# SEISMIC RISK ANALYSIS FOR

# BATTELLE MEMORIAL INSTITUTE NUCLEAR RESEARCH FACILITY

# WEST JEFFERSON, OHIO

Submitted to

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# 1.0 INTRODUCTION AND SUMMARY

In this report, TERA Corporation presents the results of a detailed seismic risk analysis of the Battelle Memorial Institute's Nuclear Research Facility at West Jefferson, Ohio.

This report is one part of a larger effort being directed by the U.S. Nuclear Regulatory Commission. The NRC's objective in commissioning the overall report is to assess and improve, to the extent practicable, the ability of this facility to withstand adverse natural phenomena without loss of capacity. This report focuses on earthquakes; the other natural hazards, which are addressed in separate reports, are severe weather (strong winds and tornados) and floods. The overall report will provide an assessment of the consequences of an accident resulting from any of these natural phenomena. The assessment will express a quantitative probabilistic measure of the potential structural damage and the release function. It will also provide a probabilistic estimate of the resulting dose of radioactivity to the public.

This study was performed under contract to the Lawrence Livermore Laboratory (LLL). The study was directed by D. L. Bernreuter of the LLL Nuclear Test Engineering Division. At TERA, the study was managed by L. Wight.

To ensure credible results, very sophisticated but well-accepted techniques were employed in the analysis. The calculational method we used, which is based on Cornell's work (1968), has been previously applied to safety evaluations of major projects.

The historical seismic record was established after a review of available literature, consultation with operators of local seismic arrays and examination of appropriate seismic data bases including the USGS, LASA, NOAA, USC and GS, and NEIS bases.

Because of the aseismicity of the region around the site, an analysis different from the conventional closest approach in a tectonic province was adopted.

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Earthquakes as far from the site as 600 km were included, as was the possibility of earthquakes at the site. In addition, various uncertainties in the input were explicitly considered in the analysis. For example, allowance was made for both the uncertainty in predicting maximum possible earthquakes in the region and the effect of the dispersion of data about the best fit attenuation relation.

The attenuation relationship we applied is, we feel, the best available. It is derived from two of the most recent, advanced studies relating earthquake intensity reports and acceleration and is unique in that

- It incorporates a thorough analysis of the effects from the 1886 Charleston, South Carolina Earthquake;
- It is based on a recent analysis of almost 1500 world-wide strong motion records; and
- It is consistent with the newly available strong motion acceleration data for the Eastern-Central United States.

Finally, and most important, the project has benefited from significant contributions from, and final review by Professor R. Herrmann, St. Louis University, a seismologist with particular expertise in the local and regional seismology.

The results of our risk analysis, which include a Bayesian estimate of the uncertainties, are presented in Figure 1-1 expressed as return period accelerations. The best estimate curve indicates that the BMI facility will experience 5% g every 200 years and 10% g every 900 years. The bounding curves roughly represent the one standard deviation confidence limits about our best estimate, reflecting the uncertainty in certain of the input. Detailed examination of the results show that the accelerations are very insensitive to the details of the source region geometries or the historical earthquake statistics in each region and that each of the source regions contributes almost equally to the cumulative risk at the site.

If required for structural analysis, acceleration response spectra for the site can be constructed by scaling the mean response spectrum for alluvium in WASH 1255 by these peak accelerations.

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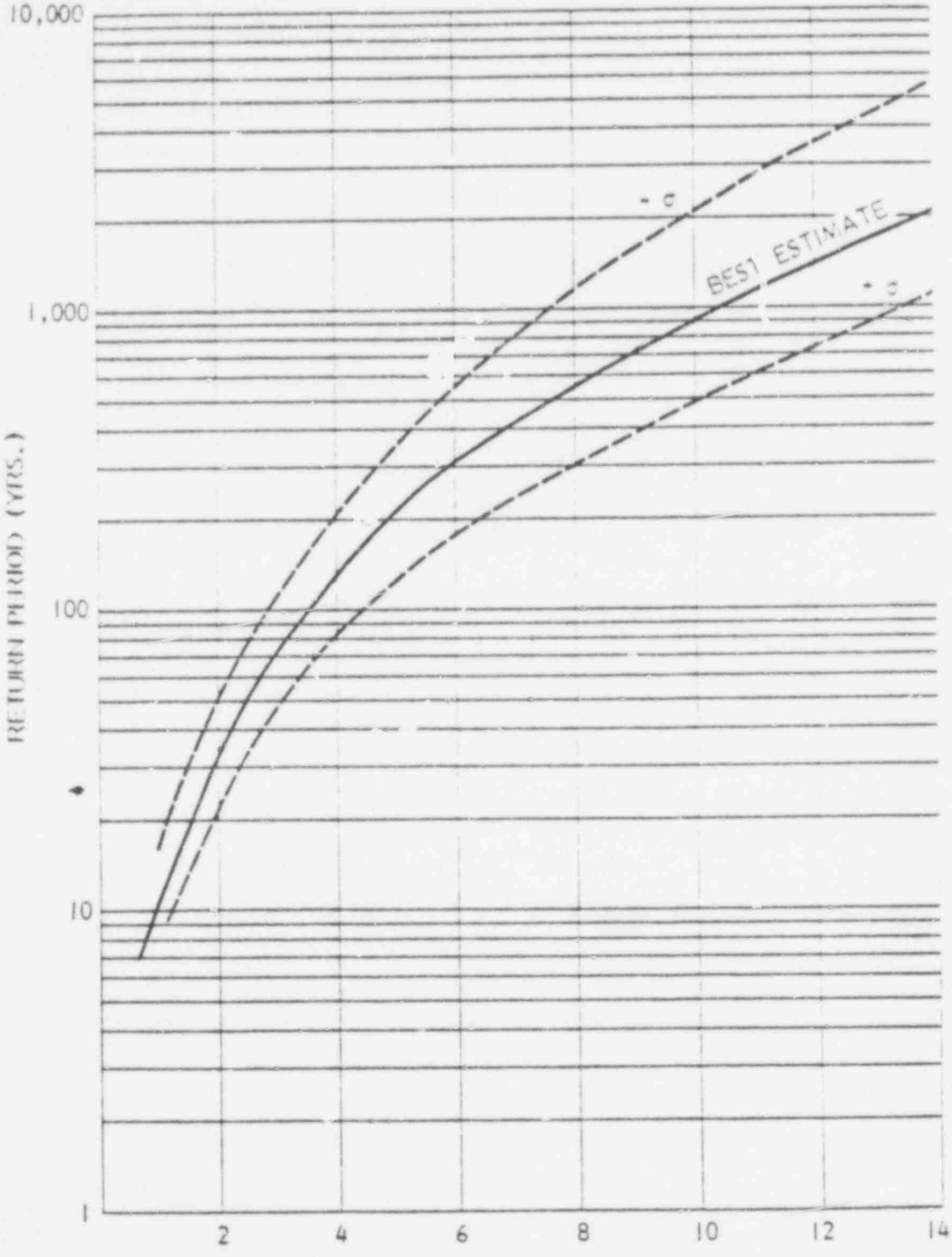

FIGURE 1-1

RETURN PERIODS FOR SEISMIC ACCELERATION
AT THE BMI WEST JEFFERSON FACILITY

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## 2.0 SEISMIC RISK METHODOLOGY

A seismic risk analysis is only as credible as the risk analysis methodology and the input to it. This section presents the basis for our selection of a probabalistic Poisson model for the risk assessment at the BMI facility.

