SENSITIVITY OF SEISMIC HAZARD RESULTS AT MILLSTONE TO LLNL STUDY ASSUMPTIONS ON ATTENUATION AND SEISMICITY

FINAL REPORT
TO
NORTHEAST UTILITIES

Dames & Moore

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INTRODUCTION

In April, 1984 the U.S. Nuclear Regulatory Commission released a seismic hazard study for nuclear plants in the eastern U.S. which was performed by the Lawrence Livermore National Laboratory (LLNL) (1984). Millstone Nuclear Power Station was one of the sites studied in that report; site-specific results were presented in terms of ground acceleration hazard curves and uniform hazard spectra.

The purpose of this study is to examine the results produced in the LLNL report for Millstone, and to assess their dependence and sensitivity to various assumptions made in the LLNL study. The basic methodology used in seismic hazard assessments today (including that used by LLNL) is well-accepted. The specific inputs to any analysis require some judgment; these inputs, and their effects on the calculated seismic hazard, are the focus of this study.

While the results presented here are precise and reliable, they do not constitute a full examination of, or a final position on, the LLNL study. Such an examination or position would be impossible to attain in the brief period since the LLNL report was released. Indeed, the LLNL study itself is in a preliminary form and has not had the benefit of outside review or of feedback from the seismicity and attenuation experts who participated in it. The final results issued by LLNL might change substantially as a result of the review and feedback process. The sensitivity results obtained here <u>do</u> indicate the quantitative effects of alternative assumptions, and thus indicate how seismic hazard estimates at Millstone might change as a result of the review and feedback process.

BASIC COMPUTATIONS

For purposes of comparison and sensitivity analysis at Millstone, we have selected a subset of the seismicity and attenuation model input used in the LLNL study. This has resulted in a workable number of seismic zones, parameters, and attenuation models.

The seismic zones used in this study are the "best estimate" zones in the northeastern U.S. indicated by each of the eleven seismicity experts. These are listed in Table 1; they were selected using Table 4.1 of the LLNL study which indicates the zones contributing most to hazard at Millstone. Figures 1 through 11 shows these zones plotted on a map of the northeastern U.S. The seismicity parameters used (upper-bound magnitude or intensity, "a" and "b" values) are the "best estimate" values indicated by each seismicity expert (Table A3 of the LLNL report).

The six attenuation functions most heavily weighted by the four LLNL attenuation experts were selected to estimate peak horizontal ground acceleration and spectral velocity for 5% damping. These functions are listed in Table 2, along with the weights placed on these functions by the attenuation experts. (To compute overall weights we elected to give each of the four attenuation experts a credibility of 0.25.) These weights constitute some 85% (for acceleration) to 92% (for spectral velocity) of the credibility assigned to ground motion functions by the experts; the results obtained using these six functions can be considered representative of what would be obtained if all attenuation functions had been used.

The uncertainty in ground motion was modeled here with a standard deviation of the natural logarithm of ground motion equal to 0.6. This is representative of the values specified by the attenuation experts for ground acceleration and spectral velocity, with the exception of one expert who preferred a best estimate value of 0.9 for spectral velocity. This difference will not have a substantial effect on the sensitivity results to be presented below.

Nine of the seismicity experts elected to represent seismicity with body-wave magnitude m_b, and two (numbers 1 and 5) used Modified Mercalli (MM) intensity for the northeastern U.S. Experts number 1 and 10 suggested special relationships between m_b and MM intensity; the others deferred to the Nuttli-Herrmann relationship presented below as equation (3). All of these preferences were considered and used to develop the proper relationship between seismicity and ground motion estimates for each seismicity expert.

A basic set of results was produced to replicate the LLNL calculations and ensure that no errors in input had been made. This set of results was obtained using the best estimate seismic zones and parameters, and the best estimate attenuation models for acceleration. Two LLNL attenuation experts chose the Nuttli (1983) model, one chose the Campbell (1982) model and one chose the Trifunac (1976) model. The resulting probabilities of exceedance at various acceleration levels for these attenuation models and each seismicity expert were then averaged. The resulting probabilities of exceedance, which LLNL labels the "best estimate" results, are shown in Figure 12 as reported by LLNL (in its Figure MI-1). Our attempt to duplicate these results is also shown in Figure 12 and is labeled "This study - average of best estimates." Our results lie slightly below the LLNL "best estimate" curve because we have not modeled all seismic zones and have elected to use approximate, more efficient calculational procedures, but the two top curves in Figure 12 are generally in reasonable agreement.

Also shown in Figure 12 is our median hazard curve for Millstone, produced using the normalized weights shown in Table 2 for the attenuation functions and weighting all seismicity experts equally. The median curve lies below the average-of-best-estimate curve by a factor of about 0.5 in probability. This indicates, in a loose way, the difference between median and mean results for highly-skewed distributions of probabilities of exceedance. As most of the results in the LLNL study are presented in terms of constant percentile (median and fractile) hazard curves, we use the median curve in Figure 12 as our base

case, and compare later results to it. This curve (and others compared to it) were produced by sixty-six hazard analyses (eleven experts times six attenuation functions).

EFFECTS OF ATTENUATION EQUATIONS

The first effect examined is that of the weights assigned to the attenuation functions. The six attenuation functions are plotted in Figures 13 through 15 for peak ground acceleration and 5% damped spectral velocity at 9 and 5 hz, respectively. The spectral velocity curves labeled RS4 and RS5 were only available at 10 hz, which was considered a close enough approximation to 9 hz to warrant their use. The Trifunac (1976) and Trifunac-Anderson (1977) curves (labeled G16 and RS6, respectively - see Table 2) lie substantially above the others at distances greater than 10 km, for several reasons. Among them is that the original Gupta-Nuttli (1976) intensity attenuation (based on isoseismals) was used, rather than the modified version of this function. A second reason which is particularly important for Millstone is that the form of these equations contains a term exp(cS), where S is a variable indicating soil conditions (0 for soft soils, 1 for medium soils, 2 for rock). Most of the data on which the calibration was based was for conditions 0 and 1, so the use of the equatio for rock sites (S = 2) constitutes an extrapolation based on the functional form of the equation, rather than on data. Moreover, the most recent attenuation equations in California indicate little effect of soil conditions on peak acceleration. The Trifunac form might be more acceptable if the intensity attenuation equation with which it is used was based on intensity values at rock sites (not on isoseismals drawn for all sites including high intensity, soft soil conditions as usually exist in towns located in river valleys) but this has not been done. A justifiable alternative is to drop the Trifunac (1976) and Trifunac-Anderson (1977) curves from the analysis on the basis that they are overly conservative for a mean-centered analysis.

To accomplish this, we used the "alternative normalized weights" shown in Table 2 to weight the remaining five attenuation functions. This has the effect of removing the Trifunac equations from the analysis and redistributing its weight among the other five attenuation functions.

The resulting median hazard curve for peak acceleration is shown in Figure 16. The change in hazard varies with acceleration level: at the SSE level (170 cm/sec^2) the probability at a given acceleration level decreases by about 25% and the acceleration at a given probability level decreases by about 10%. For a typical slope of the hazard curve these two changes are related by:

$$\text{(ground motion reduction factor)} = \text{(probability reduction factor)}^{.375} \qquad (1)$$

For example, $(.90) = (.75)^{.375}$. At high accelerations the alternate weights imply a slightly higher hazard than the base case.

Figure 17 shows equivalent results for spectral velocities at 9 hz and 5 hz. Here the effect of alternate attenuation weights is larger: at 10 cm/sec, spectral velocities decrease by about 40% in probability or 17% in spectral velocity. We conclude that the effects of attenuation functions on spectral velocities are not necessarily well-estimated by comparisons based on ground acceleration. The reason is related in part to the larger range in estimates for spectral velocity than for peak acceleration (compare m_b = 5.0 at 20 km in Figure 13 to Figures 14 and 15).

EFFECTS OF ACTIVITY RATE

One area which was left entirely to the seismicity experts in the LLNL study was the estimation of seismicity parameters (activity rates and b-values) from the seismicity catalog. Each expert was supplied with lists of historical seismicity, one list for each of the expert's zones. The list apparently included all events of MM intensity $\geq$ IV or $m_b \geq 3.75$. Aftershocks, where

identified by original sources, were tagged. Given such a summary of historical seismicity, producing meaningful estimates of activity rates and b-values is not a trivial task. One must divide the data into magnitude ranges, determine intervals of completeness for each range, select a method of mathematically fitting an equation to the data, perform the fitting process, plot the data both in the frequency sense (number of events within a magnitude range) and in the cumulative sense (number of events greater than a given magnitude), and assure oneself that the data, the functional form, and the calculated parameters are consistent. It is very difficult to allocate the time and resources to go through this estimation process rigorously for every seismic zone in the eastern U.S. How this task was accomplished by each expert is not reported in the LLNL study.

There is some evidence that the methods used by the experts to assess rates of activity have, in many cases, produced conservative estimates. These conservatisms may have been the result of one or more factors:

- o inclusion of all MM intensity IV events as $m_b > 3.75$,
- o inclusion of aftershocks in the data base,
- o use of the Nuttli-Herrmann (1978) intensity-to-magnitude conversion in New England, and
- o imperfect methods used to fit equations to seismicity data.

On the first point, the Nuttli-Herrmann (1978) intensity-to-magnitude conversion estimates $m_b = 3.75$ for intensity IV, but (even assuming that this conversion is correct) this magnitude value is more properly represented by the range $m_b = 3.5$ to 4.0. Thus the data presented to the experts are better characterized as all events with $m_b > 3.5$ (when estimated from intensity) plus all instrumental magnitudes of $m_b > 3.75$.

As to the second point above, the experts were notified by LLNL that the data base contained aftershocks, but there is no indication of if, or how, these events might have been removed or otherwise accounted for. If labeled aftershocks were not removed, this would account for about a 12% increase in perceived activity rate.

On the third point, there is some evidence (e.g. Weston Geophysical Corp, 1982) that the Nuttli-Herrmann (1973) conversion, derived for the central U.S., may not be appropriate for New England. While this point is controversial and there certainly is no scientific consensus on it, the recent instrumental seismicity suggests that use of the Nuttli-Herrmann conversion in New England over-estimates rates of activity (see figures described below). Thus if one asserts that the Nuttli-Herrmann intensity conversion applies to New England, then one must also accept the assumption that either:

- the exponential magnitude law does not hold over the m_b range 2.0 to 6.0, or
- rates of seismicity in New England have declined in the last seven years, relative to the previous several hundred years, or
- the instrumental record in central New England is incomplete for m_b >2.0 over the last seven years.

While any of these assumptions might be defended, each is unlikely. For a description of instrumental seismicity coverage in New England, refer to Ebel (1984).

To etermine the effect of alternate methods of estimating activity rates, we adopted the following procedure:

(a) historical MM intensities for New England were converted to m_b using the relation (Weston Geophysical Corp., 1982):

$$m_b = (I_o + .44)/0.67 \qquad (2)$$

(b) periods of completeness were chosen for each magnitude interval from the present back to a time just prior to an apparent decrease in activity rate (under the assumption that intervals for larger magnitudes were longer than, or equal to, intervals for smaller magnitudes),

(c) activity rates for $m_b \geq 3.75$ and b-values were computed for each zone using the best available statistical procedure (Weichert, 1980), and

(d) the 66 hazard analyses for peak acceleration were re-run using the alternative rates and b-values.

The Dames & Moore seismicity data base was used for the analysis. For New England this consists of the Chiburis earthquake catalog through 1982 with the revised event locations and magnitudes determined by Dewey and Gordon (1983). The only exceptions to this procedure were for seismicity experts 1 and 10 who chose to characterize seismicity using MM intensity. For these experts the seismicity characterization was not changed.

Figures 18 through 20 show seismicity data for zones 31, 7, and 4 specified by experts 2, 3, and 6, respectively. These zones were selected for presentation because they include only the New England area where data from the New England seismic net are relatively complete down to the magnitude 2.0 level at least, since 1976. Three sets of data are shown on these figures. The x's indicate cumulative rates of seismicity from historical data using the Nuttli-Herrmann conversion to estimate m_b from intensity:

$$m_b = 0.5\ I_o + 1.75 \qquad (3)$$

For these cumulative rates, completeness intervals were established as described in step (b) above.

The squares in Figure 18 through 20 indicate cumulative rates calculated in an equivalent manner using equation (2) instead of equation (3) to estimate m_b from I_o. The circles indicate cumulative rates calculated from instrumental seismicity from the New England seismic net (Pulli, personal communication,

1984) for the period October 1975 to March 1982. Both sets of data generally lie below the rates which are obtained if the Nuttli-Herrmann conversion is used for New England. Note that the instrumental rates at $m_b = 4.5$ and 4.0 should not be given much weight; they are determined from occurrences of one and two earthquakes, respectively. On the other hand, the rate for $m_b = 2.0$ is determined from 140 or 150 earthquakes. The bars attached to the circles show one-standard-deviation bounds, calculated as the square root of the number of observations divided by the interval of completeness. The bars graphically reinforce the last two observations about small and large sample sizes.

The dashed line on the figures indicated the seismicity distribution implied by each expert's choice of a and b-value. (The use in the LLNL study of a non-linear range between $m_b = 3.75$ and some other value of m_b specified by each expert where the semi-logarithmic plot becomes linear -- see LLNL report page A40 -- has little effect and is not followed in this study.) The dashed lines in Figures 18 through 20 are consistent with each expert's specification of a and b-value. These dashed lines are generally conservative estimates of the data, for the reasons discussed above. For example, the x's in Figures 18 through 20 at $m_b = 3.5$ were determined using all earthquakes given to the seismicity experts by LLNL and which were represented by LLNL as all events with $m_b > 3.75$. Thus there may be a quarter-magnitude-unit bias in the dashed lines compared to the x at $m_b = 3.5$.

The solid lines indicate the fit to the squares obtained by the maximum likelihood procedure. This representation of seismicity lies below that indicated by each expert, and is more consistent with instrumental seismicity rates. In particular, the solid lines represent relatively well the cumulative rate of activity at $m_b = 2.0$ (which is well-constrained with instrumental data) and for $m_b \geq 4.5$ (where differences from the conversion of historical data to magnitude by different means are relatively small and hence not controversial). Thus the solid lines are reasonable alternatives with which to examine the sensitivity of hazard results to the experts' choices of activity rates (and b-values), vis-a-vis others.

Figure 21 shows the median acceleration hazard curve over all eleven seismicity experts and six attenuation functions for Millstone, obtained using the alternative activity rates and b-values. Also shown is the base case, for comparison. In general there is a reduction of 25% in probability or 10% in acceleration implied by the alternative rates. Spectral velocity results are similar and are shown in Figure 22.

EFFECTS OF LOWER-BOUND MAGNITUDE $m_{b,min}$

One of the parameters specified by the LLNL methodology (not by the seismicity or attenuation experts) is the lower-bound magnitude $m_{b,min}$. A value of 3.75 was used in that study (or intensity IV, for experts who preferred intensity). This is quite conservative, at least for the assessment of seismic hazard to nuclear plant structures and major equipment, in that damage to engineered structures and equipment is not known for earthquakes of magnitude less than about 5, regardless of the ground motions these events generate. Thus the inclusion of ground motion hazard from smaller events increases the mathematical risk but provides a conservative estimate of hazard for ordinary plant structures and components.

