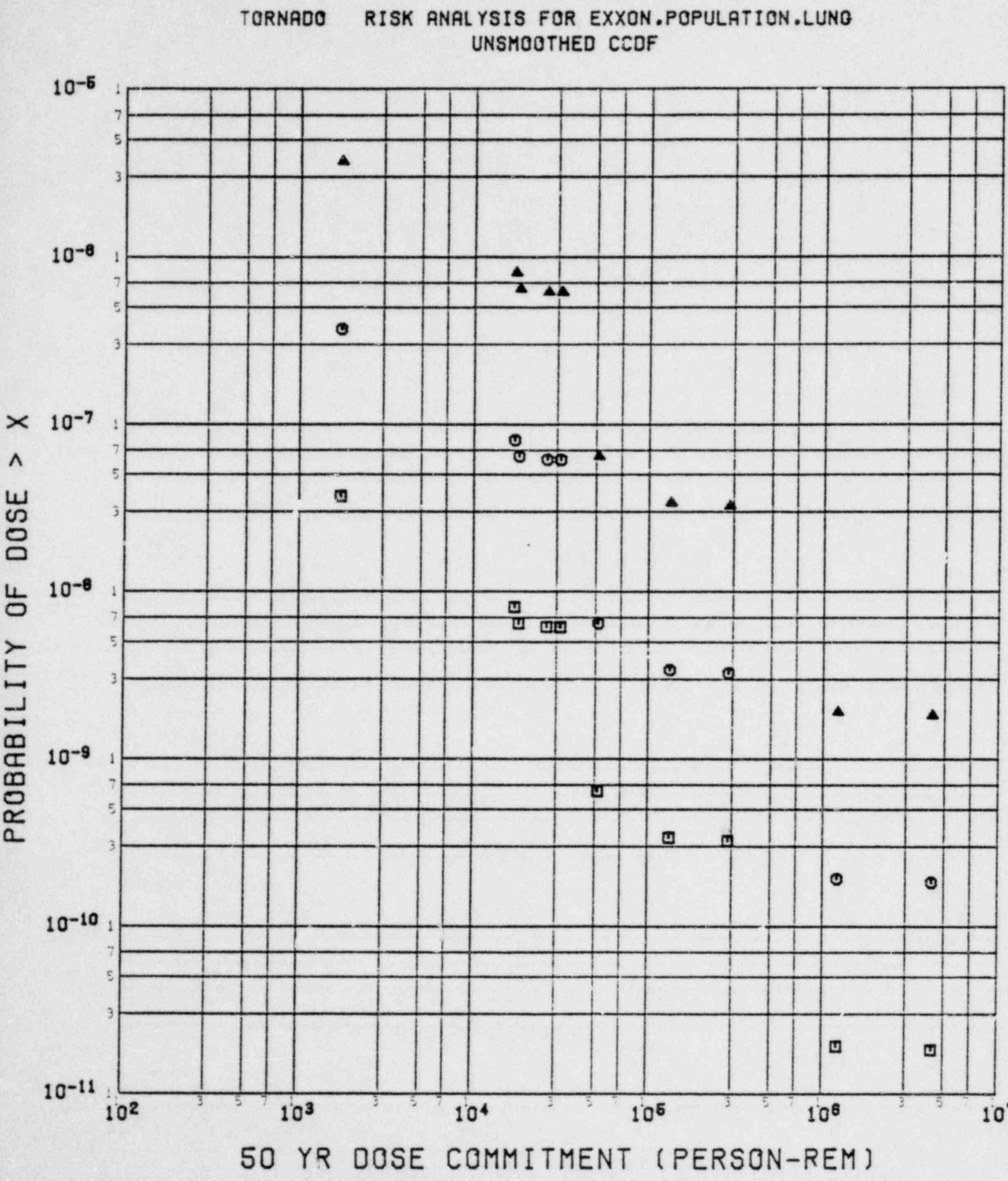
Case I: Most Likely Release (95%) and Most Likely Dispersion (95%)

Case II: Most Likely Release (95%) and Conservative Dispersion (5%)

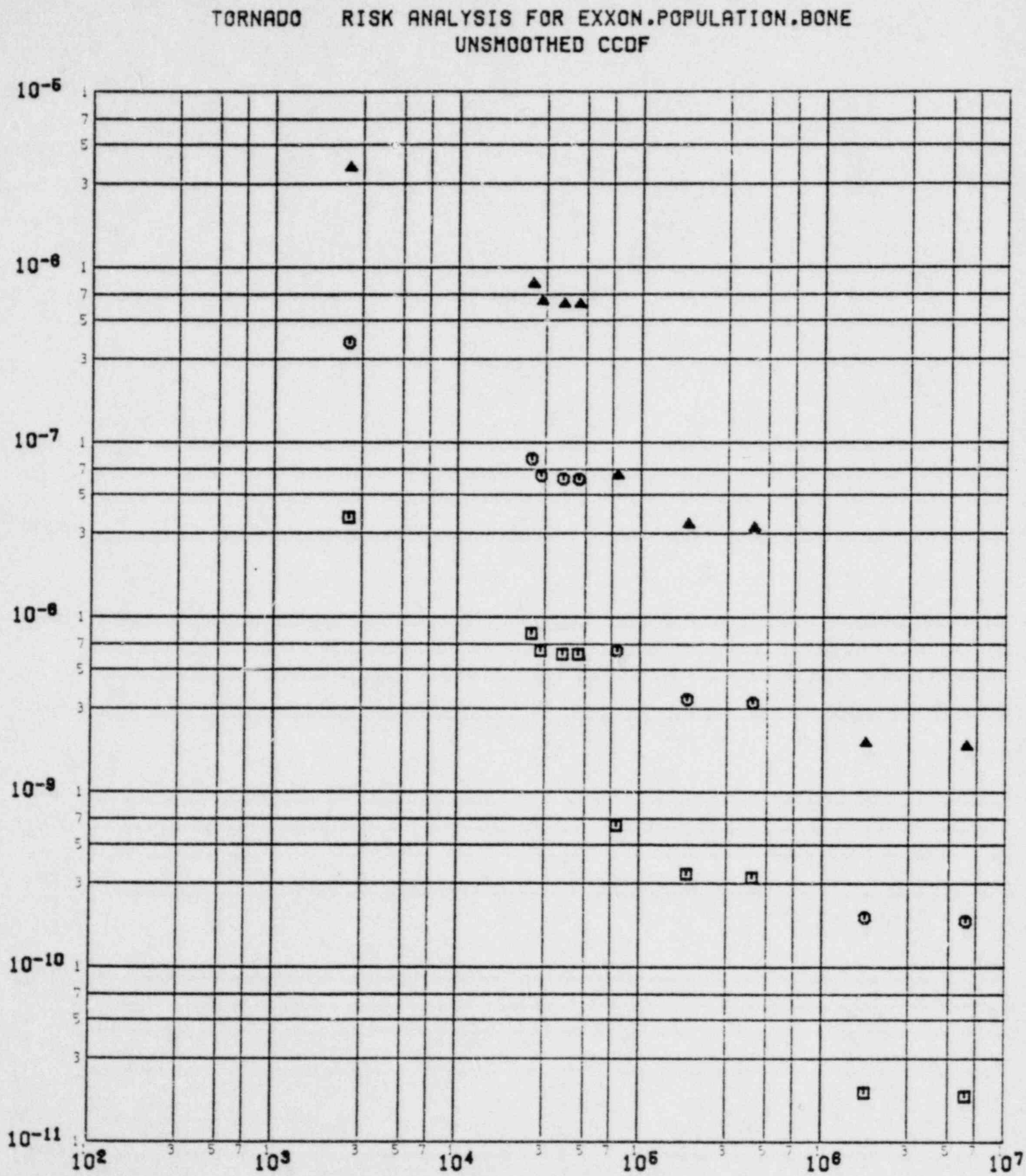
Case III: Conservative Release (5%) and Most Likely Dispersion (95%)

Case IV: Conservative Release (5%) and Conservative Dispersion (5%)

(a) The probabilities in parenthesis are the conditional probabilities given the event, where the conditional probabilities are calculated using best estimate or conservative value for source releases and dispersion.