There are generally two distinctly different approaches to seismic risk analysis: probabalistic and deterministic.

Using the deterministic approach, the analyst judgmentally decides that an earthquake of a given magnitude or intensity occurs at a specific location. He then attenuates the ground motion from the earthquake source to the site and determines the effects of that quake. The problem in using this approach is that it is difficult to define the margin of safety or the degree of conservatism in the resulting design parameters. Analysts are often asked to provide information on the "maximum possible" or "most probable" earthquakes for design purposes, but the deterministic approach does not easily provide those answers.

A probabalistic approach, on the other hand, quantifies the uncertainty in the number, size, and location of possible future earthquakes and allows an analyst to present the trade-off between more costly designs or retrofits and the economic or social impact of a failure. Because the product of a probabalistic approach is a measure of the seismic risk expressed in terms of return period, this trade-off can easily be quantified.

Although the probabilistic approach requires significantly more effort than the deterministic approach, it has the following advantages:

- It quantifies the risk in terms of return period;
- It rigorously incorporates the complete historical seismic record;
- It can incorporate the judgment and experience of the analyst;

- It accounts for incomplete knowledge regarding the location of faults;
- It has the flexibility to assess the risk at the site in terms of spectral acceleration, velocity, displacement, or earthquake intensity.

The method is particularly appropriate for the BMI facility for two reasons. First, as will be shown below, the Columbus area is very aseismic and it would therefore be very difficult, using conventional deterministic methods, to establish a design earthquake magnitude. Second, the seismicity of the eastern United States is very diffuse and cannot be correlated with surface faulting as it can be in the western United States. The location of the design earthquakes in the eastern United States is therefore particularly uncertain. The strength of the probabalistic approach is its ability to quantify these uncertainties.

The credibility of the probabilistic approach has been established through detailed technical review of its application to several important projects and areas. Recent applications include assessments of the seismic risk in Boston (Cornell, 1974), the San Francisco Bay Area (Vagliente, 1973), the Puget Sound Area (Stepp, 1971) and continental United States (Algermissen and Perkins, 1976). Results of these studies have been applied to, among other areas:

- Development of long-range earthquake engineering research goals;
- Planning decisions for urban development;
- Environmental hazards associated with the milling of uranium; and
- Design considerations for radioactive waste repositories.

This diversity of application demonstrates the inherent flexibility of the risk assessment approach.

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## THEORY

The risk calculations can be fundamentally represented by the total probability theorem

$$P[A] = \iint P[A/m \text{ and } r] \; f_M(m) \, f_R(r) \, dm dr$$

where P indicates probability, A is the event whose probability is sought, and M and R are continuous, independent random variables which influence A. The probability that A will occur can be calculated by multiplying the conditional probability of A, given events m and r, times the probabilities of m and r, and integrating over all possible values of m and r.

In our assessment of the BMI facility, A will be taken as maximum acceleration and therefore

$$P[A/m \text{ and } r]$$

will be derived from data relating peak acceleration to epicentral distance and earthquake magnitude. Often known as attenuation data, these data are usually lognormally distributed around a mean relationship of the form (McGuire, 1977a).

$$A = C_1 e^{C_2 M} (R+r_o)^{C_3} .$$

The distribution on earthquake magnitude, $f_M(m)$, can readily be derived from an actual or postulated frequency relationship of the form

$$\log N = a - bM$$

where N is the number of earthquakes having magnitude greater than M, and a and b are constants characteristic of the particular source region under consideration. It follows (Cornell, 1968) that $f_M$ can be derived from the cumulative distribution function, $F_M$, which has the form,

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$$F_M = k\,(1 - e^{-\beta M})$$

where k is a normalizing constant and $\beta = b \ln 10$.

The distribution on distance, $f_R(r)$, depends on the geometry of the problem under consideration. For simple geometries, the distributions can often be integrated analytically. Realistic geometries, however, require numerical evaluation of the integral. A very versatile computer program has been developed (McGuire, 1976b) that incorporates the theory presented above with a numerical integration scheme that allows for evaluation of very complex source-site geometries. The theory of seismic risk assessment by this approach is outlined below.

First, the historical earthquake record and local attenuation data are combined with the experience of the analyst to produce the functional relationships applicable to the area under consideration. The source regions are divided into circular sectors and proportional seismicity is allocated to each sector. The total expected number of events causing maximum accelerations at the site greater than a particular test acceleration are obtained by summing the events from each sector within each source region. The risk associated with this test acceleration is then calculated under the conventional assumption that earthquakes have a Poisson distribution in time. It then follows that the return period is simply the reciprocal of the risk.

## 3.0 GEOLOGY AND HYDROLOGY

The Battelle West Jefferson Nuclear Science Area is located in Madison County, Ohio, about 15 miles west of downtown Columbus (Figure 3-1), in an area where the geology is principally glacial in origin. The following sections which are based principally on BMI (1974), briefly summarize the geology and hydrology.

Glacial deposits at the surface of the Battelle site were deposited as the Wisconsin ice sheet, the last of the four great glaciers of the Pleistocene Age, receded. Some subsurface glacial deposits probably originated during the first of perhaps two major advances of the Wisconsin ice sheet; some of the deep glacial deposits in the buried-valley system probably are related to glacial stages earlier than the Wisconsin sheet.

Glacial deposits comprise two main types: (1) till, or material laid down directly as the ice sheet receded and wasted away, which occurs in this area principally as ground moraine or till plain; and (2) outwash, or sand and gravel, deposited in stratified layers by meltwater.

The till is an unstratified matrix of comparatively impermeable clay containing rock fragments, sand, and gravel. The upland areas of the West Jefferson Battelle site are covered with till in depths varying from 60 feet to more than 200 feet.