The effect of choosing different lower bounds was examined by using the experts' a and b-values, computing an activity rate for each zone assuming $m_{b,min}$ = 5.0, and recalculating seismic hazard for that lower bound and activity rate. The process was repeated for $m_{b,min}$ = 4.5. The results for each case are shown in Figure 23. The median curve for $m_{b,min}$ = 5.0 is about 55% lower in probability (25% lower in acceleration) than the base case. The changes for $m_{b,min}$ = 4.5 are 35% in probability and 15% in acceleration. Thus the choice by LLNL of $m_{b,min}$ = 3.75 has a major effect; the use of a more realistic lower bound for structures and mechanical equipment would lead to significant changes in the median hazard curve.

Results for spectral velocities at 9 and 5 hz are shown in Figure 24. The 9 hz results lead to the same conclusions as for acceleration, namely that the use of $m_{b,max}$ = 3.75 is extremely conservative over more realistic alterna-

tives, by a factor of 15% to 25% in spectral velocity. For 5 hz, spectral velocity is governed by the ground-velocity-amplified portion of the response spectrum for magnitudes below $m_b = 5$, and these contribute little to the seismic hazard results, so the curves are not sensitive to the choice of lower bound for spectral velocities below about 10 cm/sec.

SUMMARY

Several assumptions and analyses used in the LLNL report have a major impact on the seismic hazard at Millstone. The preliminary nature of the LLNL study, and the importance of these assumptions, require that care be taken in interpreting the LLNL results. Alternative choices and assumptions made in the future, during the review and feedback tasks, likely will lead to lower hazard curves in future reports.

A quantitative estimate of the possible size of these effects is summarized in Table 3 for accelerations around 170 cm/sec^2 and spectral velocities around 10 cm/sec. The combined reduction in spectral velocities for the effects examined here is in the range of 30% to 34% (reduction factor of .66 to .70). The corresponding reduction in estimated probability level for a given spectral ordinate is 61% to 67% (reduction factor of .39 to .33). This implies, for example, that the uniform hazard spectrum currently identified by LLNL as having a 1000-year return period for Millstone, would have a revised estimate of return period of about 3300 years.

Thus, removing the major conservatisms identified in a preliminary review of the LLNL work means that the spectral amplitudes for a given probability level would decrease significantly. A visual representation of the effect is shown on Figure 25. The peak ground acceleration hazard curve developed by Northeast Utilities is shown as the solid line, and compared to it are several original and revised hazard curves from the LLNL study. The long-dashed curves (labeled "SHCP" for "Seismic Hazard Characterization Program") are LLNL median curves, as originally published and as revised by reducing the accelerations at a given probability level by the reductions shown in Figures 16, 21, and 23 to

remove conservatisms. The revised median curve lies much closer to the Northeast Utilities' result: at the SSE level the two curves agree within a factor of 2 in probability.

Figure 26 shows original and revised hazard curves from the LLNL-SHCP study, for three fractiles (the median, 15%, and 85%). This shows that the original LLNL-SHCP median curve lies almost at the revised 85% fractile curve, illustrating the conservatism associated with the preliminary LLNL results.

With these preliminary revisions, it is clear that the LLNL study results are consistent with those of the Applicant, given the uncertainty in seismic hazard calculations. There are strong scientific justifications for the revisions we describe; use of the original LLNL results to evaluate seismic safety at Millstone is inappropriate, given the preliminary and conservative nature of the LLNL results.

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TABLE 1

SEISMIC ZONES USED

LLNL SEISMICITY EXPERT	ZONES
1	20,22
2	31,32
3	6, 7
4	16,18,19,23
5	1
6	4
7	15,24
10	2,4,22
11	1,5
12	3,16,17,18
13	10,11,12

TABLE 2

ATTENUATION EQUATIONS USED

LLNL No.	Attenuation Equation	LLNL* Weight	Normalized Weight	Alternative Normalized Weight
	Acceleration:			
G16	Trifunac (1977) + Gupta-Nuttli	0.25	0.291	0
D21	Nuttli (1983)	0.24	0.280	.395
D13	Campbell (1982)	0.175	0.204	.288
G53	Weston (1983)	0.075	0.088	.123
D12	Campbell (1981)	0.063	0.073	.104
D14	Nuttli (1979)	0.055	0.064	.090
	Total	0.858	1.000	1.000
	Spectral Velocity:			
R56	Trifunac-Anderson (1977) + Gupta-Nuttli (1976)	.263	.286	0
RS3 (101)	Newmark-Hall + Campbell (1982) and Nuttli (1983)	.225	.244	.342
RS3 (110)	Newmark-Hall + Nuttli (1983)	.200	.217	.304
R55	SEP-RS5	.088	.096	.134
R54	SEP-RS4	.075	.081	.114
R52	ATC + Nuttli (1983)	.070	.076	.106
	Total	.921	1.000	1.000

* Calculated by weighting all four attenuation experts equally

TABLE 3

SUMMARY OF CHANGES* TO LLNL HAZARD RESULTS
(At 170 cm/sec^2 Ground Acceleration and 10 cm/sec Spectral Velocity)

	EFFECT				
			$m_{b,min}$		
Parameter	Attenuation	Activity Rates	4.5	5.0	Combined
Peak	.75/.90	.72/.88	.66/ .86	-	.36/.68
Acceleration	.75/.90	.72/.88	-	.42/ .72	.23/.57
Spectral	.63/.84	.82/.93	.76/ .90	-	.39/.70
Velocity (9hz)	.63/.84	.82/.93	-	.64/ .85	.33/.66
Spectral	.55/.80	.62/.84	1.0 /1.0	-	.34/.67
Velocity (5hz)	.55/.80	.62/.84	-	1.0/1.0	.34/.67

* Effects shown as: probability reduction factor/ground motion reduction factor. Thus the first number is the factor by which the probability should be multiplied (at a given ground motion level) to represent the effect shown at the top of the column. The second number is the factor by which the ground motion level should be multiplied (at a constant probability level) to represent the effect shown at the top of the column.

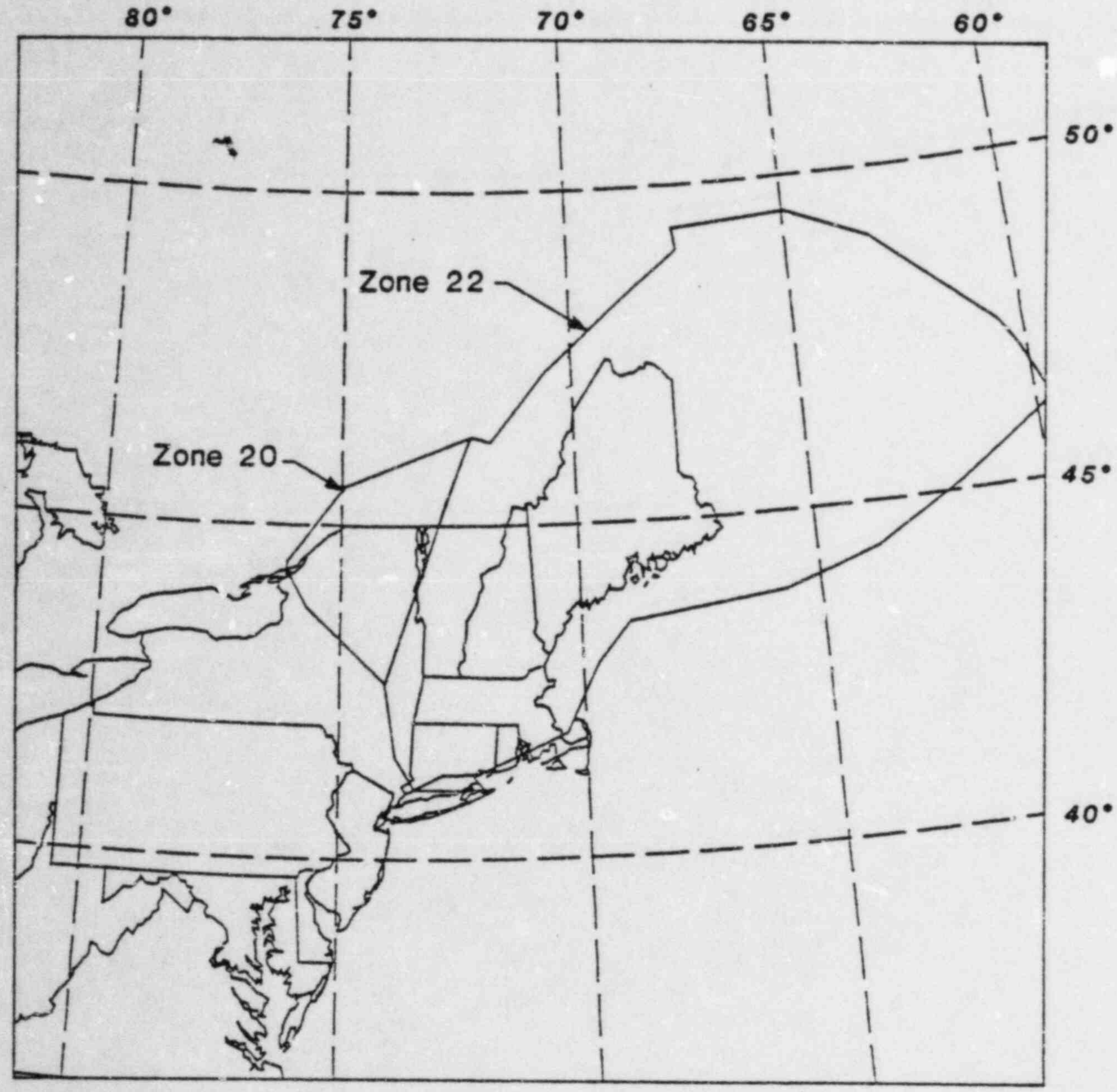

Figure 1

Zones for Seismicity Expert 1

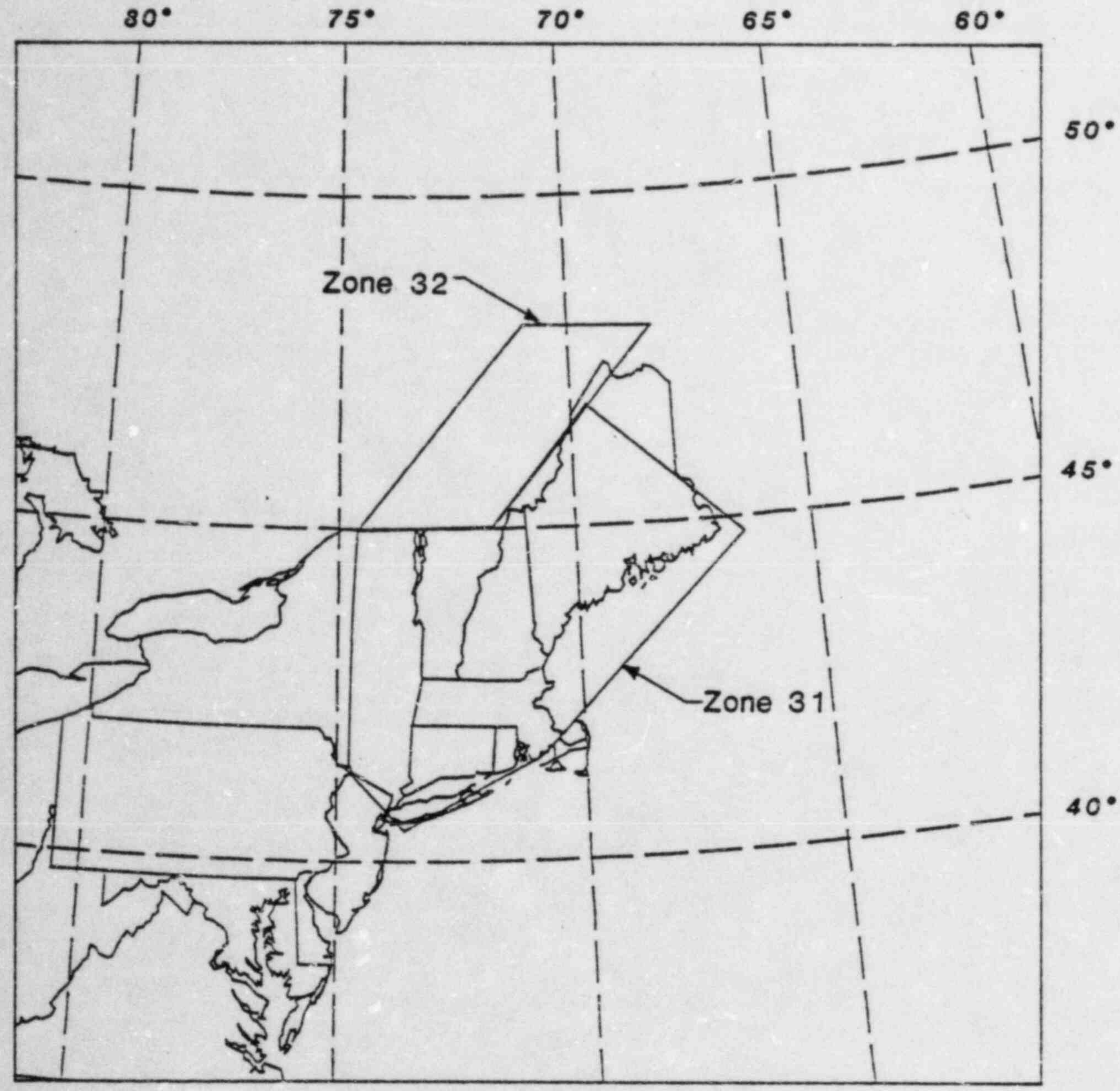

Figure 2
Zones for Seismicity Expert 2

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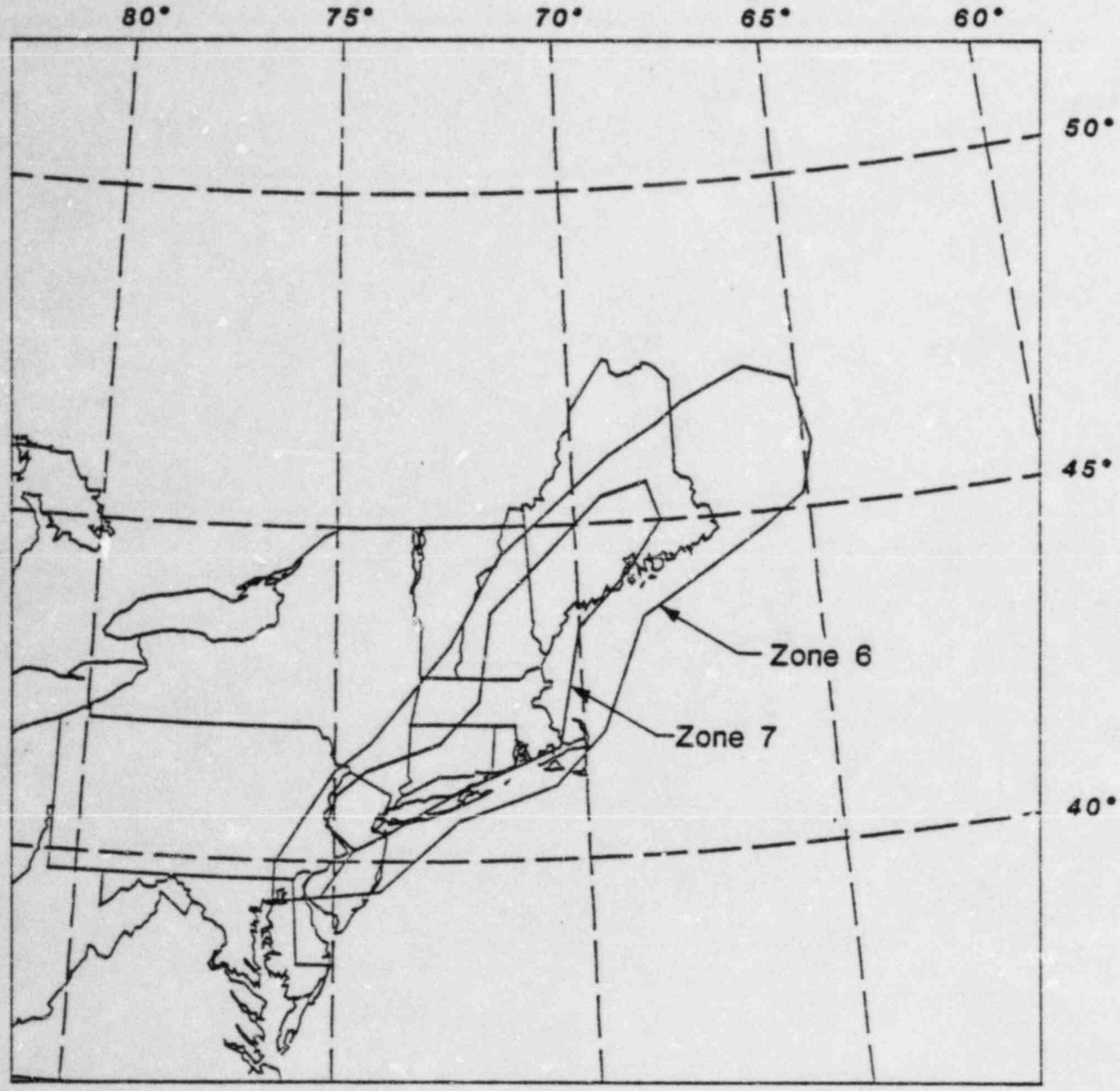