TORNADO RISK ANALYSIS FOR EXXON.POPULATION.LUNG
UNSMOOTHED CCDF
PROBABILITY OF DOSE > X
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
50 YR DOSE COMMITMENT (PERSON-REM)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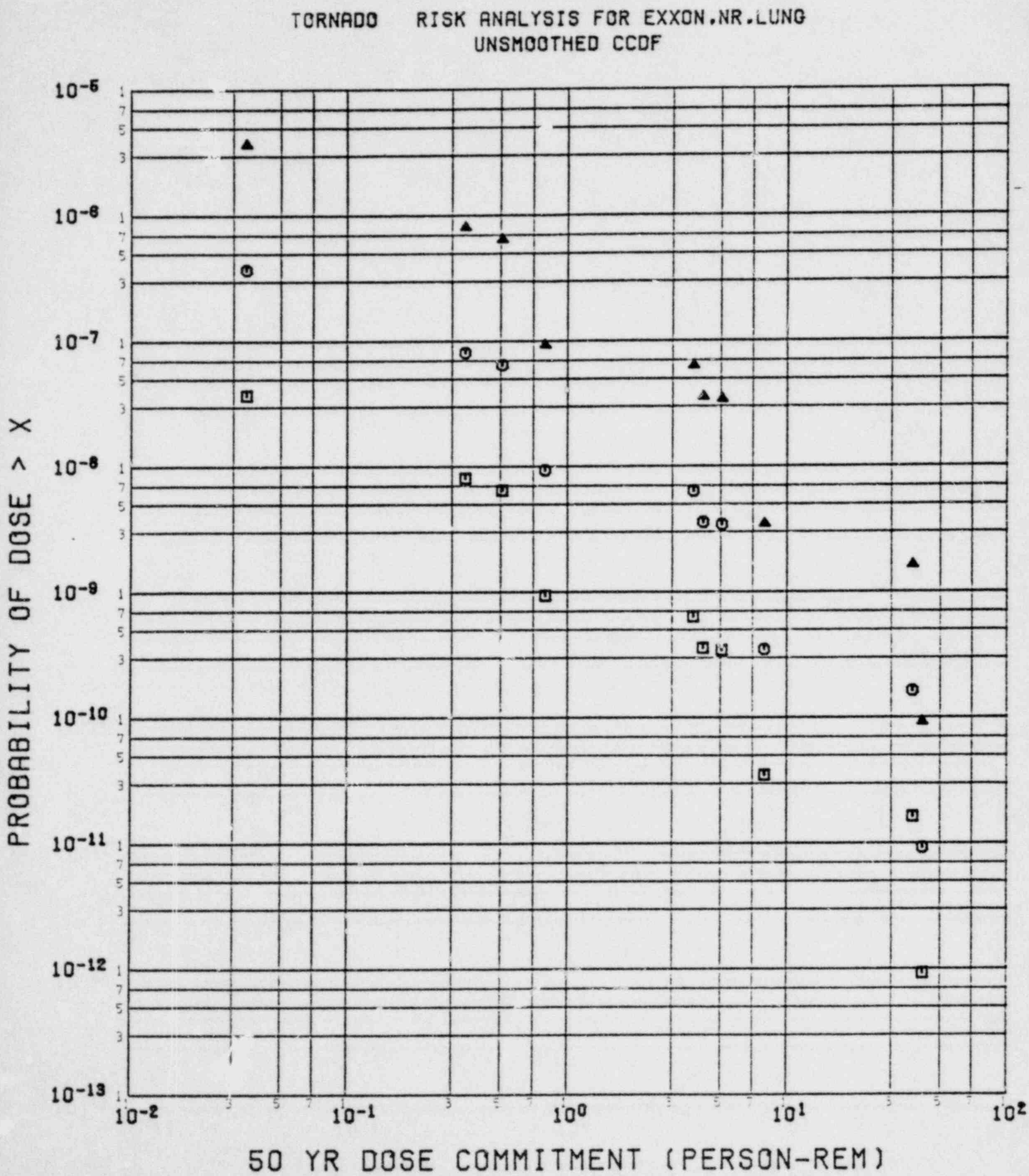
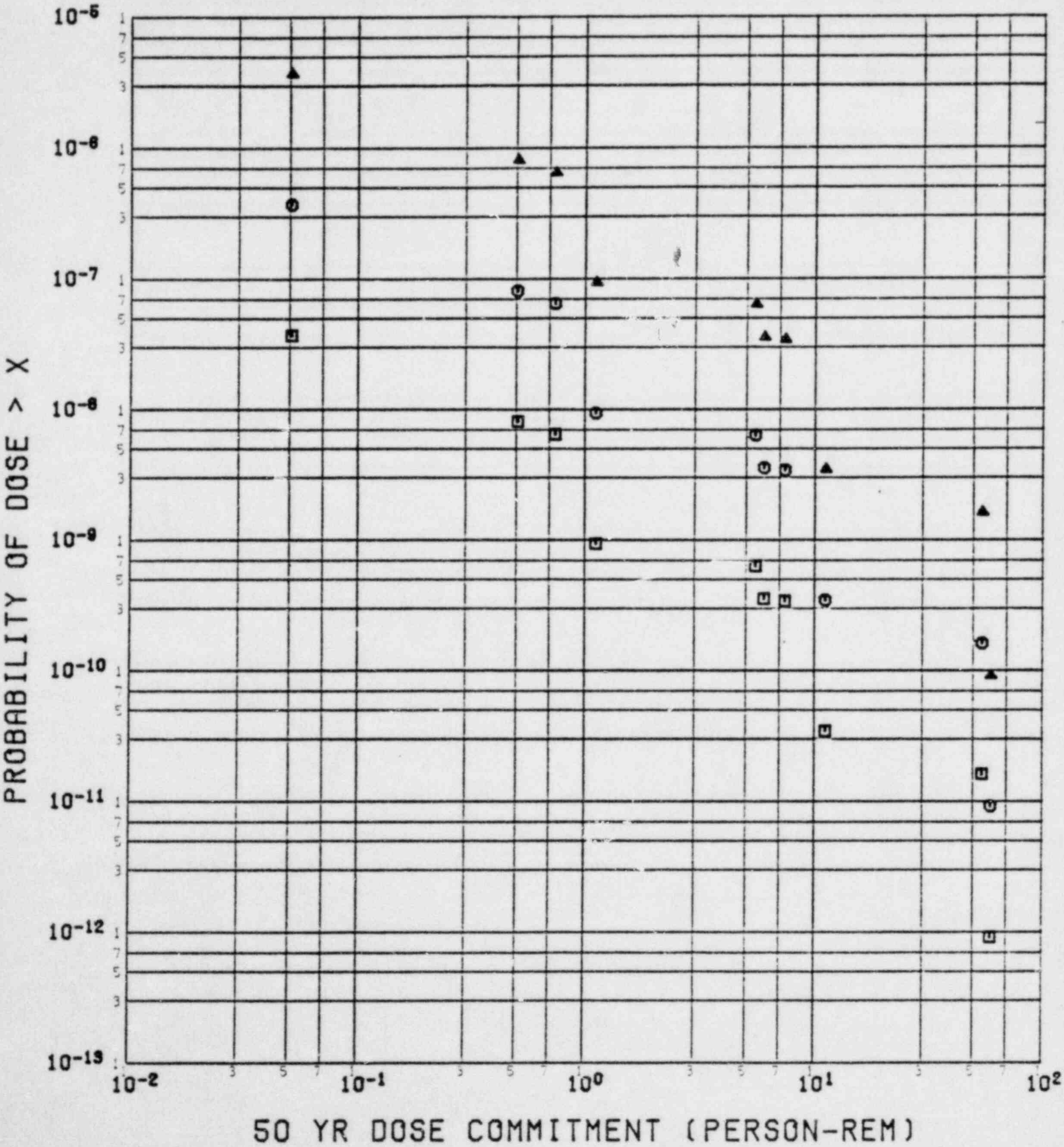
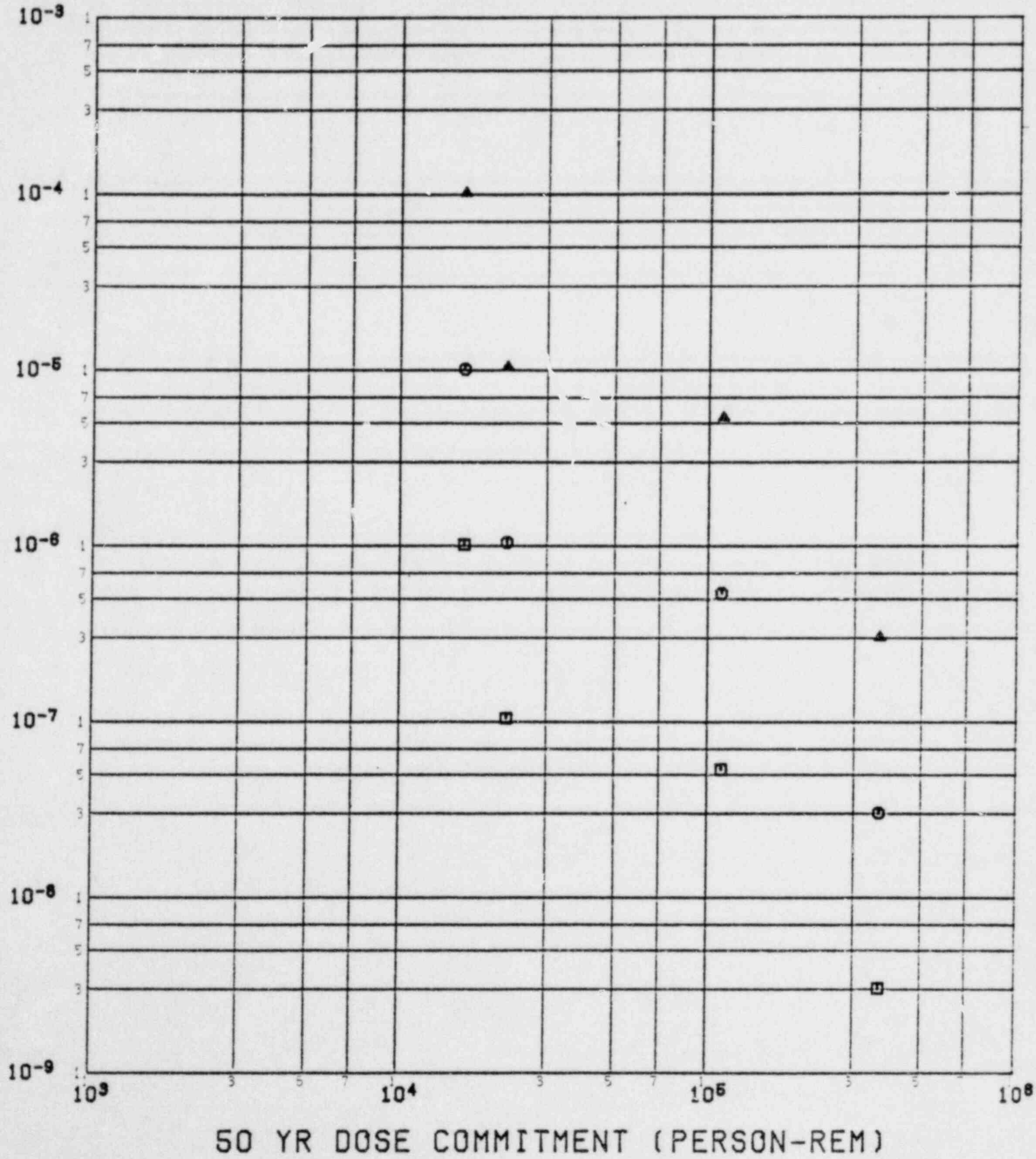
UNSMOOTHED CCDF
PROBABILITY OF DOSE > X
50 YR DOSE COMMITMENT (PERSON-REM)