In some places, sand and gravel outwash deposits underlie the ground moraine or are interbedded with the till at shallow depths; however, the sand and gravel deposits in the area are thin and discontinuous and are thinly covered with alluvium (river-laid deposits) deposited by the stream during overflow periods.

Beneath the glacial and alluvial deposits in the area are several hundred feet of almost horizontal beds of limestone, dolomite, and shale, which comprise the bedrock of the area. These rocks are of Devonian and Silurian ages. Their surface contours are approximately 750 to 800 feet mean sea level (MSL). The bedrock surface in the area is deeply cut by a buried-valley system carved by

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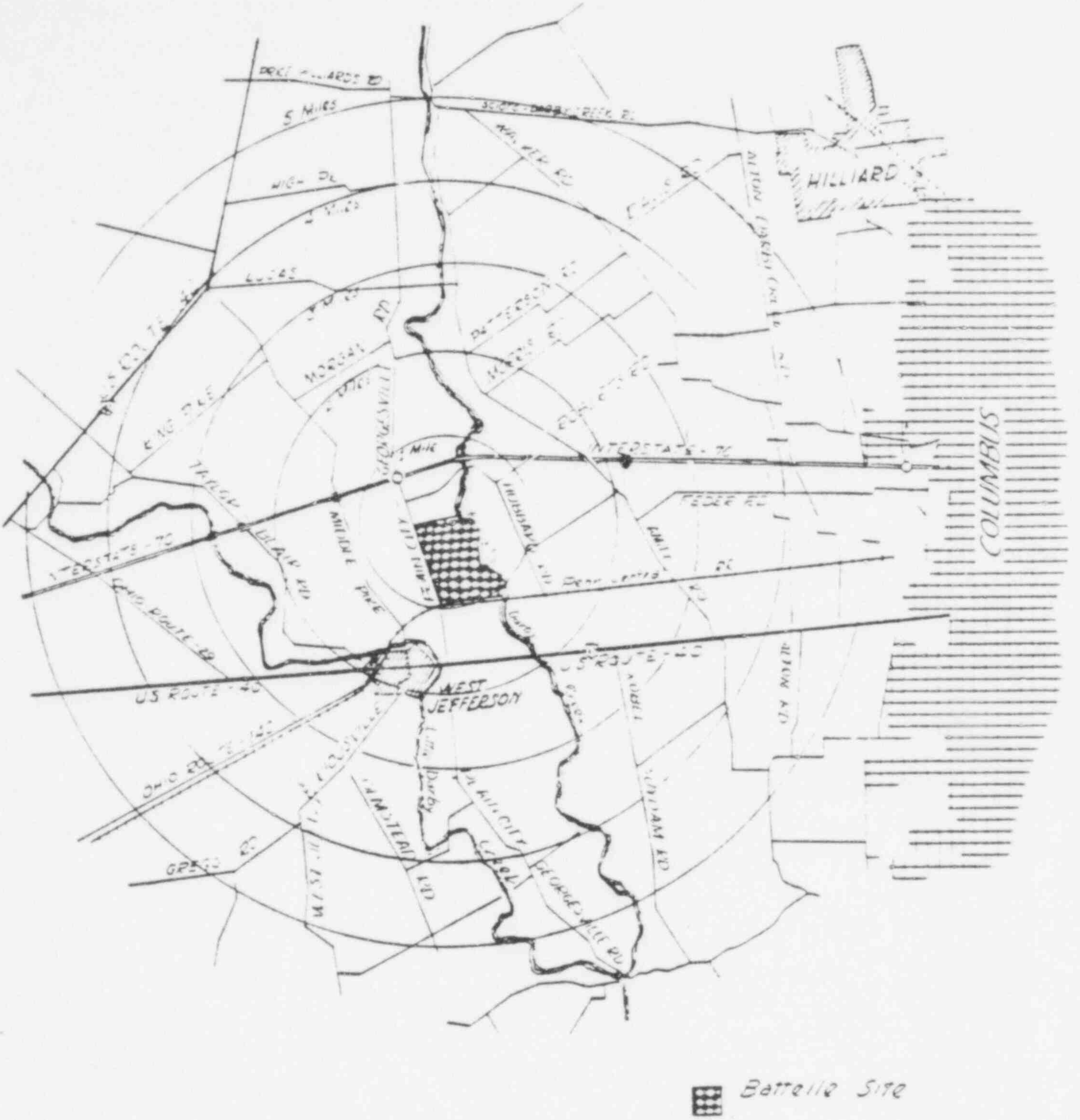

FIGURE 3-1

ROAD MAP OF BATTELLE'S WEST JEFFERSON SITE VICINITY

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streams that drained the area before the period of Pleistocene glaciation. The distance from soil surface to bedrock surface on the site varies from a few feet in places along Darby Creek to more than 200 feet in the buried-valley area near the northwest corner of the property. Clay and fine sand are the principal deposits in the deeper part of the buried-valley system and are not a source of ground water.

There are two aquifers, or sources of water, in the site area. The shallow aquifer is, of course, the dense clay till. The deep, or principal, aquifer is the limestone bedrock underlying the till. Earlier wells in the site area ranged in depth from 10 to 40 feet, which placed them in the glacial deposits. Till is not very permeable and yields water slowly. The effective velocity of water moving through clay under a hydraulic gradient of one percent is reported to be below 0.004 foot per day; for water moving through silt, sand, and loess under the same gradient, the rate is about 0.042 to 0.065 foot per day. Water movement in the till at the Battelle site is probably within the range of the latter figures, since the hydraulic gradient of the water table in the area is only slightly greater than one percent.

The present wells at the Battelle facility lie below the surface of the bedrock. The north well is about 150 feet deep, the centrally located well in the Life Sciences area is 161 feet deep, and the south well is 138 feet deep. Bedrock was encountered at approximately 103 feet below the surface in drilling these wells.

A new gelogic feature of the site is the artificial lake covering an area of about 25 acres that was formed by damming Silver Creek stream south of and down gradient from the reactor site. The surface elevation of the lake is 891 feet MSL.

The source of ground water in the site area is local precipitation. Recharge to the shallow aquifer takes place relatively uniformly over the area. Contours of the water table, which are about 40 feet below the surface, are a subdued replica of the surface topography. Ground water moves downslope at right angles to the contours and follows a path similar to surface runoff. In this case, surface runoff moves downslope into the lake, thence through the controlled dam on the site into Big Darby Creek. All ground water in the site area and that entering on the site is already near its place of discharge.