Figure 3
Zones for Seismicity Expert 3

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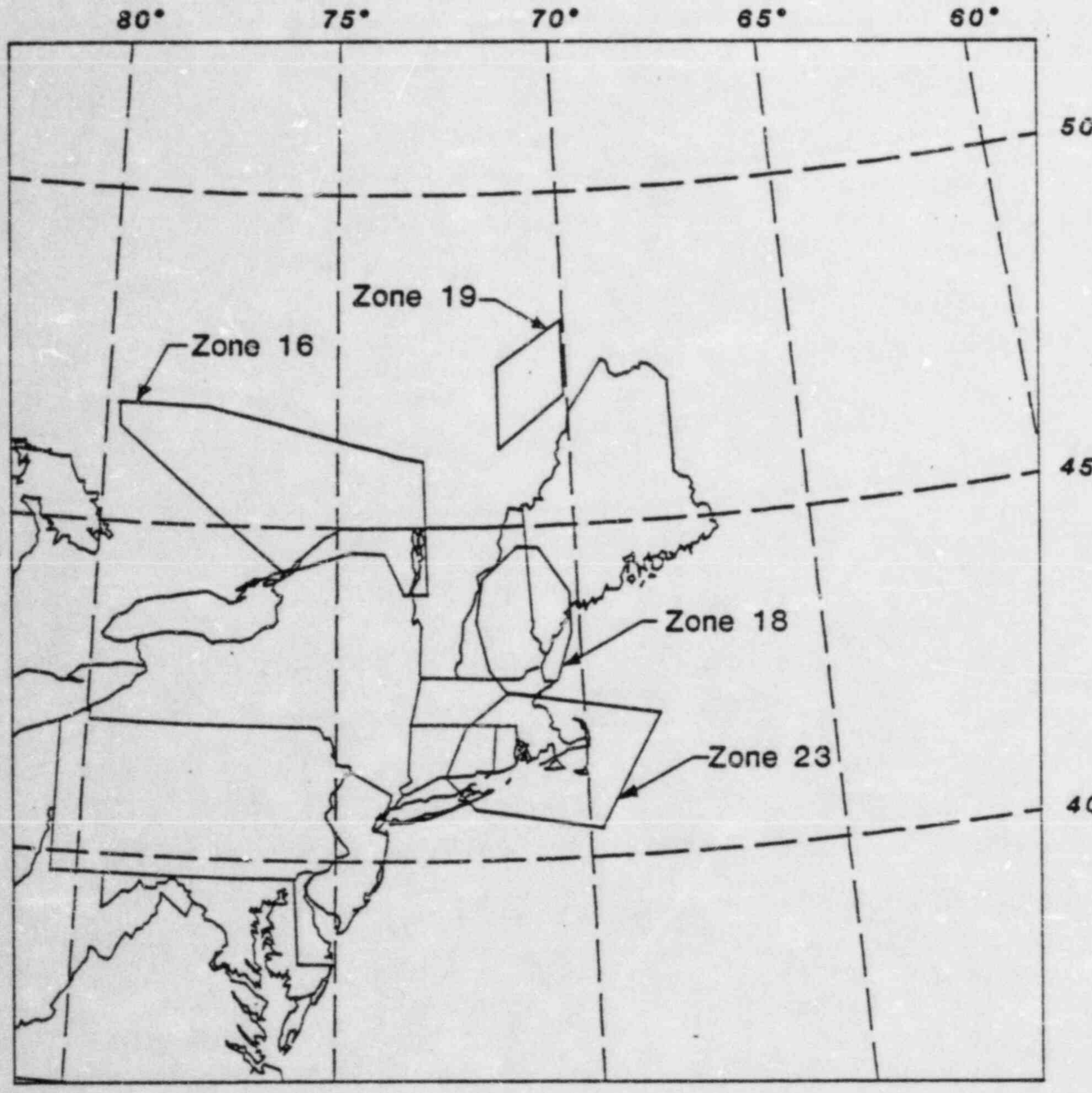

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Zones for Seismicity Expert 4

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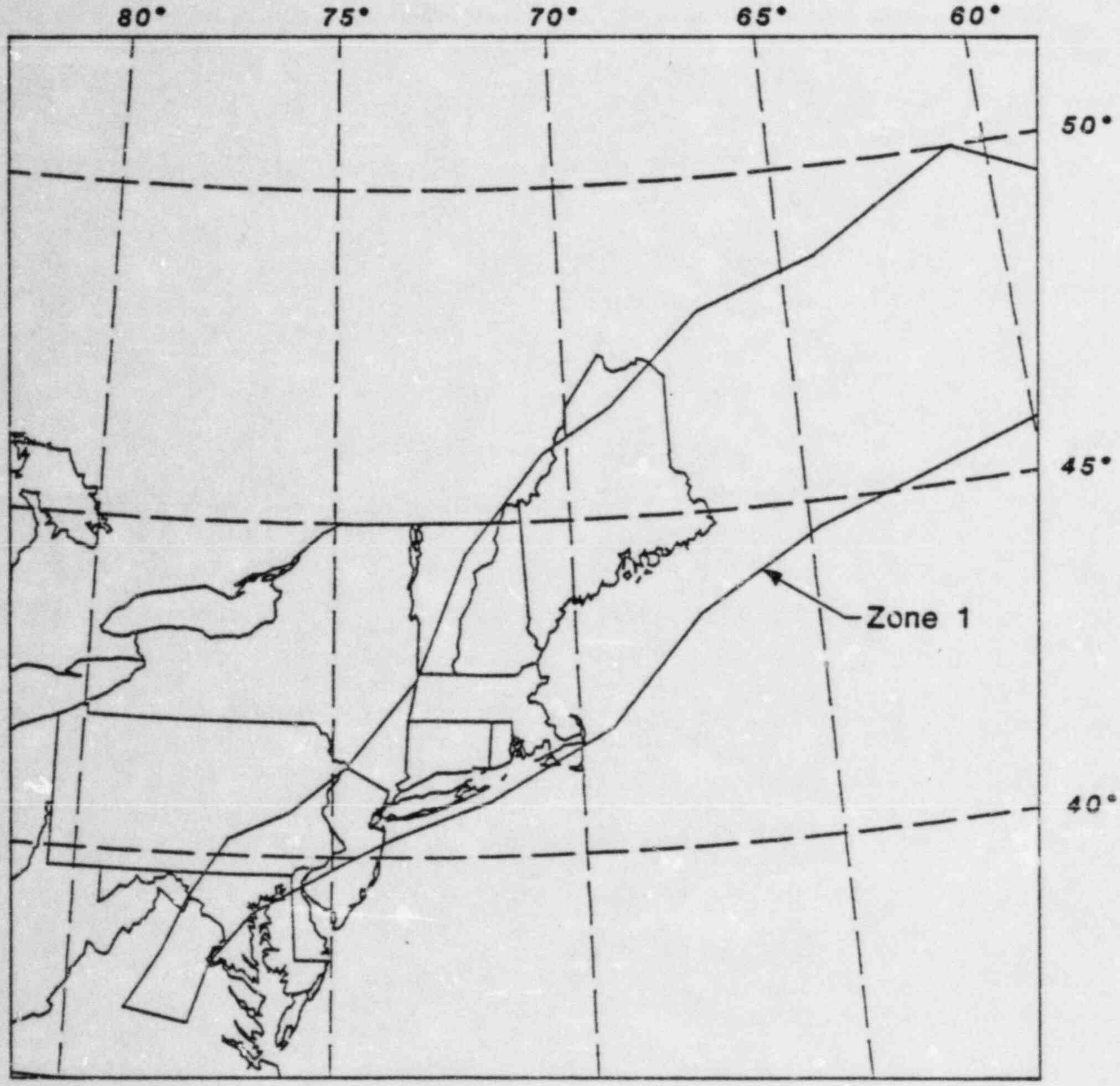

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Zones for Seismicity Expert 5

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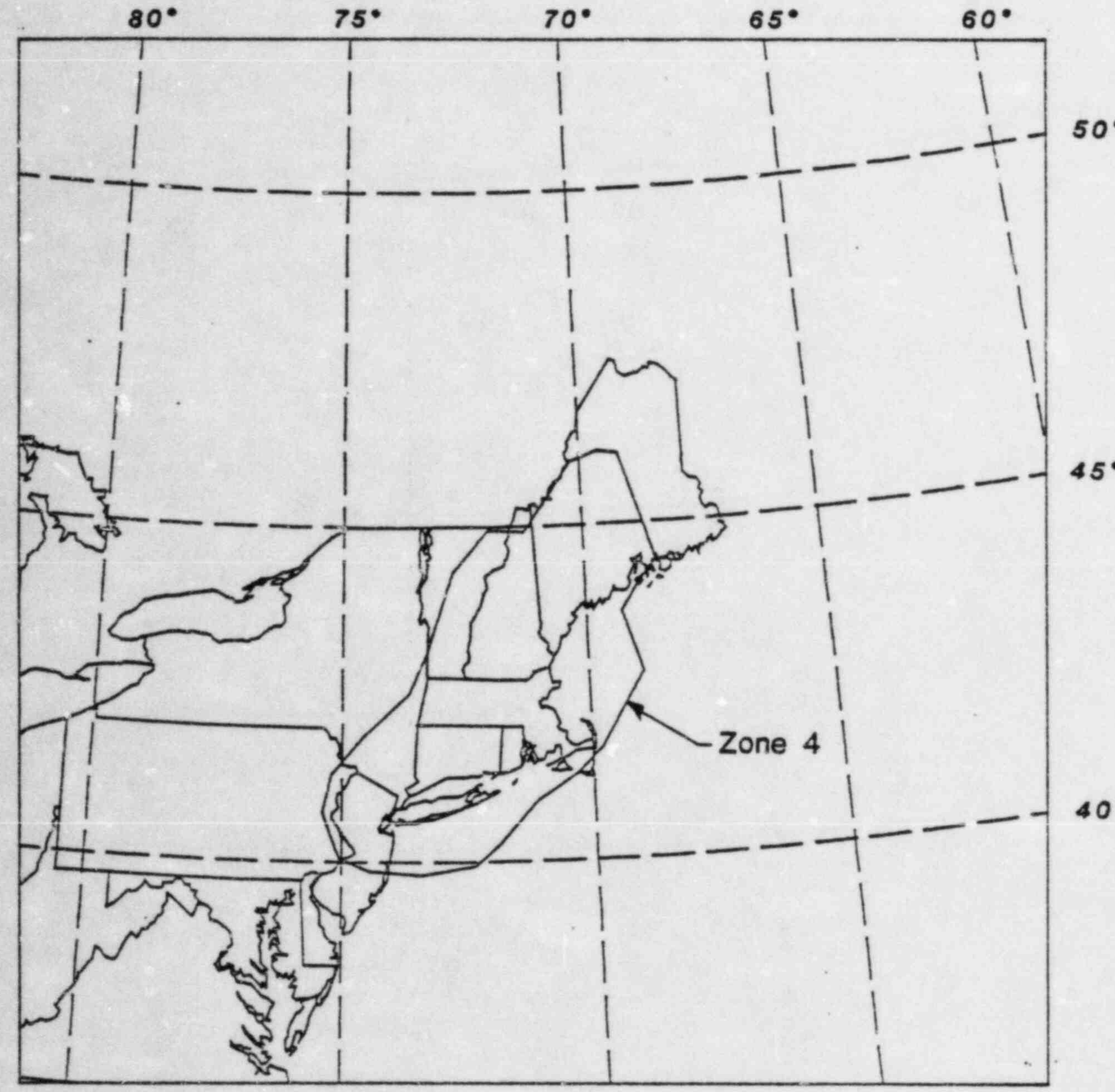