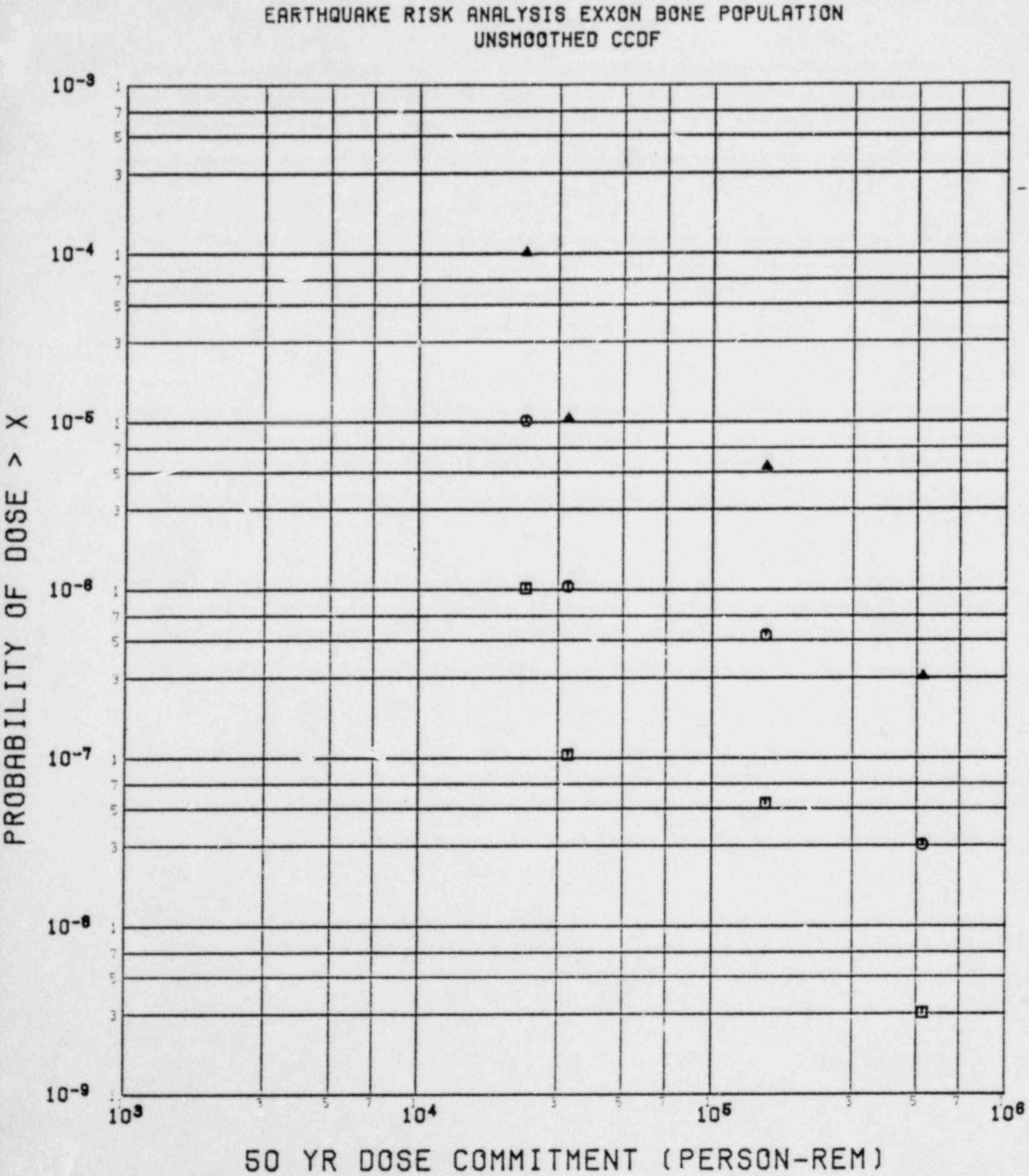

TORNADO RISK ANALYSIS FOR EXXON.NR.LUNG
UNSMOOTHED CCDF
PROBABILITY OF DOSE > X
50 YR DOSE COMMITMENT (PERSON-REM)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}