Test borings carrried out in 1970 for an addition to the Hot Laboratory reaffirmed the geology described above. Only isolated pockets of water were encountered during the boring and foundation-piling excavation operations. These pockets were readily pumped out and remained dry, which indicated that there is no interconnection of the pockets with the lake. Flood hydrology calculation indicated a capacity of releasing water that was about three times the inflow rate measured during the January 1959 floods. It can be concluded that the lake has not adversely affected the hydrology of the area.

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# 4.0 SEISMOLOGY

While the detailed elements of the seismic risk assessment are discussed in Section 5.0, the historical seismic record is of such significance that it is discussed separately below.

A complete evaluation of the historical record is the keystone to the risk assessment because of the important time and spatial distribution information it contains. With regard to time, the record provides detailed historical earthquake frequency information that can best be represented by the relationship, $\log N = a - bM$. The spatial distribution of earthquakes around the site can often be used to delineate seismic source regions within which earthquakes have common characteristics.

Unfortunately, earthquakes have been reliably reported only since the 1930s when a nationwide earthquake instrumentation program was started. The pre-1930 record is a very valuable supplement to the recent recorded data but due to sparse settlement and scattered intensity reports, much of these data cannot be reliably used in developing earthquake statistics. Our general approach is to use the recent recorded data to determine the statistics for magnitude six and less earthquakes and to include the entire historical record in determination of statistics for larger earthquake magnitudes.

We have collected and integrated the data from several seismic data bases to ensure the most complete coverage. The primary source of data was from Nuttli (1978). Data sources consulted by Nuttli include Earthquake History of the United States (Coffman and von Hake, 1973), United States Earthquakes (U.S. Department of Commerce) for the years 1928 through 1972, Preliminary Determination of Epicenters (U.S. Geological Survey) for the years 1972 through 1974, Earthquakes of the Stable Interior, with Emphasis on the Midcontinent (Docekal, 1970), A Contribution to the Seismic History of Missouri (Heinrich, 1941), Seismological Notes (Seismological Society of America) for the years 1911 through 1975, Quarterly Seismological Bulletins of Saint Louis University

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(Stauder et al., 1974-1976) for the interval June 1974 through March 1976, unpublished lists of earthquakes compiled by J. E. Zollweg of Saint Louis University, a list of earthquakes compiled by M. M. Varma and R. F. Blakely of Indiana University and the Preliminary Safety Analysis Reports for proposed nuclear power plant sites at Marble Hill (Jefferson County, Indiana), Calloway (Calloway County, Missouri), Koshkonong (Jefferson County, Wisconsin), Hartsville (Troudale-Smith Counties, Tennessee), Perry (Lake County, Ohio) and Sterling (Cayuga County, New York).

For identification of possible seismic source regions outside the region investigated by Nuttli (central United States), we examined the seismic data base maintained by the U. S. Department of Commerce NOAA. The data for the site area were checked and extended to 1977 by comparing them with other independent data. The Alexandria Laboratories of Teledyne Geotech maintains a data base which consists of LASA, USGS, USC & GS and NEIS data, and these data provided the most complete check and extension. The data through 1974 were checked against the USGS data, provided by D. Perkins. Besides these direct comparisons, the availability of local unreported data was considered by checking with local experts:

Professor G.A. Bollinger
Virginia Polytechnic Institute and State University

Professor Shelton Alexander
Pennsylvania State University

Professor Walter Pilant
University of Pittsburgh

The resulting integrated data base for the area around Columbus is plotted in Figure 4-1. Note that the data base is specified in terms of earthquake magnitude; this follows from our emphasis on the recent recorded data, which is in terms of magnitude. Nuttli's data base is already in terms of magnitude; when we require converting intensities to magnitudes in other data bases, we use the Gutenberg-Richter relationship (1956)M = I

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FIGURE 4-1

SEISMICITY IN VICINITY OF
BMI SITE

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$$M = 1.3 + 0.6I_e.$$

The validity of this relation for the eastern United States has been confirmed by comparisons between it and the more current seismic data base (Chinnery and Rodgers, 1973).

There are several important features of the historical data that must be included in any risk assessment. The most important is the obvious clustering of seismicity in several localities.

The most apparent clustering is in the New Madrid area, site of the famous 1811-12 earthquakes. These earthquakes, which were the largest ever experienced in the eastern United States, resulted in intensities as high as V (M.M.) in the Pittsburgh area. The shocks were felt as far away as Boston, Massachusetts, and the total felt area was by far the largest ever experienced on this continent. The area was well known for its seismicity even before the 1811-12 earthquakes, with historical accounts going back even into Indian legends. As can be seen from Figure 4.1, the seismicity around New Madrid has been relatively contained, thus suggesting a local tectonic origin.

Another area of significant seismicity is the region around Anna, Ohio. This area has been subjected to several earthquakes that produced moderate damage (Bradley and Bennett, 1965) including those of:

| | |
|---|---|
| June 18, 1875 | $m_b = 5.3$ |
| September 19, 1884 | $m_b = 4.7$ |
| September 30, 1930 | $m_b = 5.3$ |
| September 20, 1931 | $m_b = 5.3$ |
| March 2, 1937 | $m_b = 5.3$ |
| March 9, 1937 | $m_b = 5.3$ |

Other areas of repetitive seismic activity include the Fairport-Cleveland, Ohio area, the Attica, New York area, and the Anna, Ohio, area. The activity in the

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Fairport-Cleveland, Ohio, area has been minor. The largest earthquakes associated with this area are of intensity V (M.M.). The Attica, New York, area experienced an earthquake of intensity VIII (M.M.) (August 12, 1929) and two earthquakes of intensity VI (M.M.). Another important, although very distant, source region exists along the St. Lawrence Seaway. This region, which is one of the two most active regions in Canada, has experienced several earthquakes--most notably the February 28, 1925, St. Lawrence Earthquake.

# 5.0 CALCULATIONS AND RESULTS

In the previous sections, we have described the regional seismicity around Pittsburgh and have discussed the most appropriate method of risk analysis. In this section, we apply these concepts to the BMI site. The detailed input to the calculational model is described below, followed by a presentation of the results.

## INPUT

As described in Section 2.0, Seismic Risk Methodology, the input to a probabilistic risk assessment comprises earthquake frequency relations, attenuation functions and a specification of local source regions. Because risk assessment calculations are very sensitive to the particular composition of the input, we consulted with several eminent seismologists during the preparation of input for the BMI facility analysis. Major contributions in this effort were made first by Professor R. Herrmann (St. Louis University), and Professor S. Alexander (Pennsylvania State University).