Figure 6
Zones for Seismicity Expert 6

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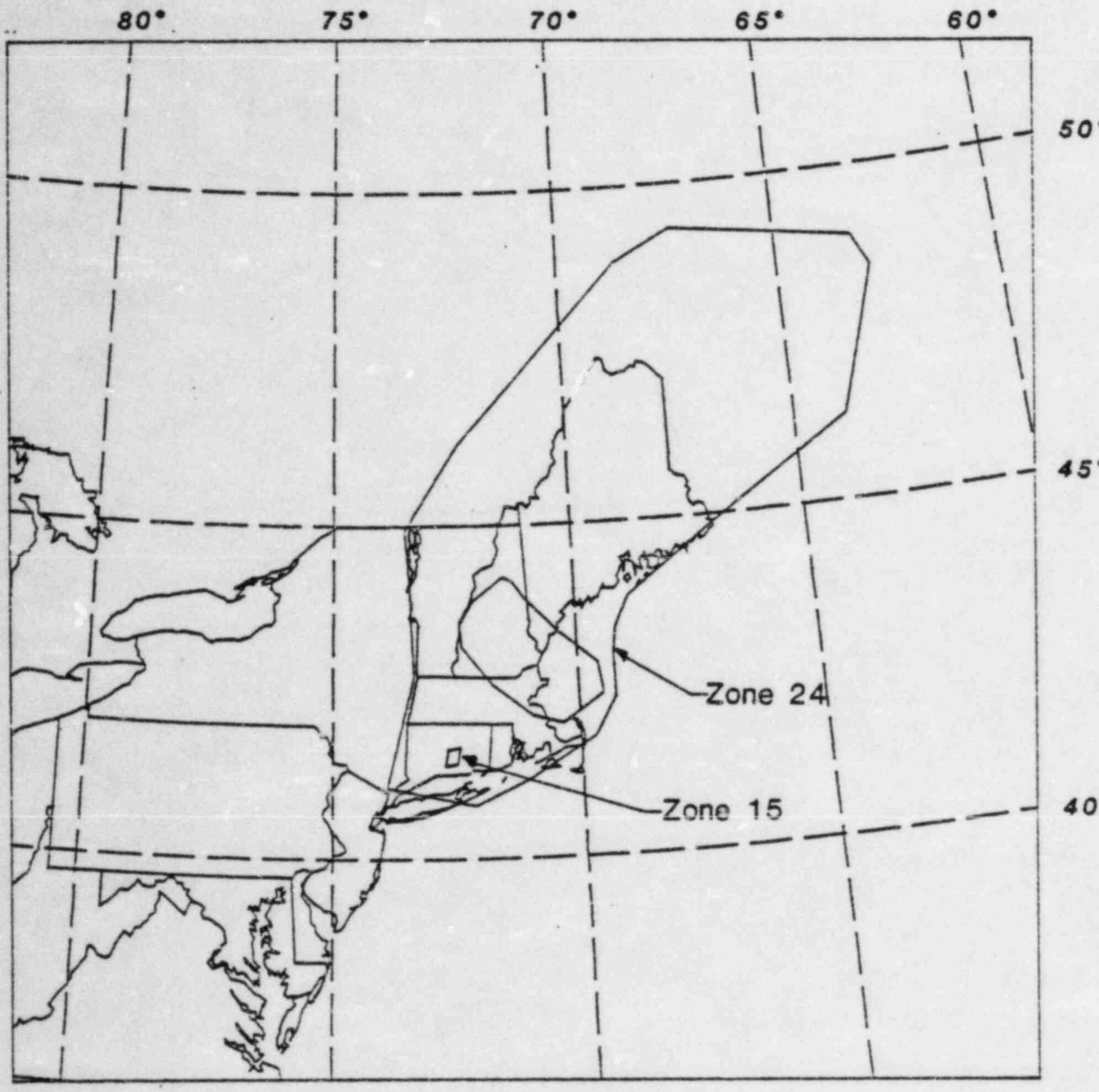

Figure 7

Zones for Seismicity Expert 7

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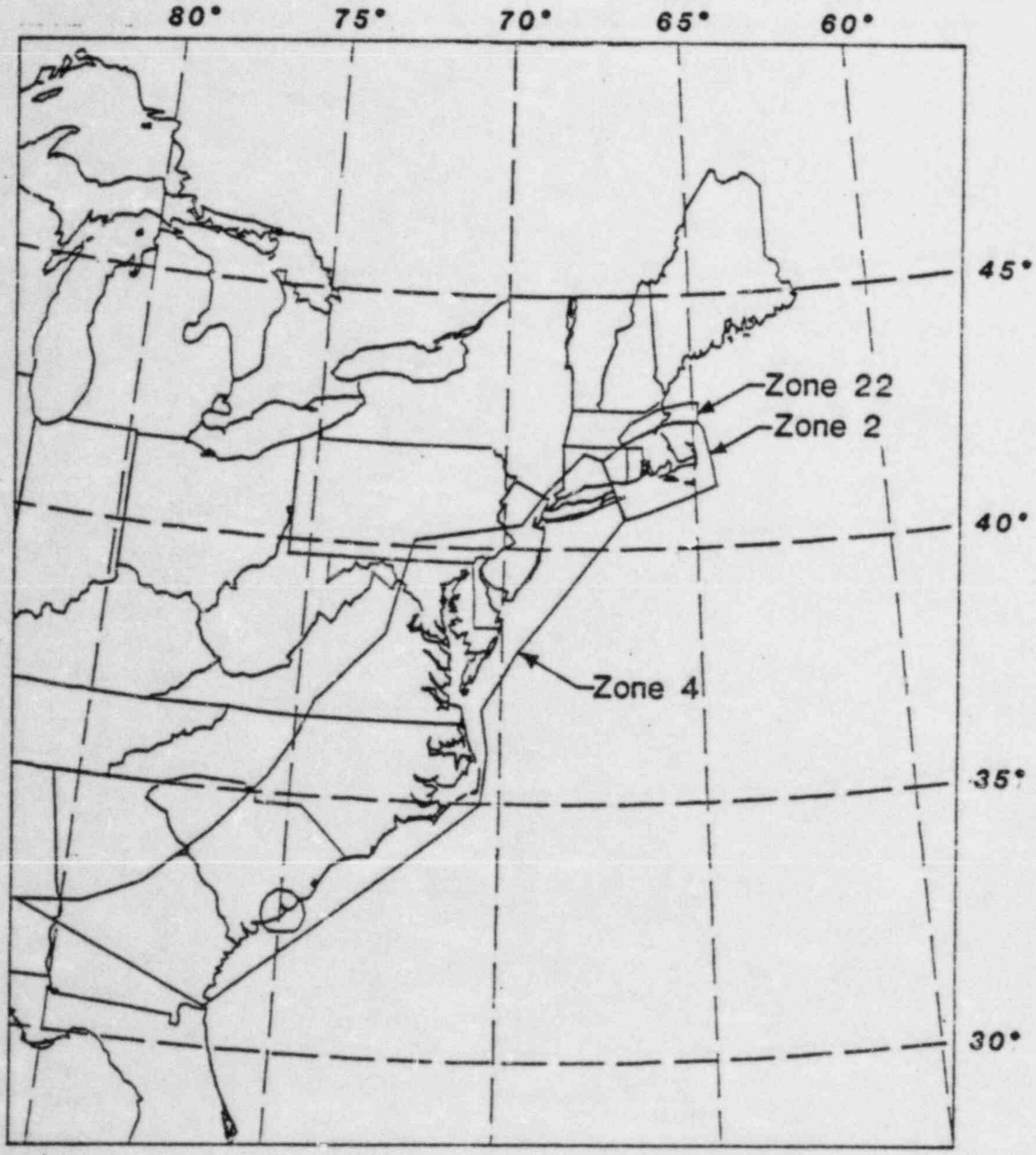

Figure 8

Zones for Seismicity Expert 10

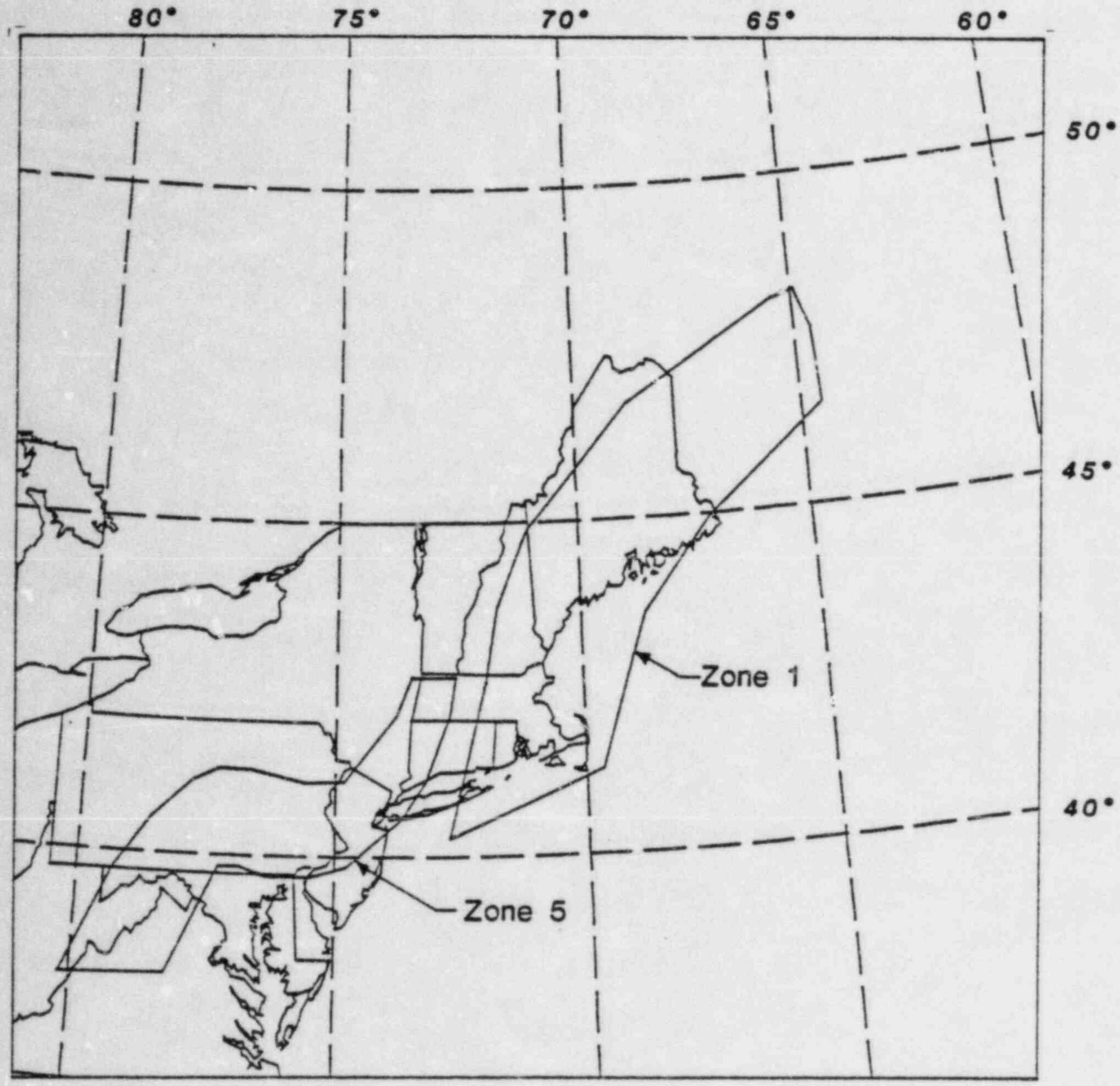

Figure 9

Zones for Seismicity Expert 11

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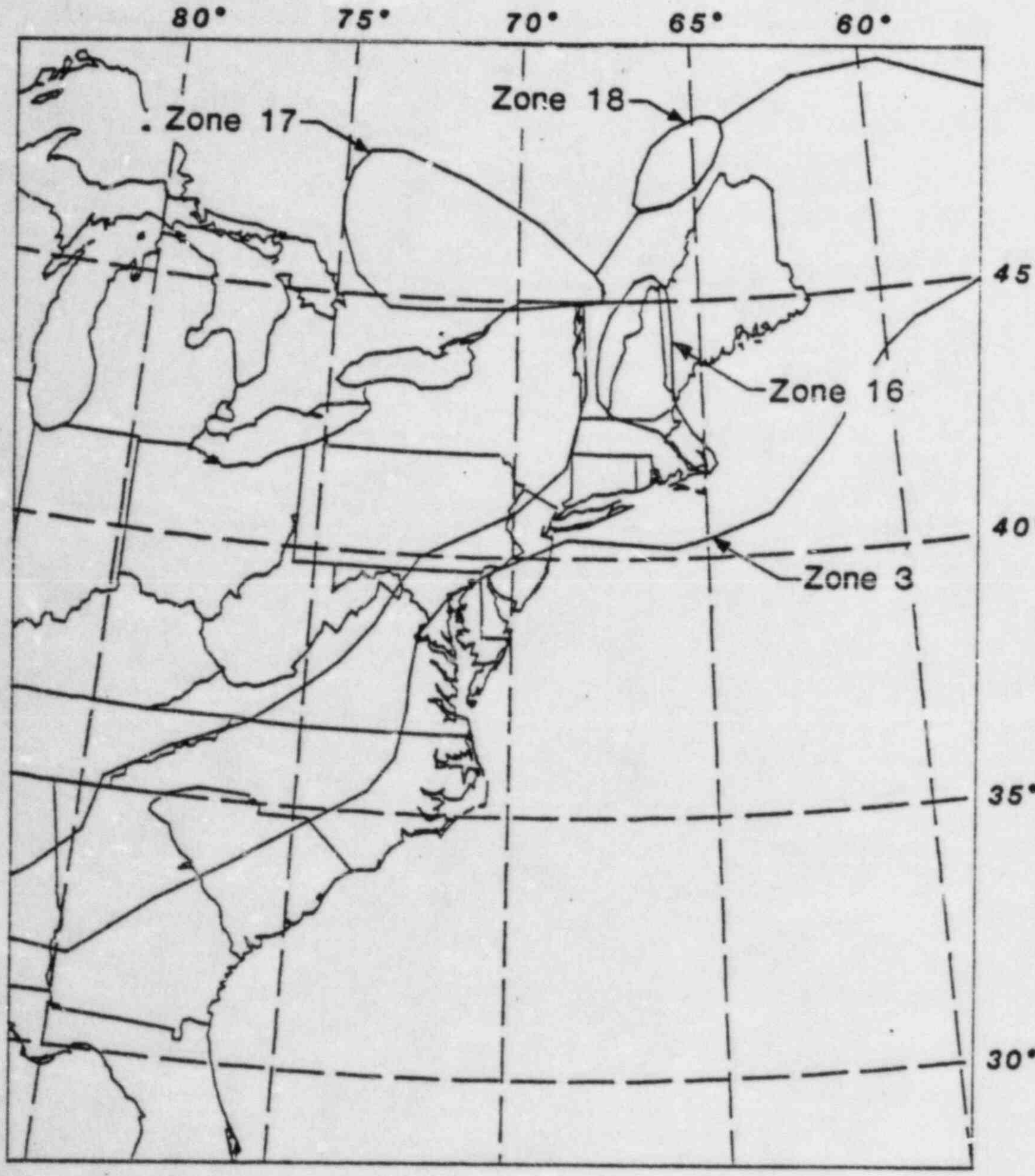