TORNADO RISK ANALYSIS FOR EXXON.NR.BONE
UNSMOOTHED CCDF

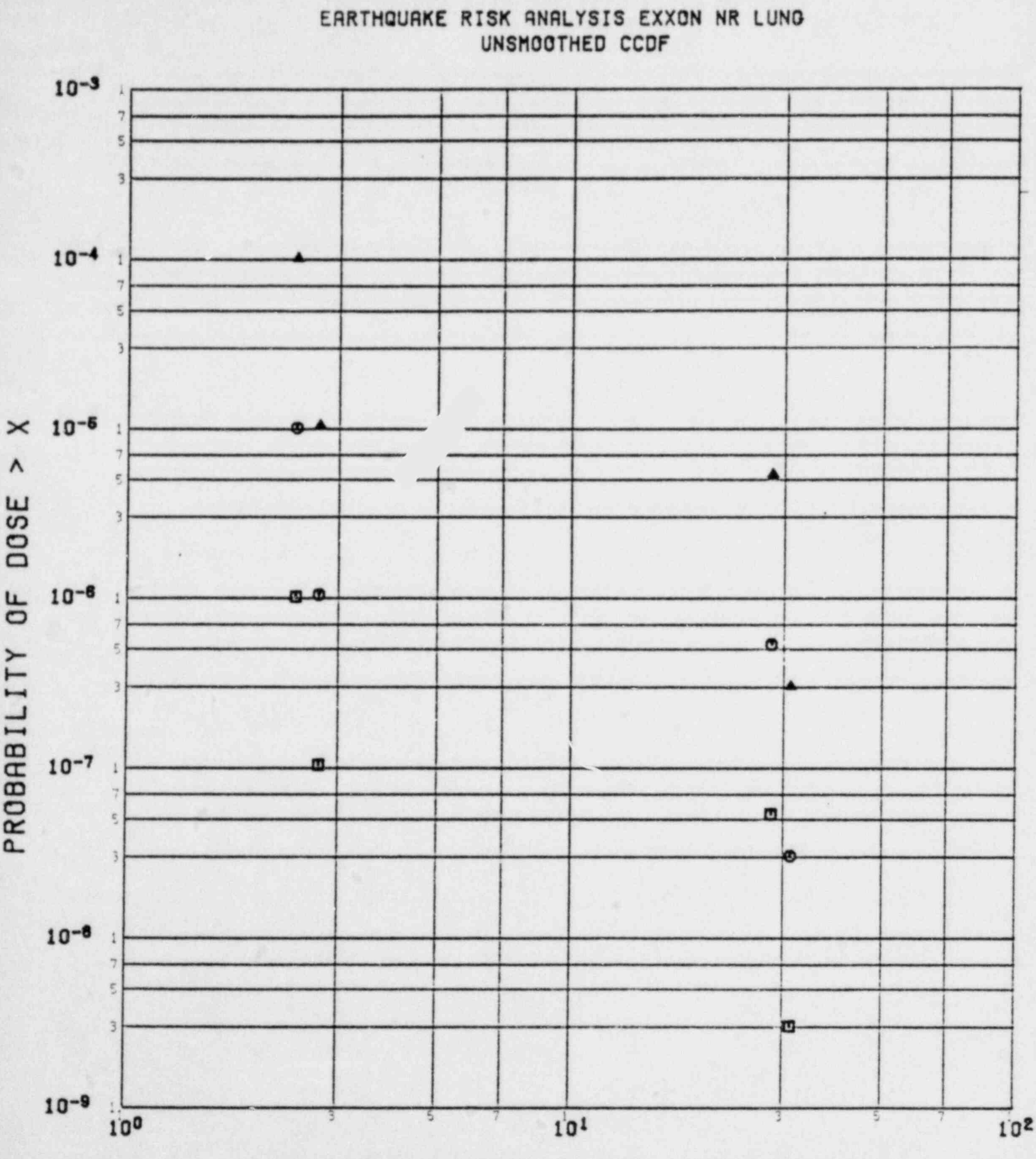


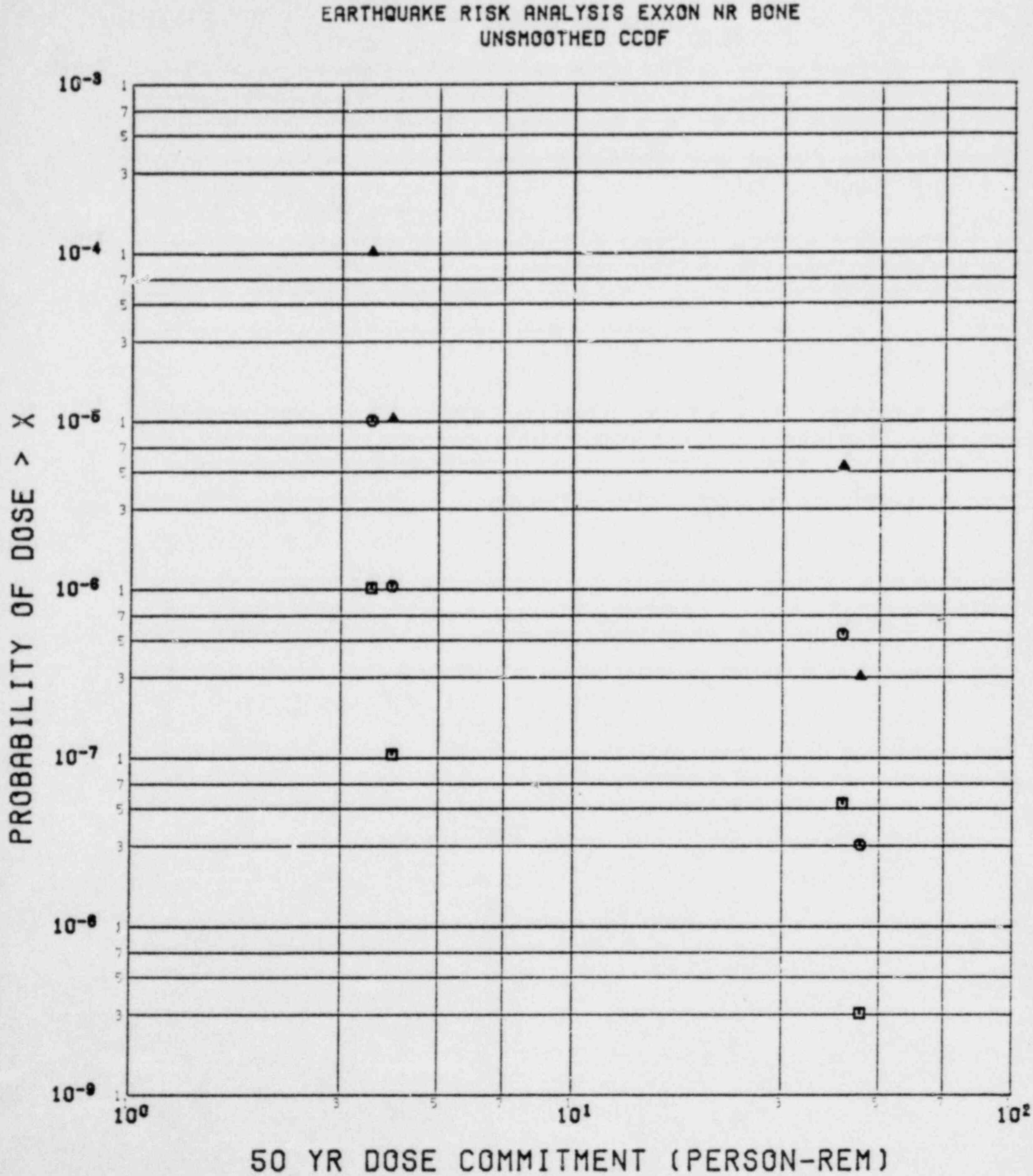
EARTHQUAKE RISK ANALYSIS EXXON POPULATION LUNG
UNSMOOTHED CCDF





EARTHQUAKE RISK ANALYSIS EXXON BONE POPULATION
UNSMOOTHED CCDF
PROBABILITY OF DOSE > X
10-3
10-4
10-5
10-6
10-7
10-8
10-9
10^3
10^4
10^5
10^6
50 YR DOSE COMMITMENT (PERSON-REM)


EARTHQUAKE RISK ANALYSIS EXXON NR LUNG
UNSMOOTHED CCDF
PROBABILITY OF DOSE > X
50 YR DOSE COMMITMENT (PERSON-REM)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{0}
10^{1}
10^{2}


EARTHQUAKE RISK ANALYSIS EXXON NR BONE
UNSMOOTHED CCDF
PROBABILITY OF DOSE > X
50 YR DOSE COMMITMENT (PERSON-REM)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{0}
10^{1}
10^{2}

For all figures, the confidence bounds on the smallest dose point included in the cc summation were used as the confidence bounds for the cc distribution. This approximation assumes the cc probability is dominated by the probability of the smallest dose point. If the assumption is not true (e.g., at smallest dose values of the cc curve) then the confidence bounds may be somewhat conservative. The confidence bounds used are those given earlier and summarized in Table 2. Because of the approximations used in obtaining them, the confidence bounds should be interpreted as only indicating the order of magnitude precision associated with the cc curves.