### Source Regions

After a thorough review of the historical seismicity (Figure 5-1) and geologic/geophysical parameters such as gravity, magnetics, tectonics, and surface geology, it was agreed that the most appropriate source regions should be very similar to those defined by Algermissen and Perkins (1976). Their definition of the source zones was based on the reasonable assumption that future earthquake occurrences will have the same general statistics as historical earthquakes and that the historical variation of earthquake statistics from region to region can be used to delimit general source regions. The final definition of the source region's boundaries was based on the average separation distance for earthquakes of the largest intensities. The representation of the source regions synthesized all the available historical seismicity data and the state of knowledge of the relationship between geologic structure and historical seismicity. We depart from their definition of source regions only where it is necessary to provide more resolution into the seismicity around the site, or to analyze the uncertainty in definition of source regions.

FIGURE 5-1

SEISMICITY IN VICINITY OF BMI SITE

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Figure 5-2 shows the appropriate source regions for the BMI facility. The final determination of the most appropriate set of regions evolved from sensitivity studies. The regions are generally those contained in a 400-kilometer radius around the site.

Our modifications to the Algermissen and Perkins source regions are as follows. First, source zone 64 has been truncated and the seismicity allocated in proportion to the area remaining. Second, source zone 61 (New Madrid) has been extended up the Wabash Valley to the north in accordance with current NRC tectonic interpretation. Finally, we have divided source zone 62 into two parts in an attempt to better segregate the Anna, Ohio, seismicity from the rest of the zone. The three alternative segregations used in our analyses are presented in Figure 5-3. The first model is based on the work of Nuttli and Herrmann (personal communication, August 1978) in their seismic hazard analysis of the central United States. The other two segregations are, in our judgment, reasonable alternatives to this. In the second case, the Anna seismicity is constrained to occur in the vicinity of the historical earthquake activity. The geophysical basis for this particular zonation is that the Anna area is at a hinge of the two geologic structures, the Findley Arch and the Kankakee Arch, where there could be local stress concentrations. The third case is built upon the historical aseismicity of the Columbus vicinity. Nuttli's catalog shows that in the last 70 years no earthquakes have been reported within 60 kilometers of Columbus. Given the apparent geologic stability of the Columbus area as determined from, for example, basement contours, we judge that continued aseismicity of the area is quite plausible.

Source Region Seismicity

Algermissen and Perkins (1976) calculated the rates at which earthquakes occur in each of their source regions based on the seismic data available at that time (1974). These rates, which are related to coefficients in the expression

$$\log N = a - bI$$

are presented in Table 5-1.

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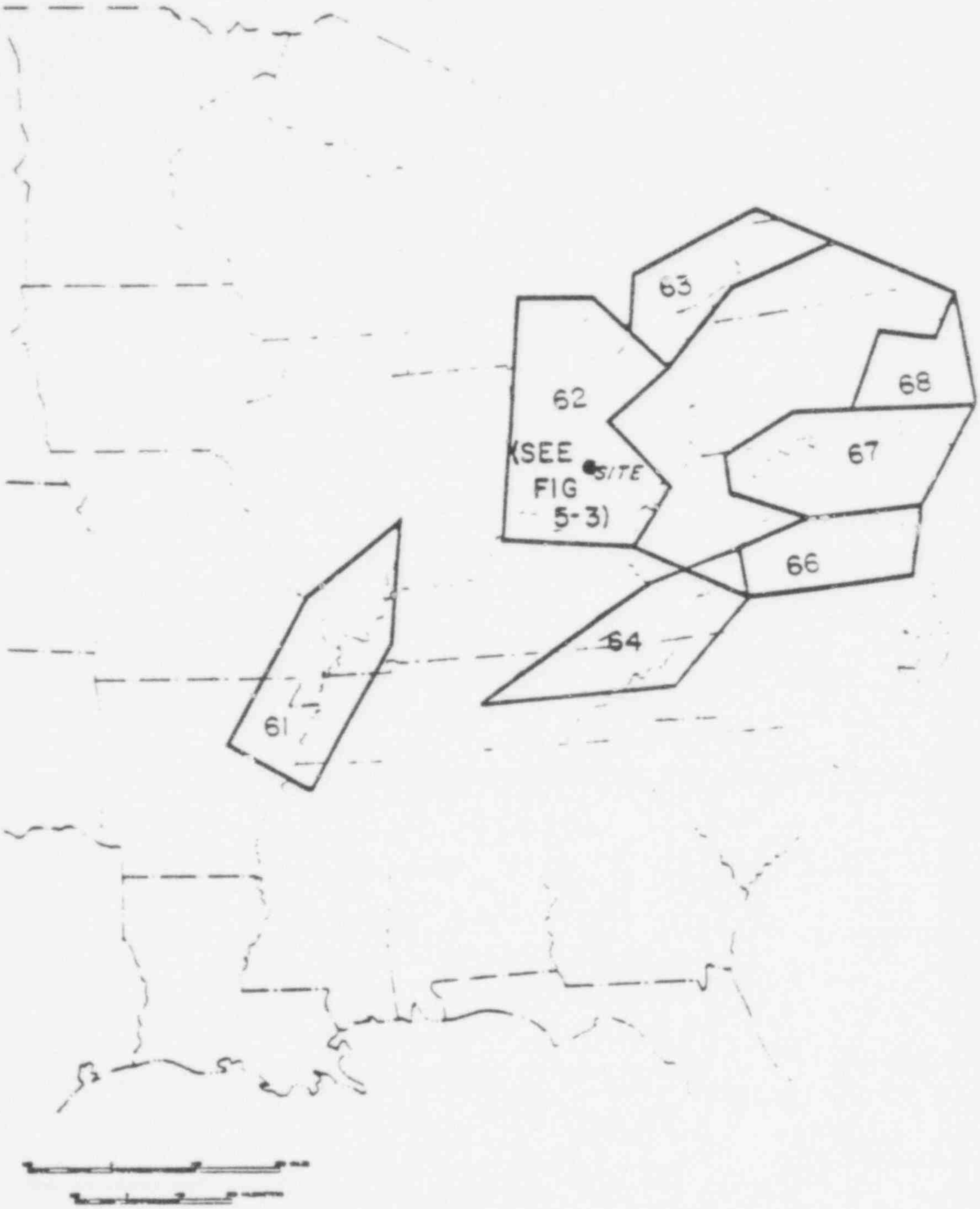
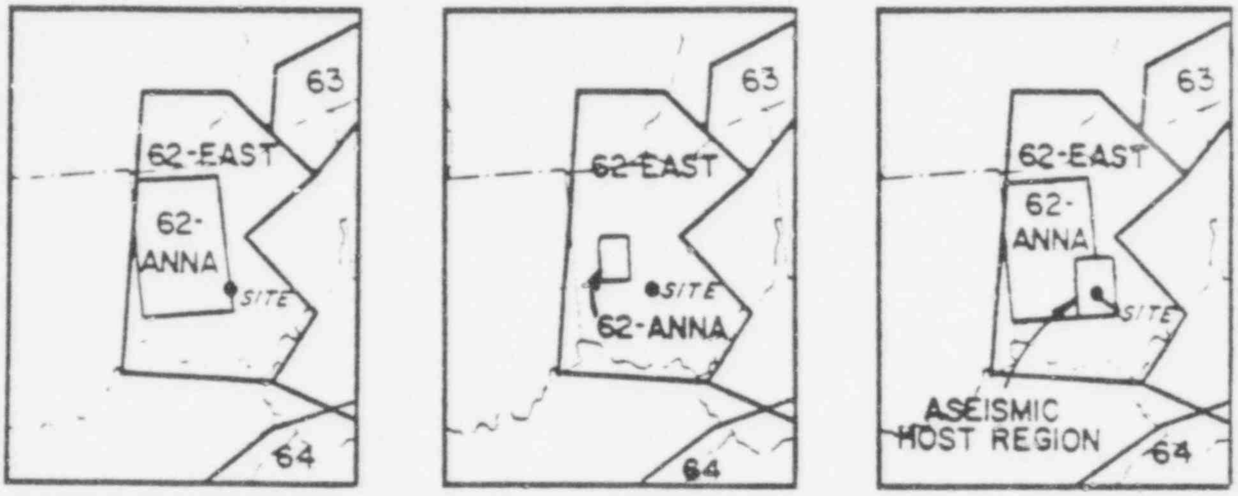