Figure 10

Zones for Seismicity Expert 12

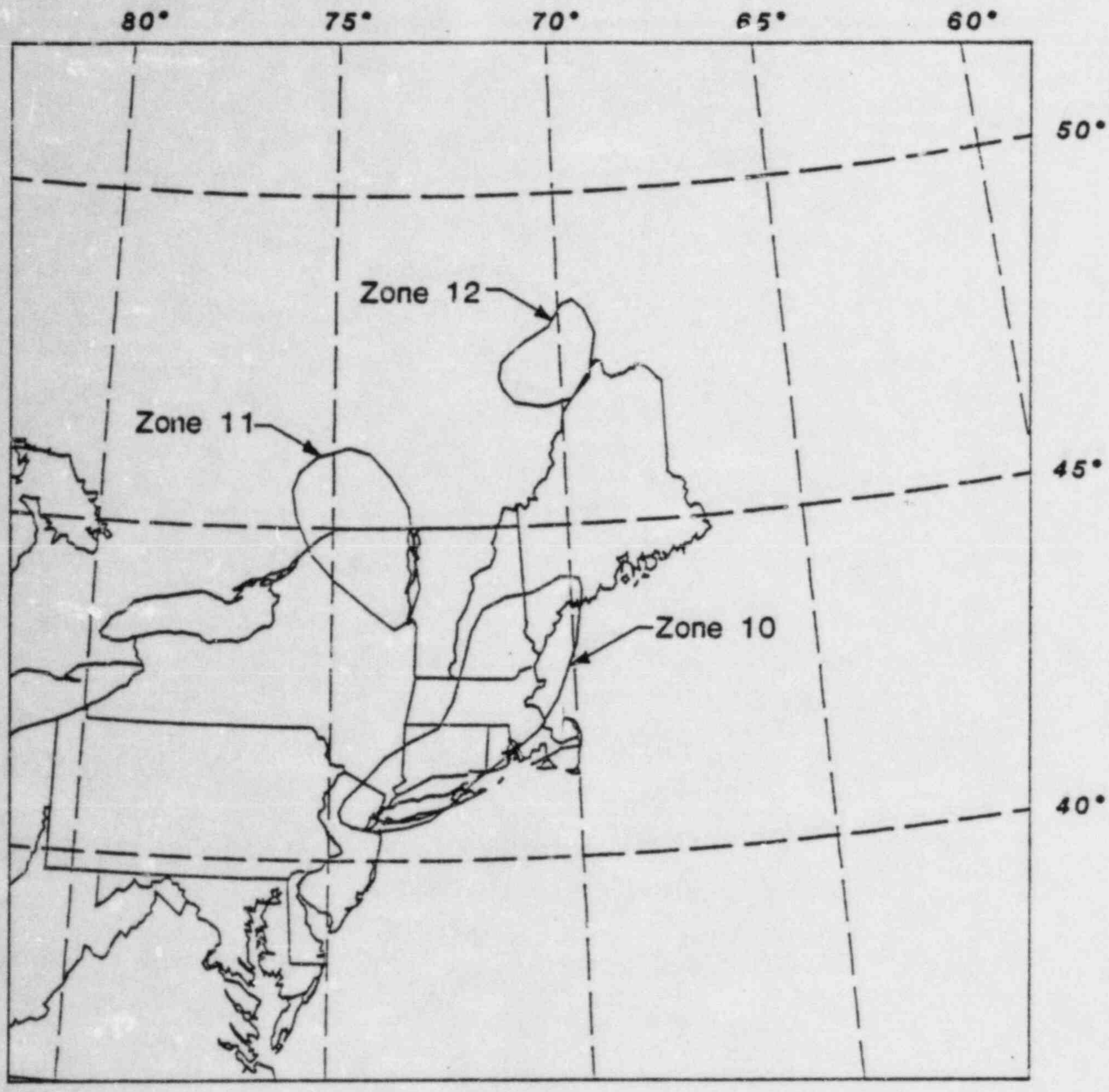

Figure 11
Zones for Seismicity Expert 13

Dames & Moore

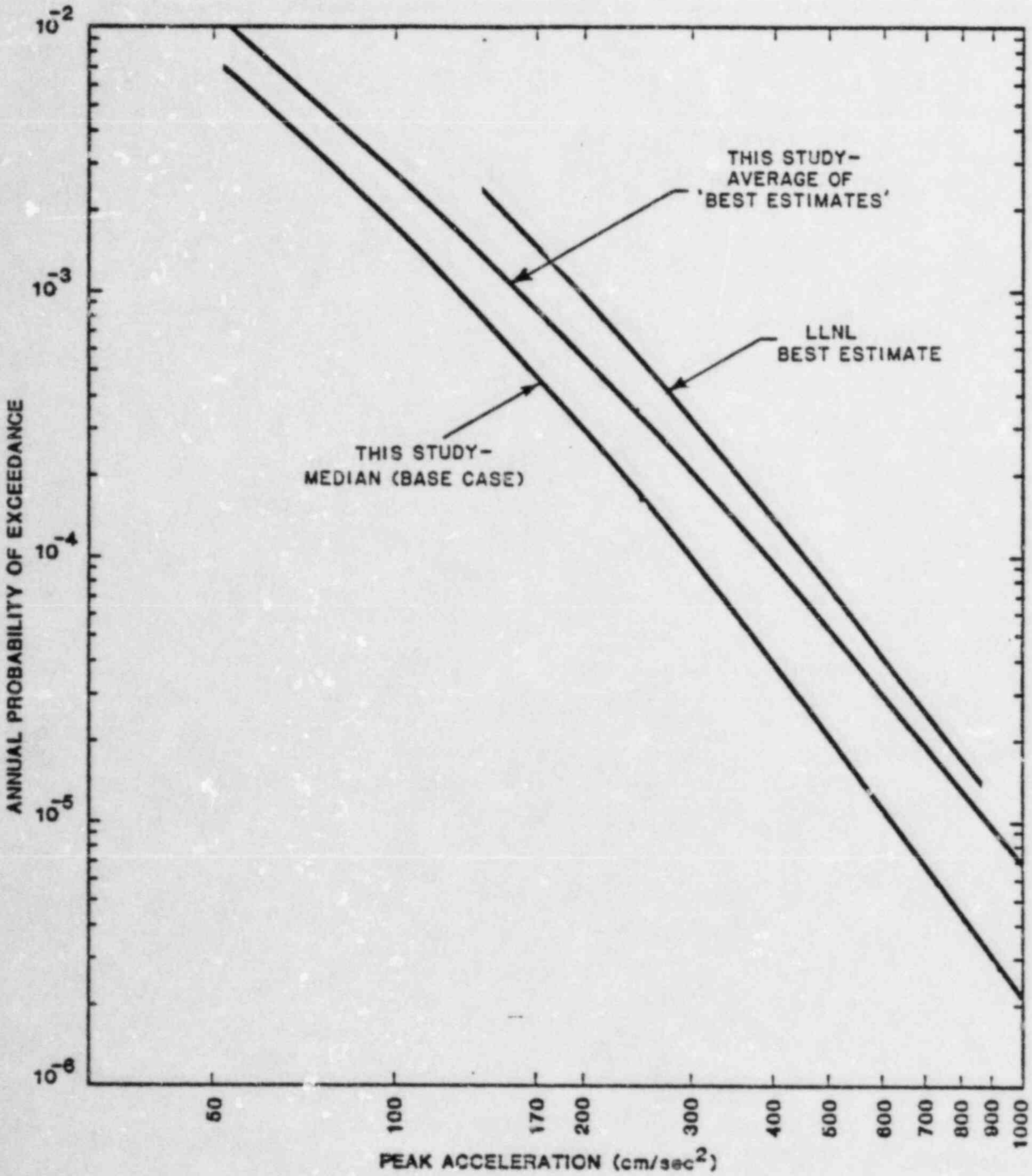

Figure 12

Hazard Curves for Median and Average of "Best Estimates"

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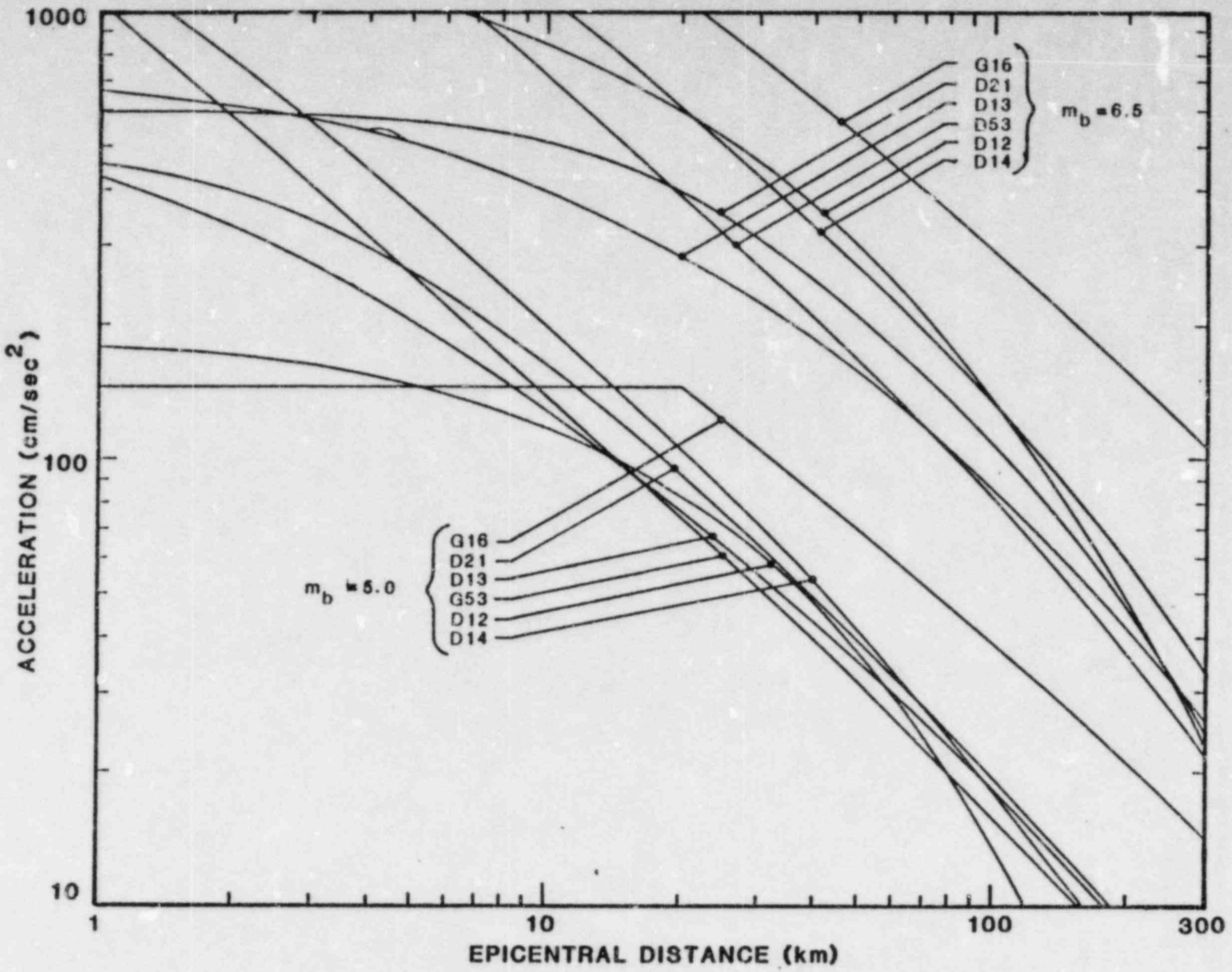