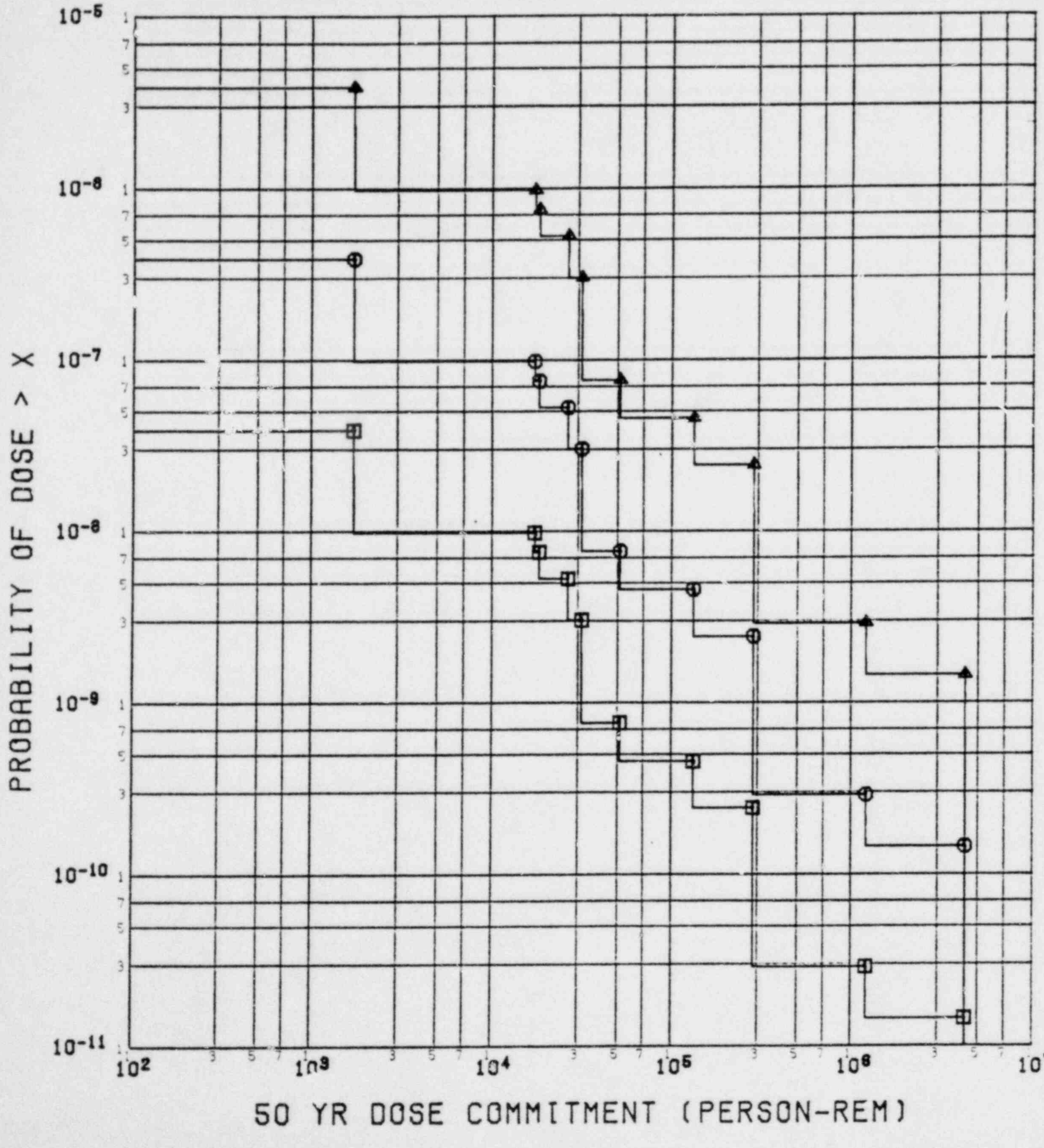
Figures 10 through 17 present the step function cc curves obtained by applying isotonic regressions to the probability mass functions (probability versus dose) used to construct the basic cc curves in Figures 2 through 9. The isotonic curves in Figures 10 through 17 are thus smoothed versions of the basic step function cc curves in Figures 2 through 9. Isotonic regression is a nonparametric method of smoothing the basic step function cc curves which does not require assuming specific distribution forms for the cc curve. (Other approaches are called parametric approaches and involve, for example, assuming that a Weibull distribution fits the points and then finding the parameters of the best Weibull.) Since the isotonic regression does not require as many assumptions as the parametric approaches, it is more suited to situations where there are relatively few points calculated for the cc curve--as was the case in this analysis. The isotonic regression approach, however, does have the disadvantage that it still produces step functions and not smooth, continuous curves. The isotonic regression method is explained in greater detail in the appendix to this report.