FIGURE 5-2

SEISMIC SOURCE REGIONS USED IN THE ANALYSIS

(Source Region Numbers From Algermissen and Perkins, 1976)



(1) (2) (3)

FIGURE 5-3

THREE ANNA OHIO SEISMIC MODELS
USED IN THE CALCULATIONS

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# TABLE 5-1

## ALGERMISSEN AND PERKINS (1976) EARTHQUAKE PARAMETERS

| Zone No. | Maximum Historical Earthquake | No. of MM Maximum Intensity V's per 100 Years | b-value |
|---|---|---|---|
| 61 | X | 84.5 | .50 |
| 62 | VIII | 22.0 | .50 |
| 63 | VIII | 22.1 | .64 |
| 64 | VIII | 54.4 | .59 |
| 66 | VIII | 13.0 | .59 |
| 67 | VII | 7.8 | .59 |

These parameters define the incremental distribution of earthquake magnitudes (that is the number of earthquakes between I and I + dI) up to an hypothesized maximum intensity. The Algermissen and Perkins (1976) maximum magnitudes corresponded to the largest historically observed earthquakes.

We updated this data base to 1977 as described in Section 4.0 and our re-examination of the seismicity in each region, except source region 61, indicated that there was no change in the earthquake statistics and therefore no basis for altering the Algermissen and Perkins statistical parameters. Source region 61 has recently been carefully reviewed by Nuttli (1978), and his analysis, which includes substantial microseismic data, indicates that the frequency of large earthquakes is substantially greater than as reported by Algermissen and Perkins. We use Nuttli's values in our calculations. The maximum magnitude earthquake is a very uncertain parameter, particularly in the less seismic areas that we are considering here. Accordingly, we judged that it was reasonable and moderate to assume that each region was capable of earthquakes of roughly one-half magnitude unit greater than the largest magnitude earthquake in the historical record. The Gutenberg-Richter relationship is here, again, generally used to relate historical intensity to magnitude. For calculational simplicity, we also specify a lower cut-off magnitude for each region. Sensitivity studies showed that earthquakes with magnitudes less than the lower cut-off do not affect the risk at the site. Finally, the calculational risk model requires that the distribution of earthquakes be specified as a complementary cumulative distribution (number of earthquakes with magnitudes greater than M) rather than incrementally. The results of this integration, up to the upper cut-off magnitude, are presented in Table 5-2 along with the upper and lower cut-off magnitudes.

Attenuation

The attenuation relationship was chosen for the credibility it has obtained from extensive review and evaluation. None of the other available relationships (McGuire, 1976b lists 25 published relations) has been reviewed or scrutinized as carefully as the components of the one used in this analysis.

## TABLE 5-2

| ZONE | $N = N_o \, 10^{-b(M-M_o)}$ | | | MAXIMUM EARTHQUAKE MAGNITUDE | LARGEST HISTORICAL EARTHQUAKE (MM) |
|---|---|---|---|---|---|
| | $N_o$ | $M_o$ | b | | |
| 61 | 10.3 | 4.0 | 0.75 | 8.0 | X |
| 62-Anna | 0.14 | 4.0 | 0.92 | 6.5 | VIII |
| 62-East | 0.42 | 4.0 | 0.92 | 5.5 | VII |
| 63 | 0.63 | 4.0 | 1.13 | 6.5 | VIII |
| 64 | 1.29 | 4.0 | 1.00 | 6.5 | VIII |
| 66 | 0.36 | 4.0 | 1.05 | 6.5 | VIII |
| 67 | 0.21 | 4.0 | 1.05 | 6.0 | VII |

The basic approach is to develop the functional form of the relationship by synthesizing the results of several previous investigations. The specific relationship is then defined by a fit of the resulting functional form to the only available strong motion data in Central/Eastern United States.

The functional form is developed from three separate regression analyses. The analyses resulted in best fits to the data for:

- Site intensity vs. distance and epicentral intensity
- Peak acceleration vs. site intensity, earthquake magnitude and distance
- Earthquake magnitude vs. epicentral intensity

The first of these relationships is contained in Professor Bollinger's contribution to USGS Professional Paper 1028 on the Charleston, South Carolina, 1886 earthquake (Bollinger, 1977). Bollinger's analysis of the 800 intensity observations from that earthquake resulted in the development of a new intensity attenuation relation that is similar to other published relations but has the added credibility of being based on the most complete set of East Coast data. Bollinger's use of the actual intensity observations rather than the isoseismals permits the specification of fractile variations to the fit. Bollinger's 50 percent fractile relationship is

$$I = I_e + 2.87 - 0.0052\,\Delta - 2.88\log\Delta$$

$I$ = site MM intensity

$I_e$ = epicentral MM intensity

$\Delta$ = epicentral distance (km)

Figure 5-4 compares several of Bollinger's fractile relations with other recently published attenuation functions.

The return period associated with the specified acceleration is then the reciprocal of the risk. It follows from the definition of return period that accelerations with a particular return period have a 63 percent probability of being exceeded within the return period.