Figure 13: Acceleration Estimates for $m_b = 5.0$ and 6.5

Dames & Moore

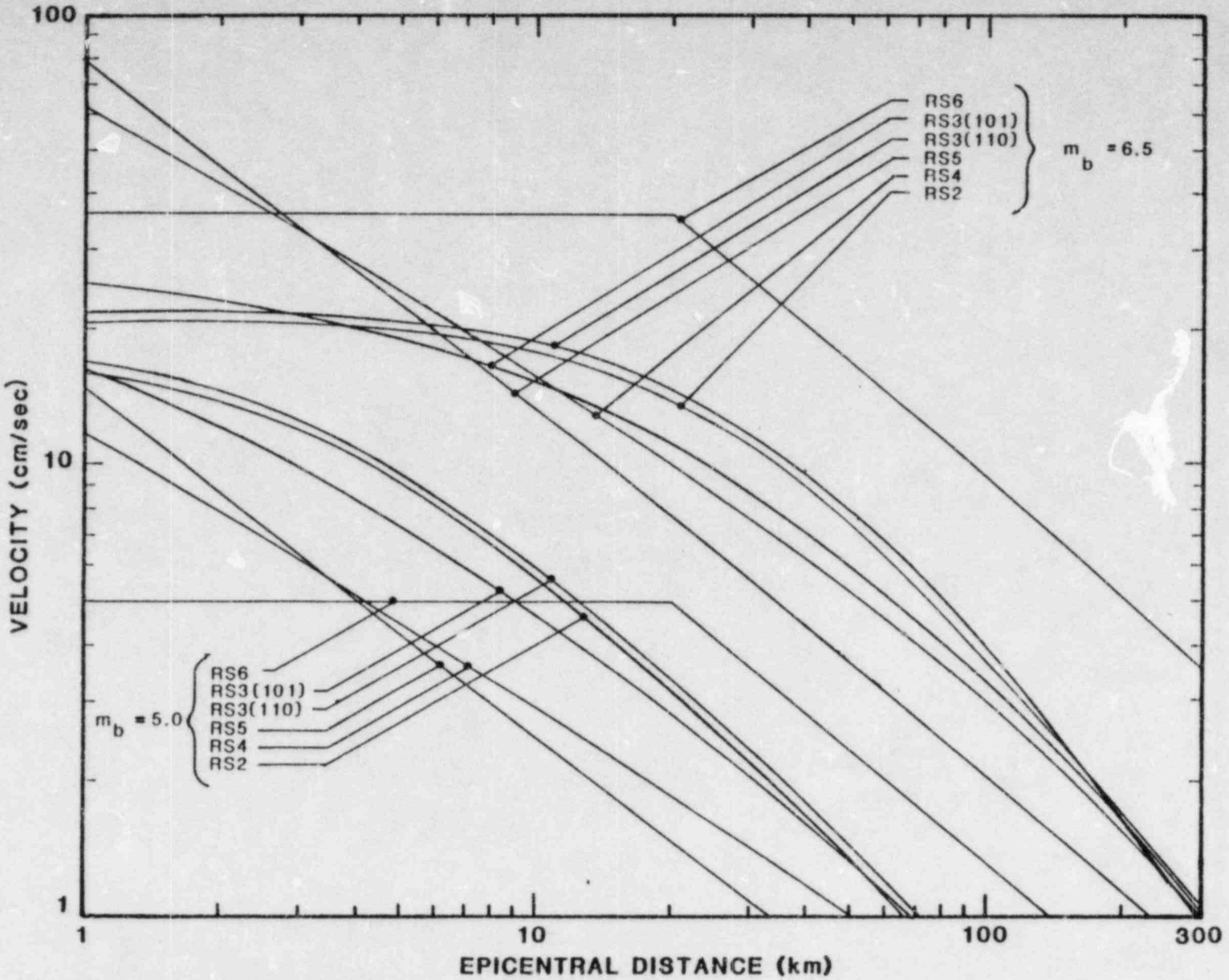

Figure 14: Spectral Velocity (9hz) Estimates for $m_b = 5.0$ and 6.5

Dames & Moore

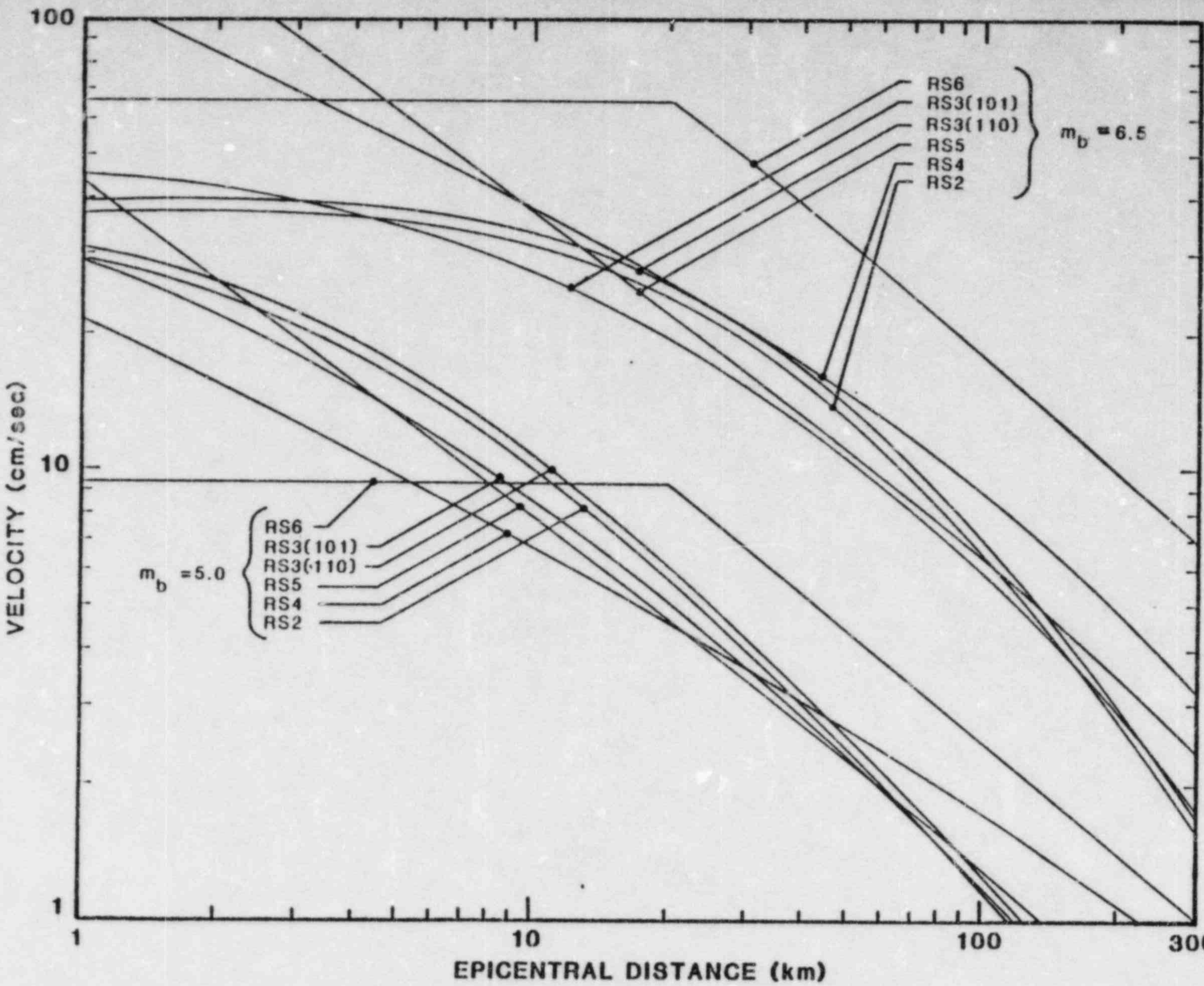

Figure 15: Spectral Velocity (5hz) Estimates for $m_b = 5.0$ and 6.5

Dames & Moore

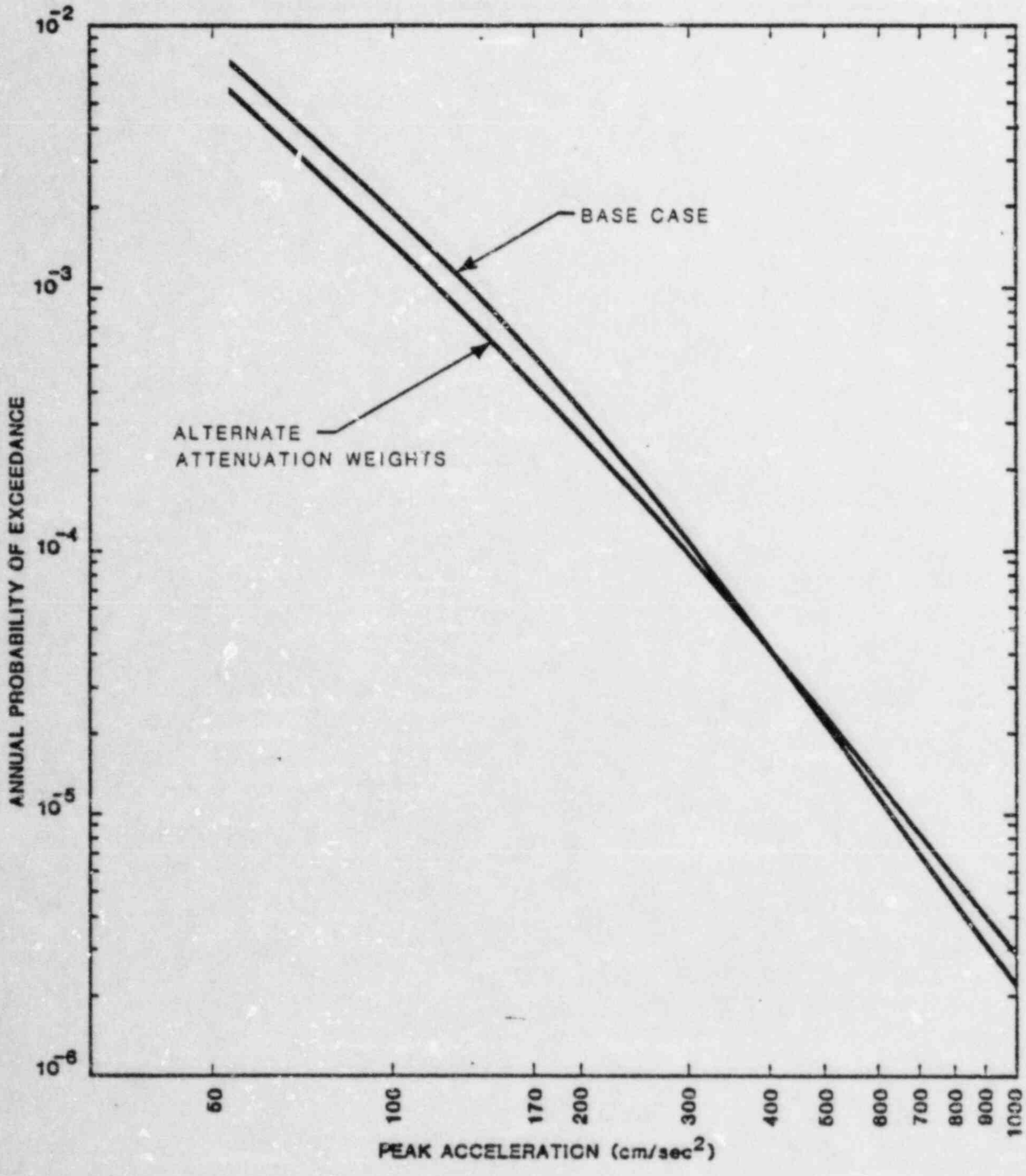

Figure 16

Median Acceleration Hazard Curves,
Base Case And Results Without Trifunac Attenuation

Dames & Moore

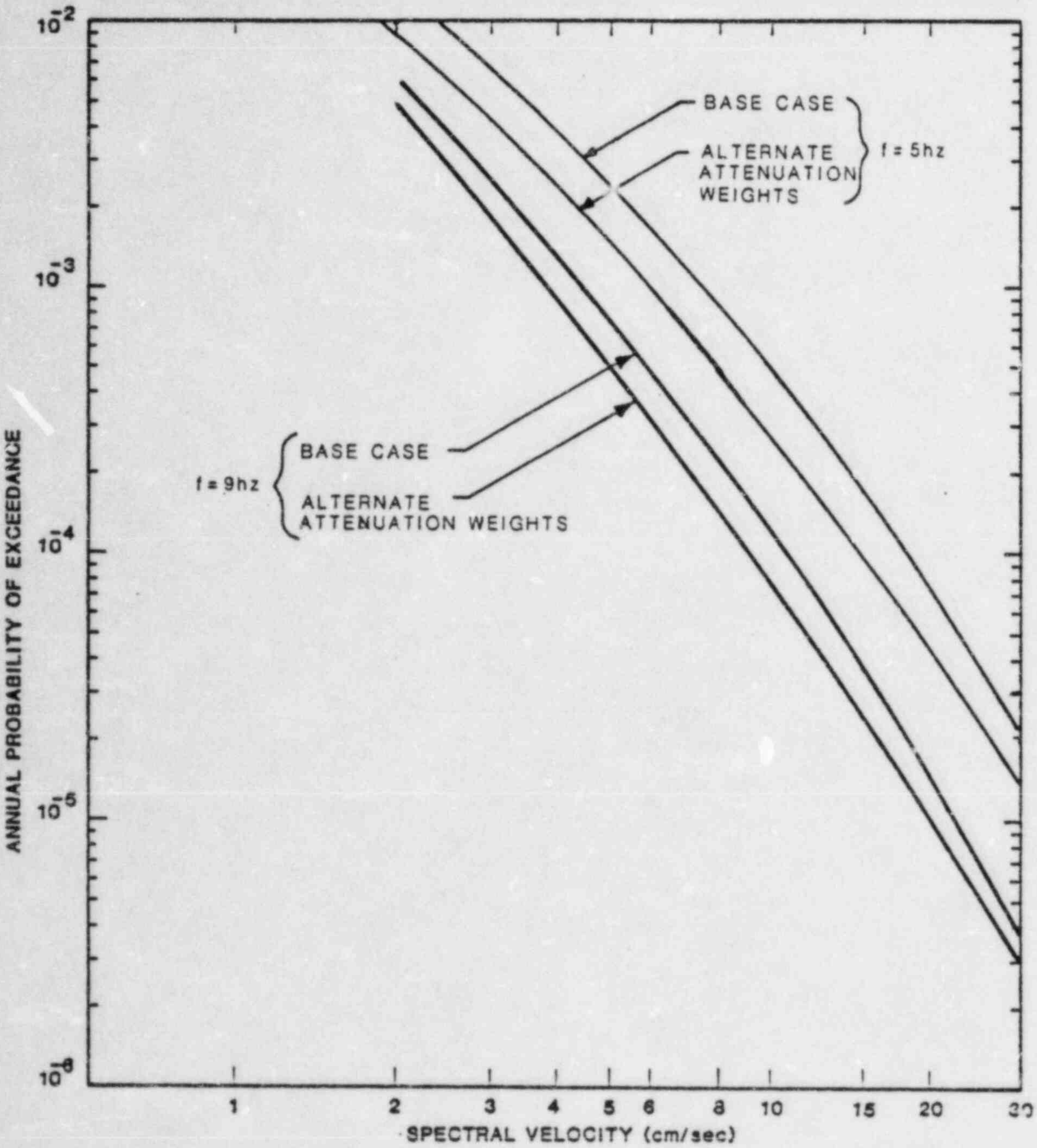

Figure 17

Median Spectral Velocity (9 and 5hz) Hazard Curves
(5% Damping), Base Cases and
Results Without Trifunac Attenuation