RISK TABLES

Table 4 tabulates the risk, defined as probability times consequence for the various events analyzed in Table 3. The risk tables indicate the contribution to the total risk from the various events considered. The total risk is the sum of the various contributions. The error factors on the risk contributions are roughly the error factors on the probability for the event, assuming the uncertainties on the probability estimates dominate (or at most, are comparable to the consequence uncertainties.*

*The error factors are the upper confidence level divided by the best estimate divided by the lower confidence bound.

TORNADO RISK ANALYSIS FOR EXXON.POPULATION.LUNG
SMOOTHED CCDF



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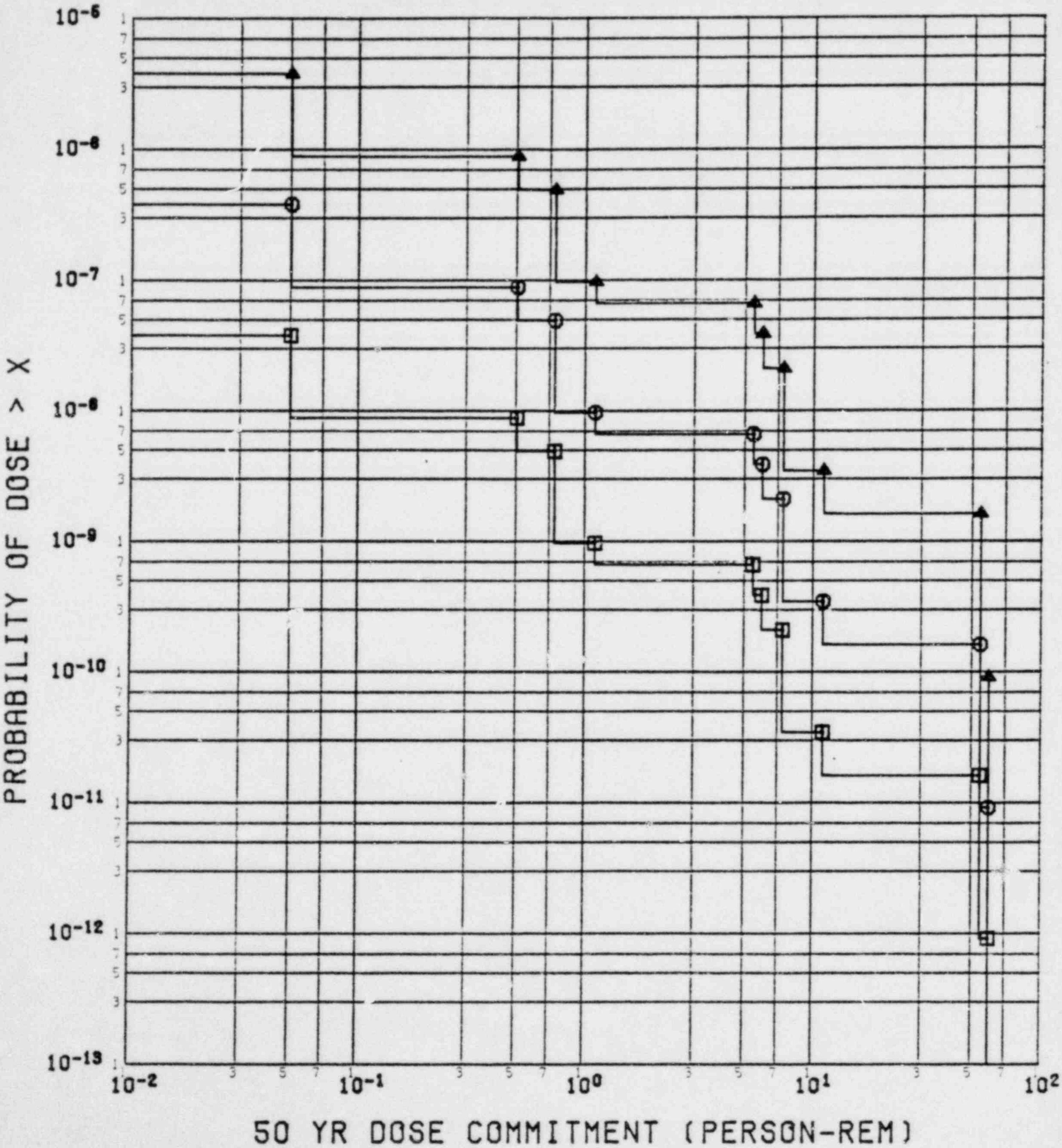
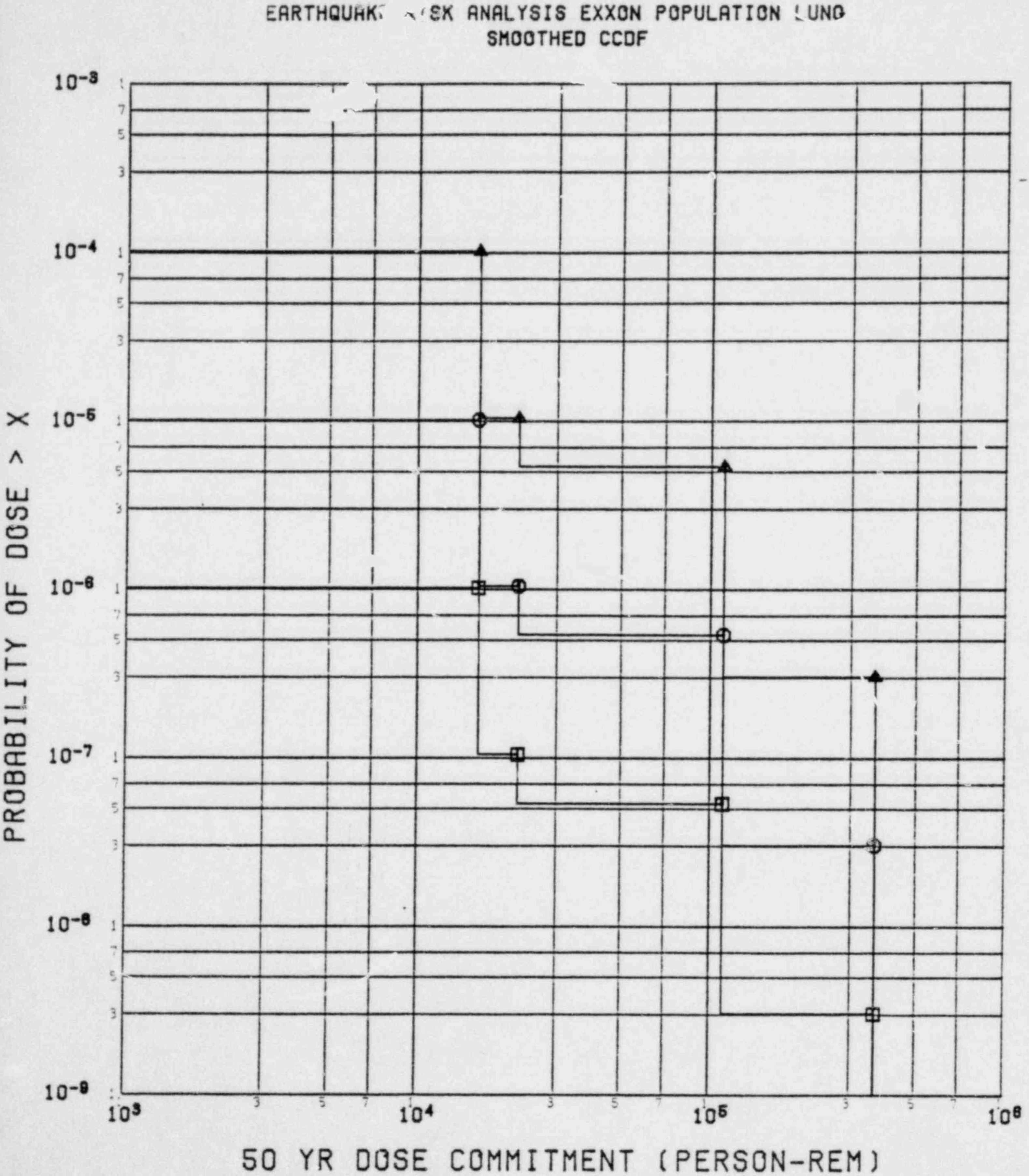
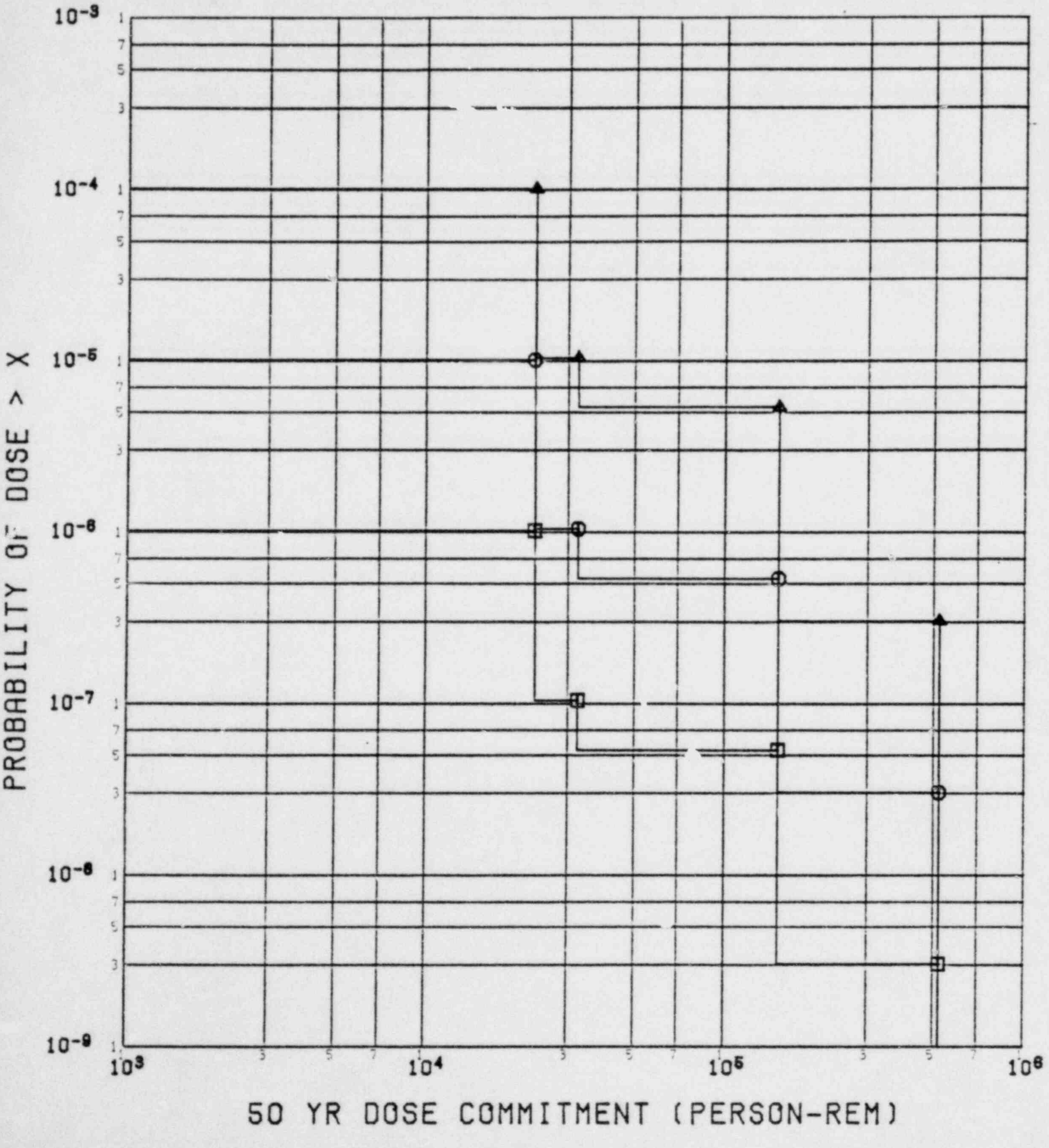
SMOOTHED CCDF