Our estimate of the seismic risk represents the weighted results from 18 individual calculations. The five calculations represent six base cases and 12 perturbations of input parameters about these bases. The perturbations are weighted by subjective estimates of their probability of occurrence to derive a weighted best estimate of the seismic hazard.

The parameters that are considered uncertain and which are included in our estimate of the risk are the intercept of the attenuation relation expressed through the value of $\gamma$ , and the value of the acceleration dispersion.

The base cases are considered to consist of the following input:

- The three separate definitions of Anna, Ohio, source regions
- Maximum earthquake = largest historical plus one-half magnitude unit
- Attenuation intercept, $\gamma = 0.90$
- Acceleration dispersion, $\sigma_{\ell nA} = 0.60$

We characterize the uncertainty in these data by considering that the value $\gamma$ = 0.9 to be also 70 percent probable with perturbations of $\gamma = 1.0$ and $\gamma = 0.80$ to be respectively 15 percent probable. We further weight the acceleration dispersion of 0.60 at 70 percent with 15 percent weights respectively being assigned to 0.50 and 0.70. The three Anna, Ohio, source region definitions are weighted equally.

The best estimate in Figure 5-7 is the weighted summation of these 15 calculations. The plus one standard deviation is derived from 50 percent-50 percent

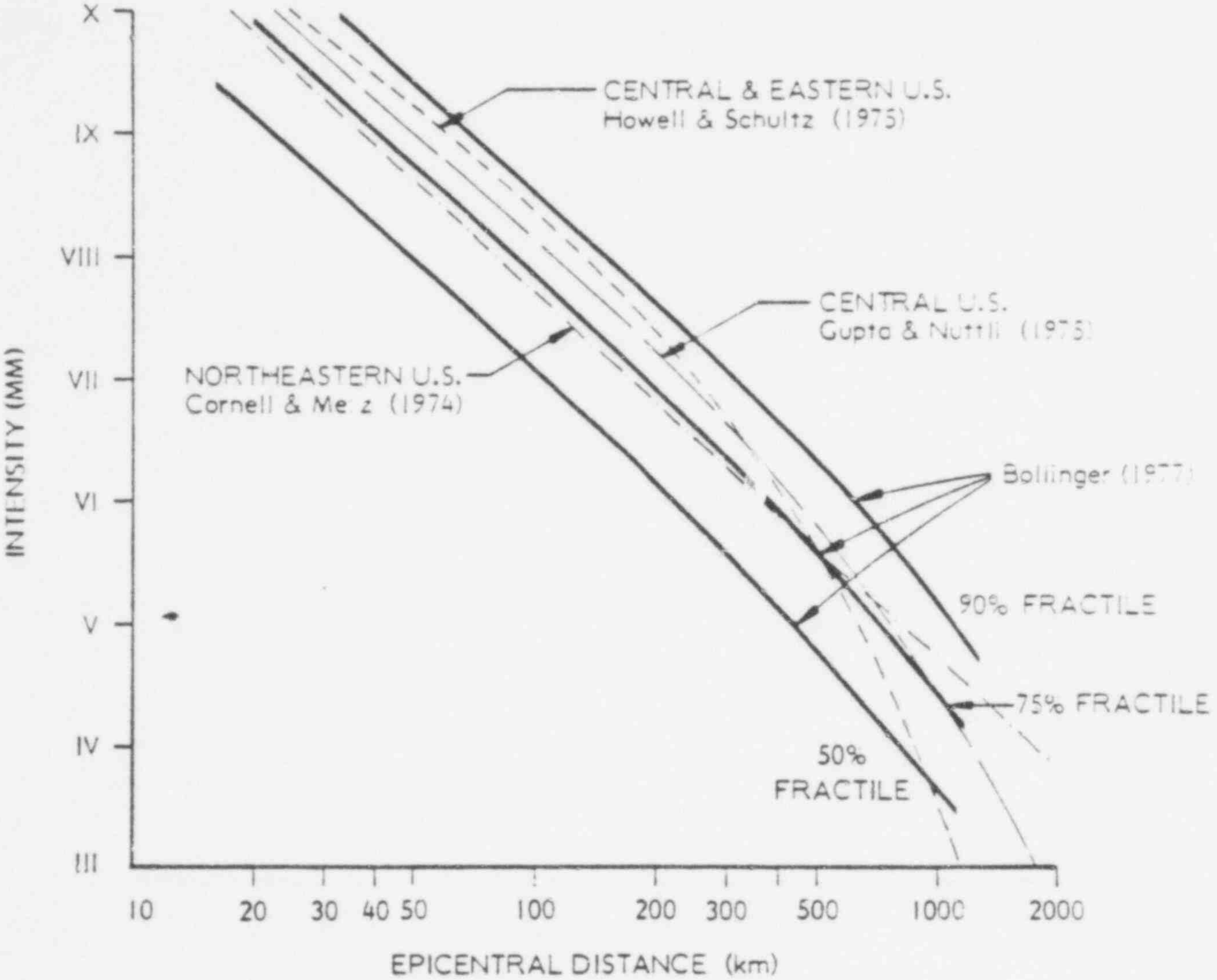

FIGURE 5-4

COMPARISON OF ATTENUATION FUNCTIONS

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The acceleration relation that couples with Bollinger's relationship was derived from analysis on nearly 1500 world-wide accelerograms (USNRC, 1977). Extensive statistical analysis resulted in the following correlation

$$\log A_H = 0.14 I + 0.24 M - 0.68 \log \Delta + \gamma$$

$A_H$ = peak horizontal acceleration

$M$ = earthquake magnitude

$\gamma$ = region-specific parameter.

Finally, we again use the Gutenberg-Richter relationship to relate earthquake magnitude to epicentral intensity,

$$M = 1.3 = 0.6 I_e.$$

Combination of these three correlations results in

$$\log A_H = 0.47 M + 0.0905 - 1.08 \log \Delta - 0.0007 \Delta + \gamma$$

The value of $\gamma$ was determined by fitting this relationship to the only available acceleration data from Eastern/Central United States (Herrmann et al., 1977 and USGS, 1976). Note from Table 5-3 that three instruments did not trigger during the March 25, 1976, earthquake. The accelerations at these stations are assumed to be just under the trigger level for the instruments, 1 percent g. Although the recording sites for these data are similar to the BMI site, we allow for the possibility for some site amplification in these data by considering three different fits to the data. We judge that the most appropriate fit to the data is for $\gamma = 0.9$. In consideration of the importance of this parameter, we also include the alternative values of $\gamma = 0.8$ and $\gamma = 1.0$ in our analysis. These three relationships are compared to the data in Figure 5-5.