Dames & Moore

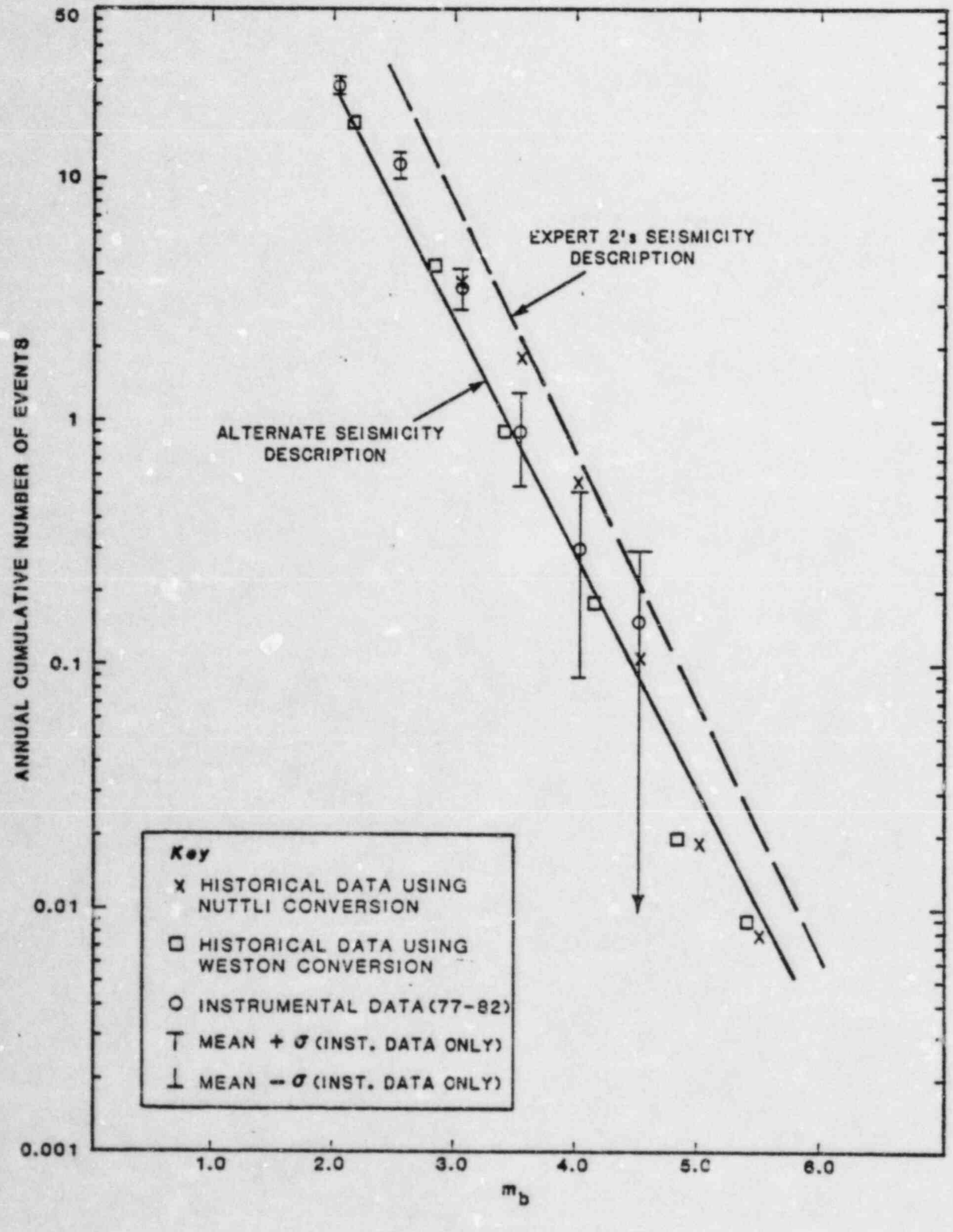

Figure 18

Seismicity Data, Zone 31 of Expert 2

Dames & Moore

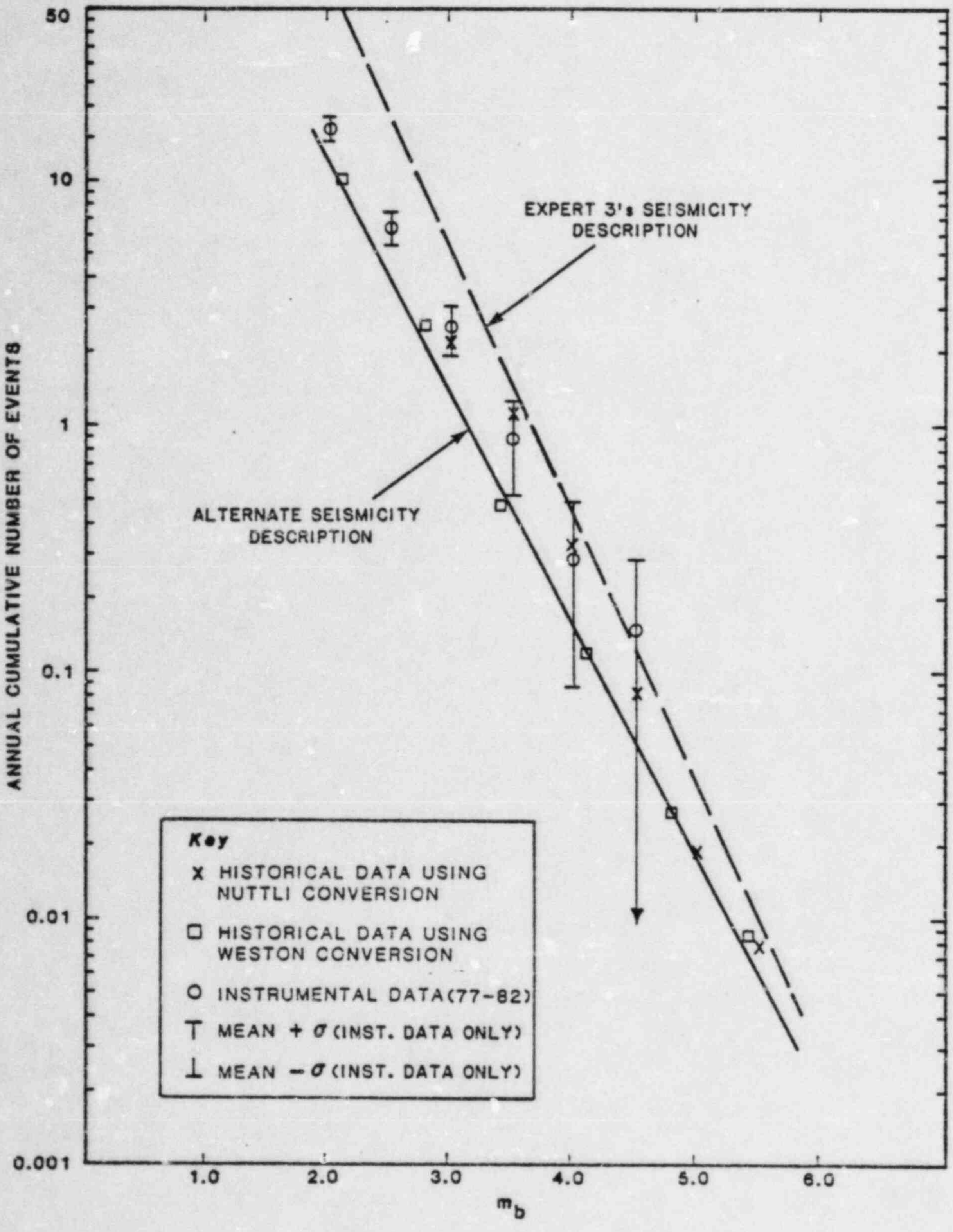

Figure 19

Seismicity Data, Zone 7 of Expert 3

Dames & Moore

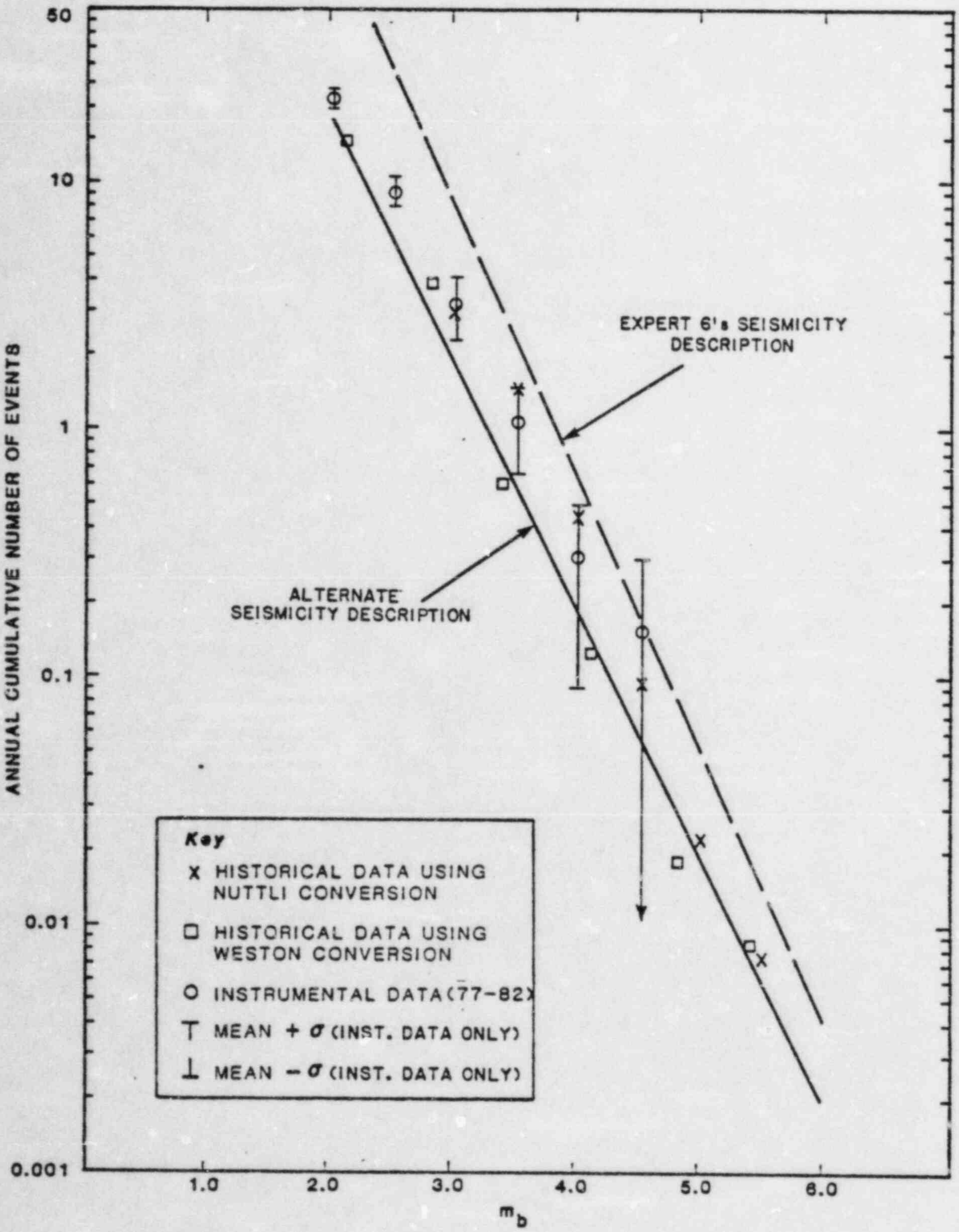

Figure 20

Seismicity Data, Zone 4 of Expert 6

Dames & Moore

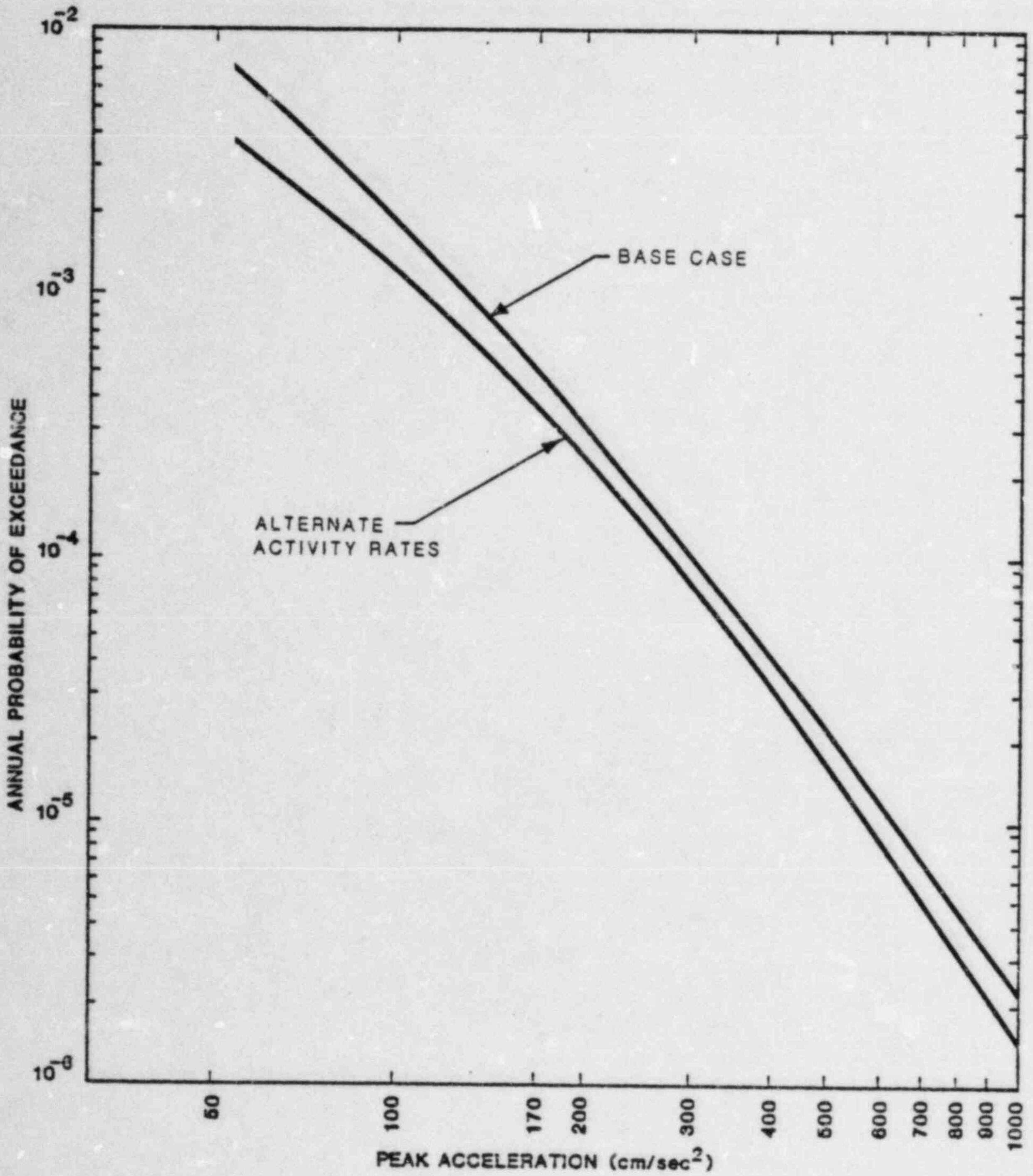

Figure 21

Median Acceleration Hazard Curves, Base Case and Alternate Activity Rates

Dames & Moore

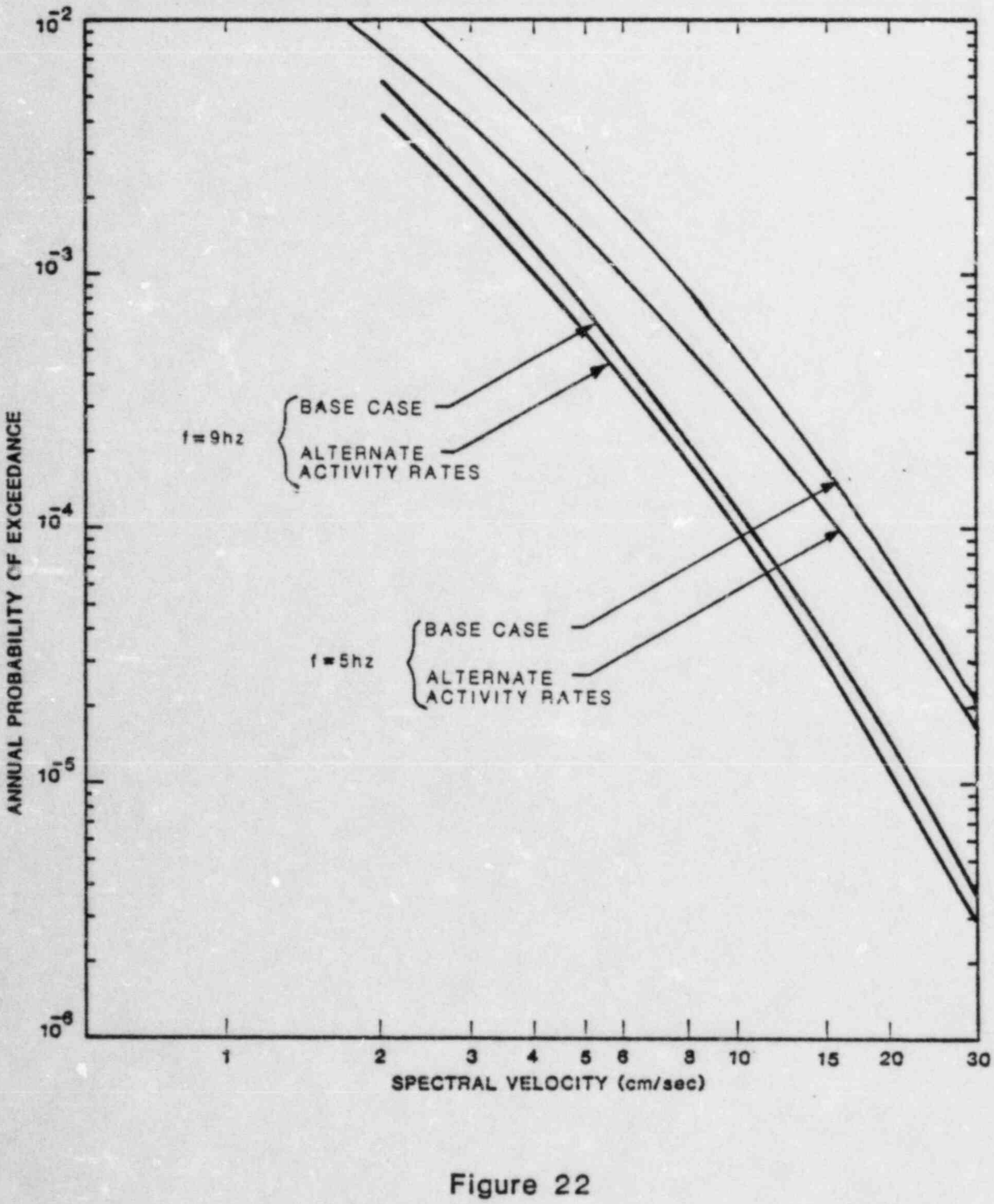

Figure 22

Median Spectral Velocity (9 and 5hz) Hazard Curves (5% Damping), Base Cases and Alternate Activity Rates