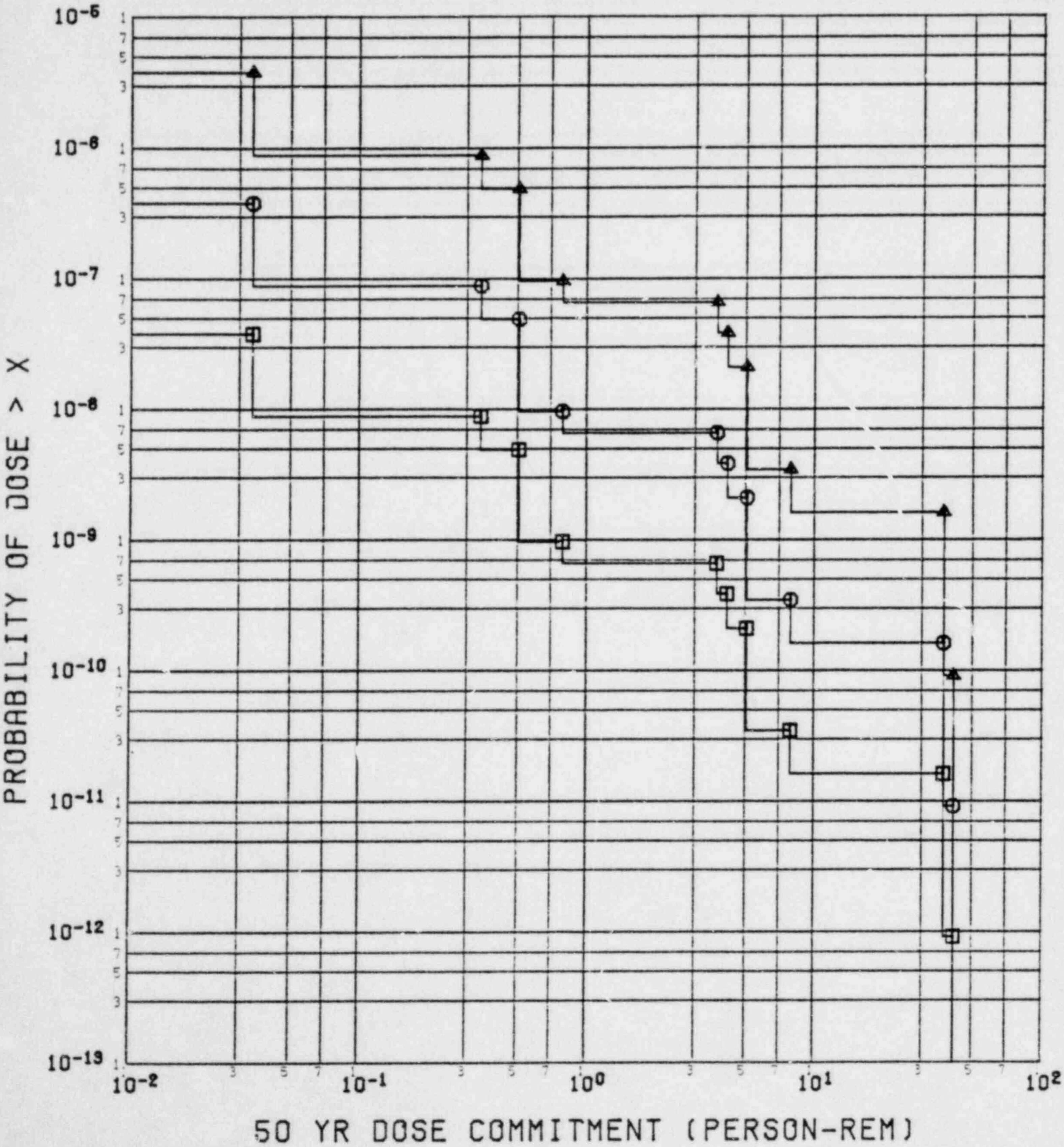


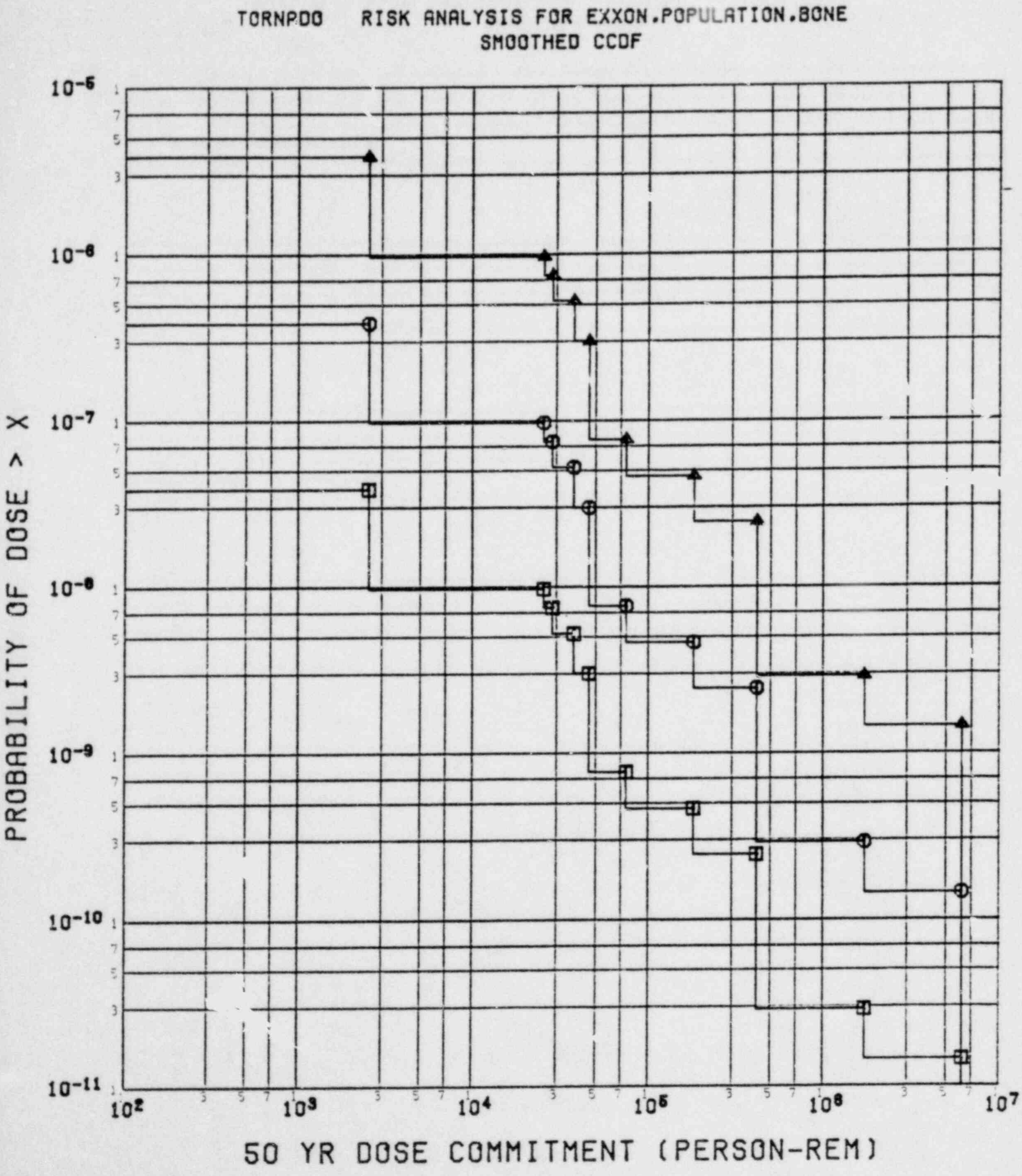

EARTHQUAK[illegible] [illegible]SK ANALYSIS EXXON POPULATION [illegible]UNG
SMOOTHED CCDF
PROBABILITY OF DOSE > X
50 YR DOSE COMMITMENT (PERSON-REM)

EARTHQUAKE RISK ANALYSIS EXXON BONE POPULATION
SMOOTHED CCDF

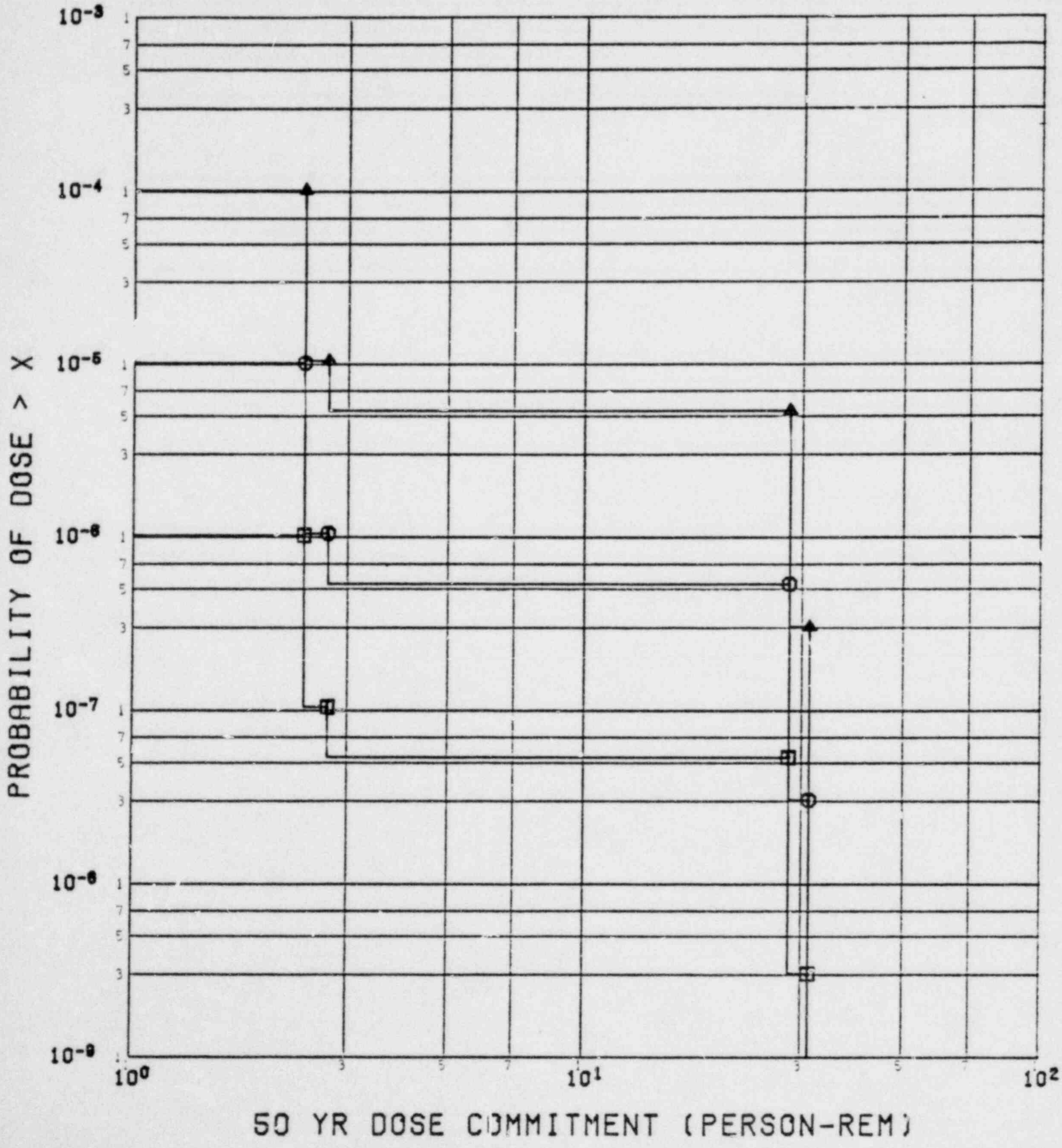


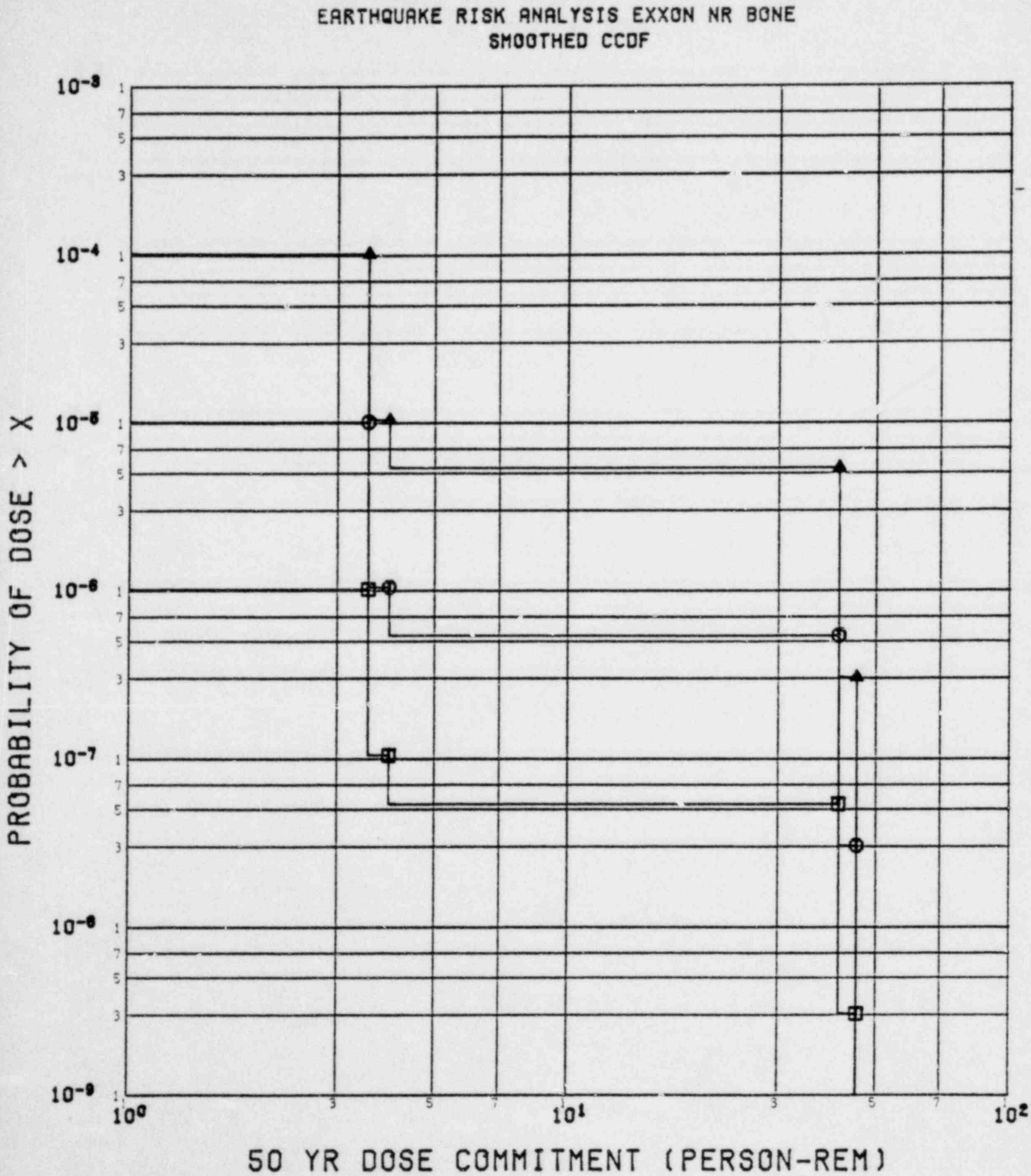
TORNADO RISK ANALYSIS FOR EXXON.NR.LUNG
SMOOTHED CCDF




TORNADO RISK ANALYSIS FOR EXXON.POPULATION.BONE
SMOOTHED CCDF
PROBABILITY OF DOSE > X
50 YR DOSE COMMITMENT (PERSON-REM)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}

EARTHQUAKE RISK ANALYSIS EXXON NR LUNG
SMOOTHED CCDF





EARTHQUAKE RISK ANALYSIS EXXON NR BONE
SMOOTHED CCDF
PROBABILITY OF DOSE > X
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{0}
10^{1}
10^{2}
50 YR DOSE COMMITMENT (PERSON-REM)

TABLE 4

RISK TO NEAREST RESIDENT AND NEARBY POPULATION FROM POSTULATED DAMAGE DUE TO NATURAL PHENOMENA

Event	Organ	Population Dose (person-rem) Case[a] I (0.90)	Case II (5E-2)	Case III (5E-2)	Case IV (3E-3)	Dose at Nearest Residence (rem) Case I (0.90)	Case II (5E-2)	Case III (5E-2)	Case IV (3E-3)
Tornado wind Speeds									
150 mph	Lung	4.6E-4	2.6E-4	2.6E-5	1.5E-5	9.2E-9	5.1E-9	5.1E-10	3.1E-10
	Bone	6.8E-4	3.8E-4	3.8E-5	2.3E-5	1.4E-8	7.5E-9	7.5E-10	4.5E-10
190 mph	Lung	1.7E-3	8.4E-4	1.5E-4	7.6E-4	2.7E-8	1.5E-8	2.3E-9	1.4E-9
	Bone	2.4E-3	1.2E-3	2.2E-4	1.1E-3	3.9E-8	2.2E-8	3.3E-9	2.0E-9
250 mph	Lung	5.1E-5	2.0E-5	3.9E-6	1.1E-5	1.0E-8	5.6E-9	6.2E-10	3.7E-10
	Bone	7.6E-5	2.7E-5	5.6E-6	1.5E-5	1.5E-8	8.1E-9	8.9E-10	5.3E-10
Earthquake Acceleration									
1.0g	Lung	1.4E-1	6.0E-2	1.0E-2	1.0E-2	2.2E-5	1.4E-5	1.4E-6	9.3E-7
	Bone	2.1E-1	8.0E-2	2.0E-2	2.0E-2	3.2E-5	2.1E-5	2.0E-6	1.5E-6

Case I: Most Likely Release (95%) and Most Likely Dispersion (95%)

Case II: Most Likely Release (95%) and Conservative Dispersion (5%)

Case III: Conservative Release (5%) and Most Likely Dispersion (95%)

Case IV: Conservative Release (5%) and Conservative Dispersion (5%)

(a) The probabilities in parenthesis are the conditional probabilities given the event, where the conditional probabilities are calculated using best estimate or conservative value for source releases and dispersion.

References

1. "Review of Severe Weather Meteorology at Exxon Nuclear Company, Inc., Richland Washington," T. T. Fujita, University of Chicago, March 31, 1977.

2. "Seismic Risk Analysis for the Westinghouse Electric Facility, Cheswick, Pennsylvania," Tera Corporation, 2150 Shattuck Avenue, Berkeley, California, 947-4, October 21, 1977.

. McPherson, R. B., and Watson, E. C., "Environmental Consequences of Postulated Plutonium Releases from the Exxon Nuclear MOFP, Richland, Washington, as a Result of Severe Natural Phenomena," Battelle Pacific Northwest Laboratory, Richland, Washington 99352, PNL-2984, February 1980.

4. Barlow, R. E., et. al., Statistical Inference Under Order Restrictions, The Theory and Application of Isotonic Regression, John Wiley and Sons, London, 1972.

APPENDIX

ISOTONIC REGRESSION (Ref. 5)

Isotonic regression was used to develop the risk curves in Figures 10 through 17. The only basic assumption in an isotonic regression is that the probability of dose to the population or to the nearest residence is non-increasing as the dose increases. The assumption is that the probability decreases (or is constant) as the consequence increases, which is not an unreasonable assumption for risk analyses. We should note that we make the monotonic assumption on the probability versus dose and not on the cc curve (which decreases by its definition). A general statement of our isotonic regression problem is as follows:

We are given a sequence of doses $(D_1, \ldots D_n)$ where $D_i \leq D_{i+1}$, $i = 1, \ldots n-1$ and we give estimates of the probability $\hat{P}(D_i)$ that the population or nearest residence receives dose D_i. We are interested in minimizing the expression:

$$\sum_{i-1}^{\hat{n}} \left[\hat{P}(D_i) - P(D_i)\right]^2 D_i$$

among all isotonic functions P on the sequence $(D_1, \ldots D_n)$. We call the function that minimizes this sum of sequences (P^*) the isotonic regression of $\hat{P}$. The isotonic regression is thus similar to a least squares type of analysis (a usual regression analysis) where we impose the restriction that $P(D_i)$ is non-increasing as D_i increases.

The Pool-Adjacent-Violators Algorithm was used to compute P*.

Plots of the isotonic regressions of P* versus dose are presented in Figures 10 through 17. The probability mass functions were used to obtain the isotonic curves.

The isotonic regression P* of $\hat{P}$ has the following desirable properties.

1. The isotonic regression P* of $\hat{P}$ minimizes the weighted squared error loss, i.e.:

$$\sum_{i=1}^{n} \left[P(D_i) - P^*(D_i)\right]^2 D_i \leq \sum_{i=1}^{n}\left[P(D_i) - \hat{P}(D_i)\right]^2 D_i$$

for any isotonic function P.

2. The isotonic regression P* of $\hat{P}$ minimizes the error in the risk, i.e.:

$$\max_i \left| \sum_{i=1}^{n} D_i P(D_i) - \sum_{i=1}^{n} D_i P^*(D_i) \right|$$

$$\leq \max_i \left| \sum_{i=1}^{n} D_i P(D_i) = \sum_{i=1}^{n} D_i \hat{P} (D_i) \right|$$