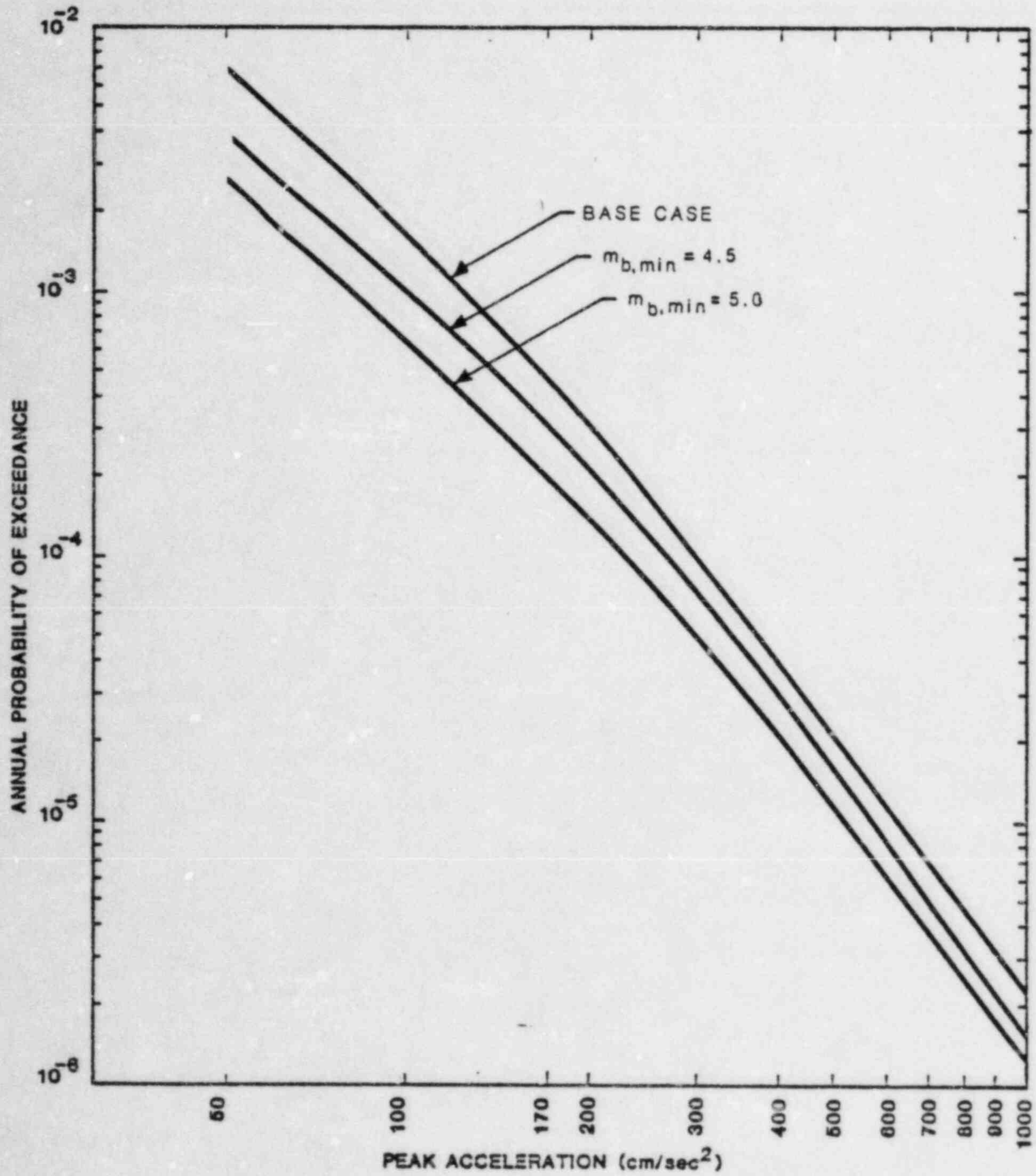

Figure 23

Median Acceleration Hazard Curves, Base Case, $m_{b,\ min} = 4.5$ and 5.0

Dames & Moore

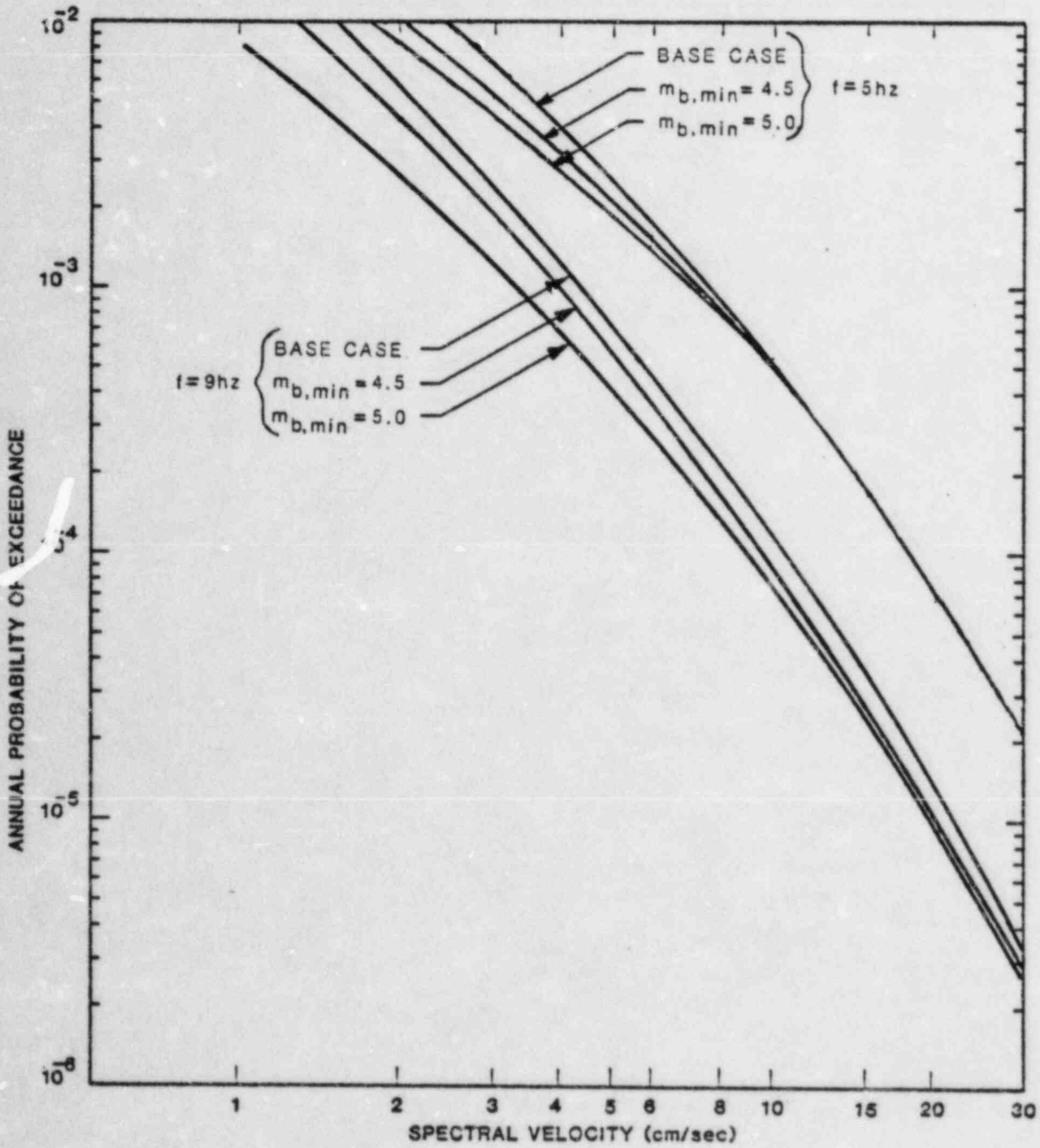

Figure 24

Median Spectral Velocity (9 and 5hz) Hazard Curves (5% Damping), Base Cases, $m_{b,\ min}$=4.5 and 5.0

Dames & Moore

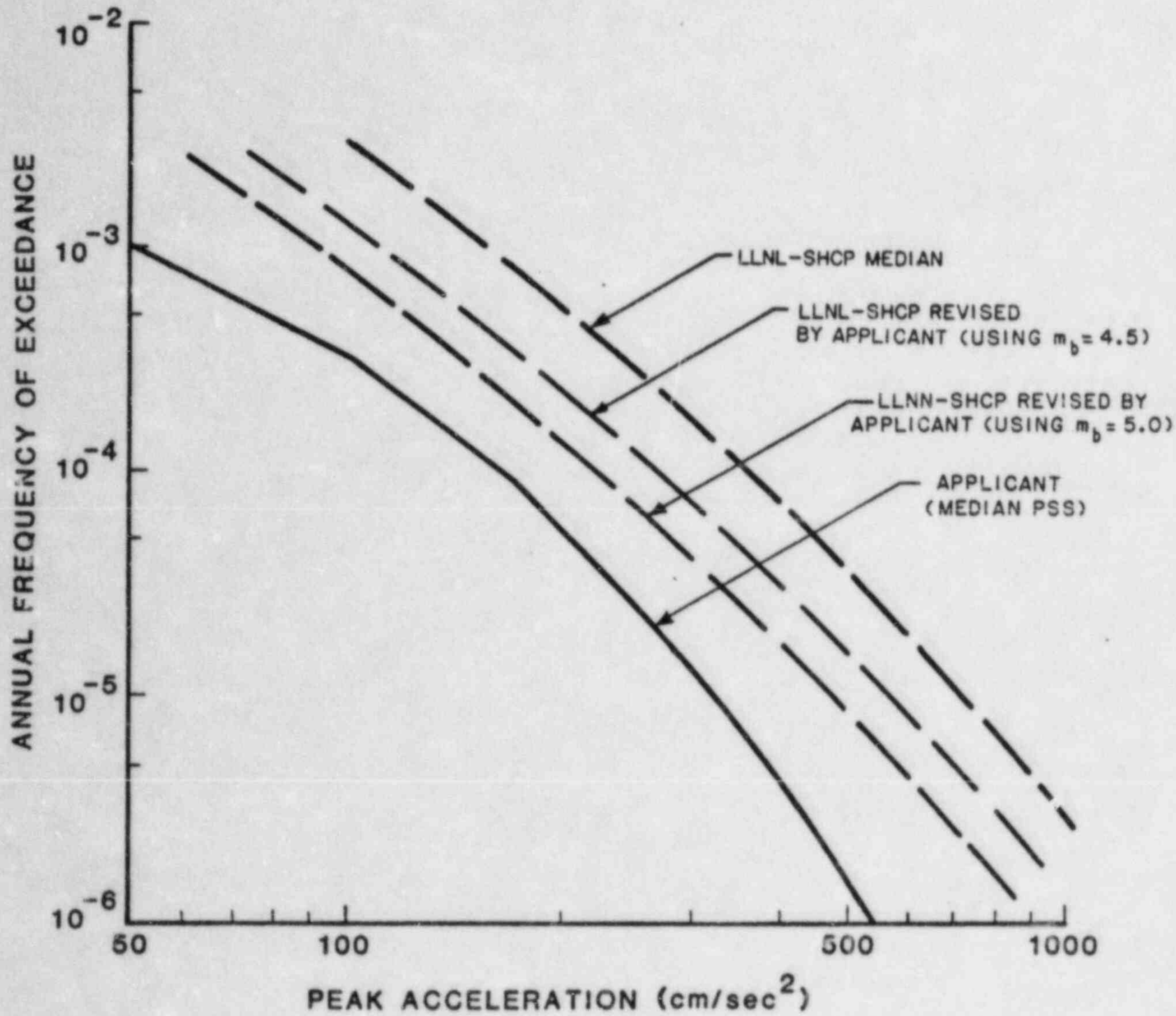

Figure 25
Acceleration Hazard Curves

Dames & Moore

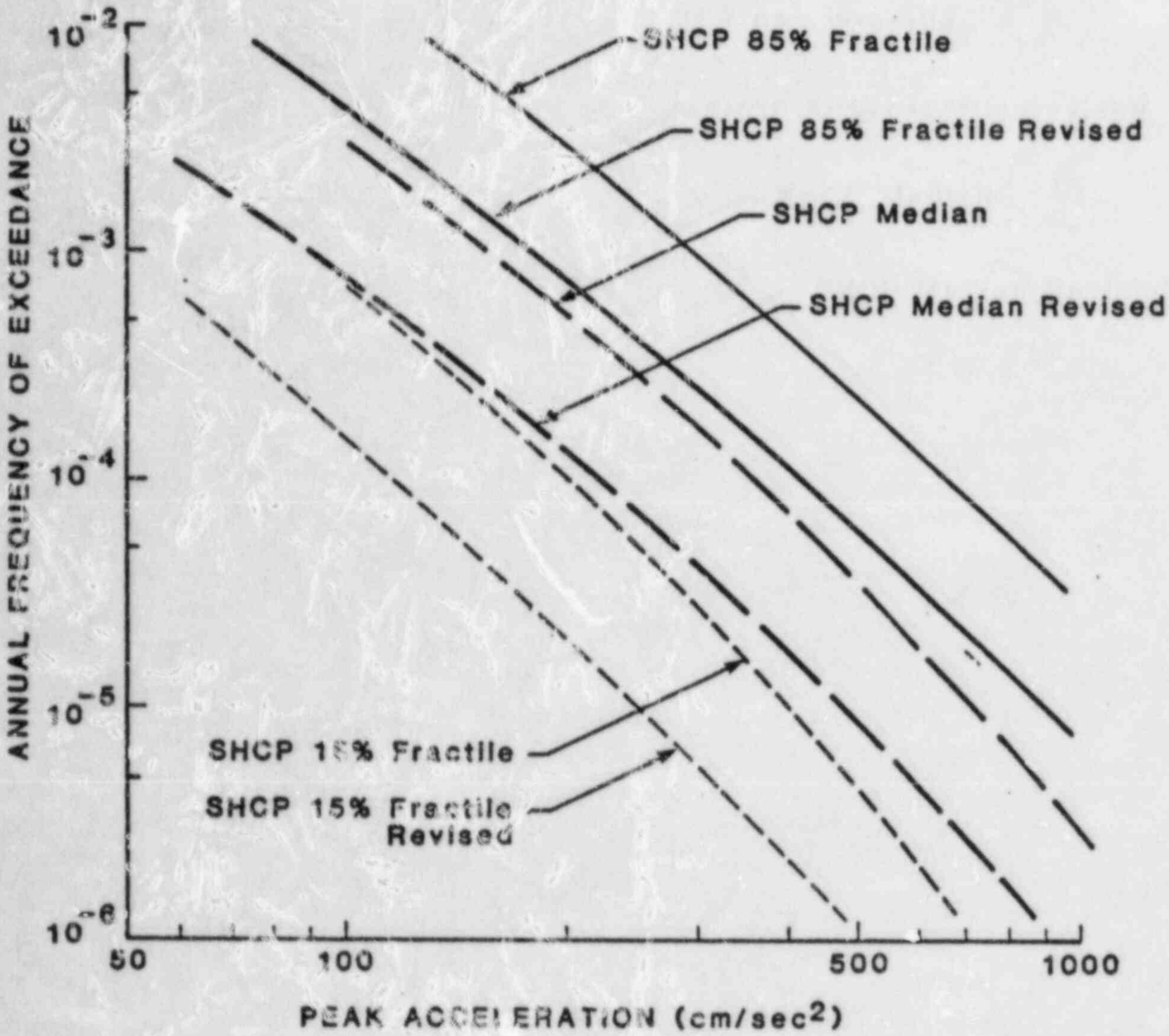

Figure 26

Acceleration Hazard Curves

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