As Figure 5-5 suggests, it is very important to consider the magnitude of the data dispersion about our mean attenuation relationship. Each of the component relationships that were synthesized into our attenuation relationship were themselves best fits to data with associated dispersion. Because the data set used in

## TABLE 5-3

## LOCATIONS OF ONLY APPROPRIATE STRONG MOTION RECORDINGS

| | | | | |
|---|---|---|---|---|
| 1 | 6 13 75 | N MADRID, MISSOURI | | |
| 2 | 3 25 76 | ARKABUTLA DAM, MISSISSIPPI | L | TOE |
| 3 | " | " | L | CREST |
| 4 | " | " | R | ABUT |
| 5 | " | TIPTONVILLE, TENNESSEE | | |
| 6 | " | N MADRID, MISSOURI | | |
| 7 | " | WAPPAPELLO DAM | | CREST |
| 8 | " | " | | TOE |
| 9* | " | MEMPHIS, TENNESSEE | | |
| 10* | " | SARDIS DAM, MISSISSIPPI | | |
| 11* | " | POPLAR BLUFF, MISSOURI | | |

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*Instrument, set at 1 percent g, did not trigger

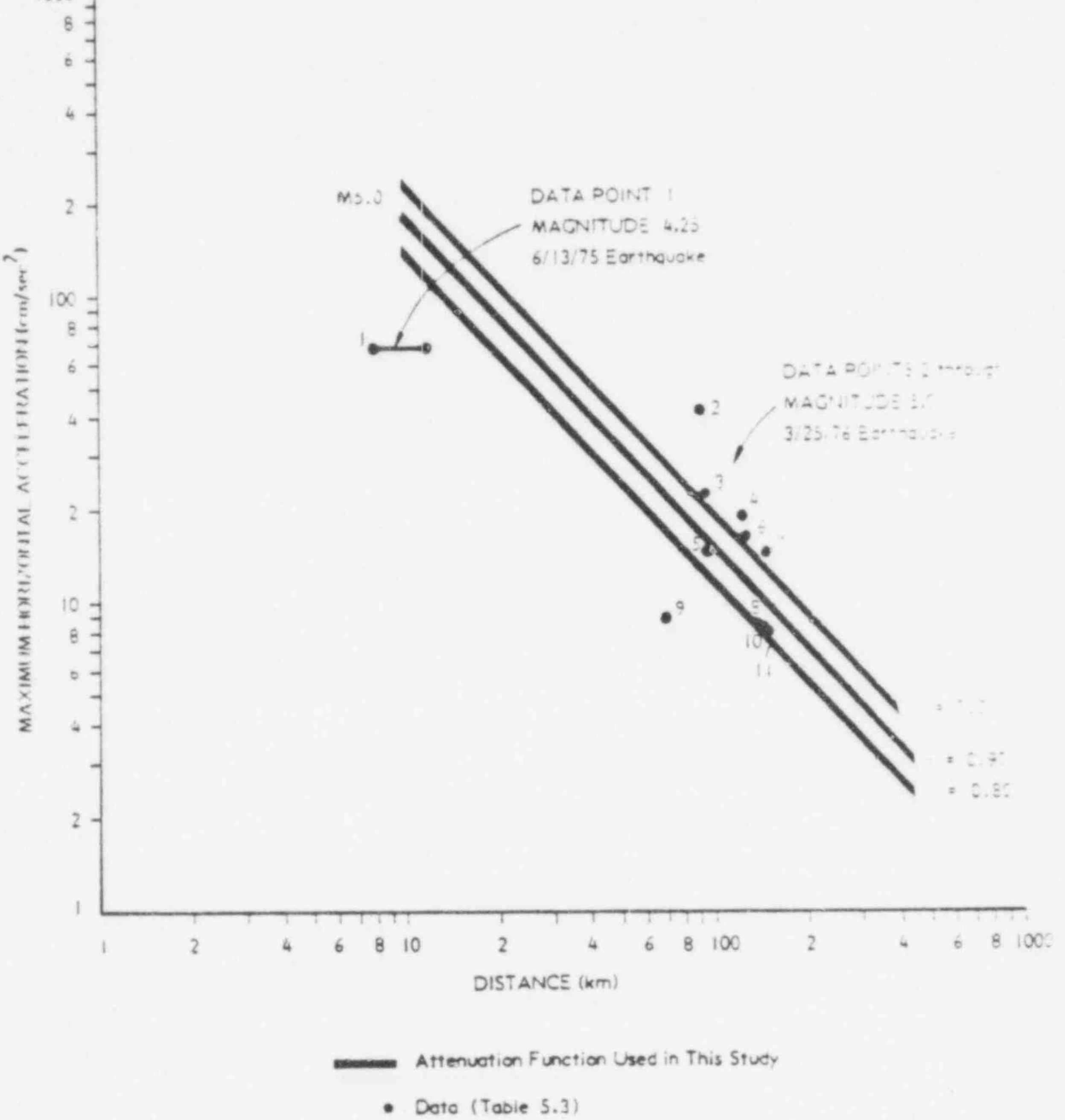

FIGURE 5-5

COMPARISON BETWEEN
ATTENUATION FUNCTION AND DATA

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these individual analyses is diverse and not readily available, we choose to assess the dispersion for our attenuation relationship through consideration of other data sets and other attenuation analyses. The statistical properties of peak acceleration are usually characterized in terms of the natural logarithm of acceleration and thus the dispersions are dispersions of ln $(A_H)$. Typical standard deviations of this parameter range from .51 (McGuire, 1974) to 1.2 (Esteva, 1970) with a median value close to the value of 0.707 determined by Donovan (1974). Since these assessments of the data dispersion are statistical averages over all possible site conditions, travel paths, and tectonic settings, we judge that the value of 0.60 is a reasonable best estimate of the one standard deviation dispersion on acceleration for our specific site.

Because the data base from which our attenuation relation was derived consists of predominantly far-field accelerations, the relation is less valid in the near-field. We account for this by limiting the peak accelerations in the near field. The details of this near field response are not important because of the aseismicity of the Columbus area and the distance from the site to significant sources. This complete attenuation relationship is presented in Figure 5-6 for several magnitudes.

## RESULTS

The results were obtained by computer calculations with a risk analysis code (McGuire, 1976b) that is based on the work of Cornell (1968). The basis for this approach was summarized in Section 2.0.

As described in Section 2.0, the computer code calculates, for circular sectors within each source region at the site, the expected number of earthquakes causing accelerations greater than a specified acceleration and this is done for each source region and the host region. The expected numbers are summed for each region, and the resulting risk calculated from

risk = 1.0 - exp(- total expected number).

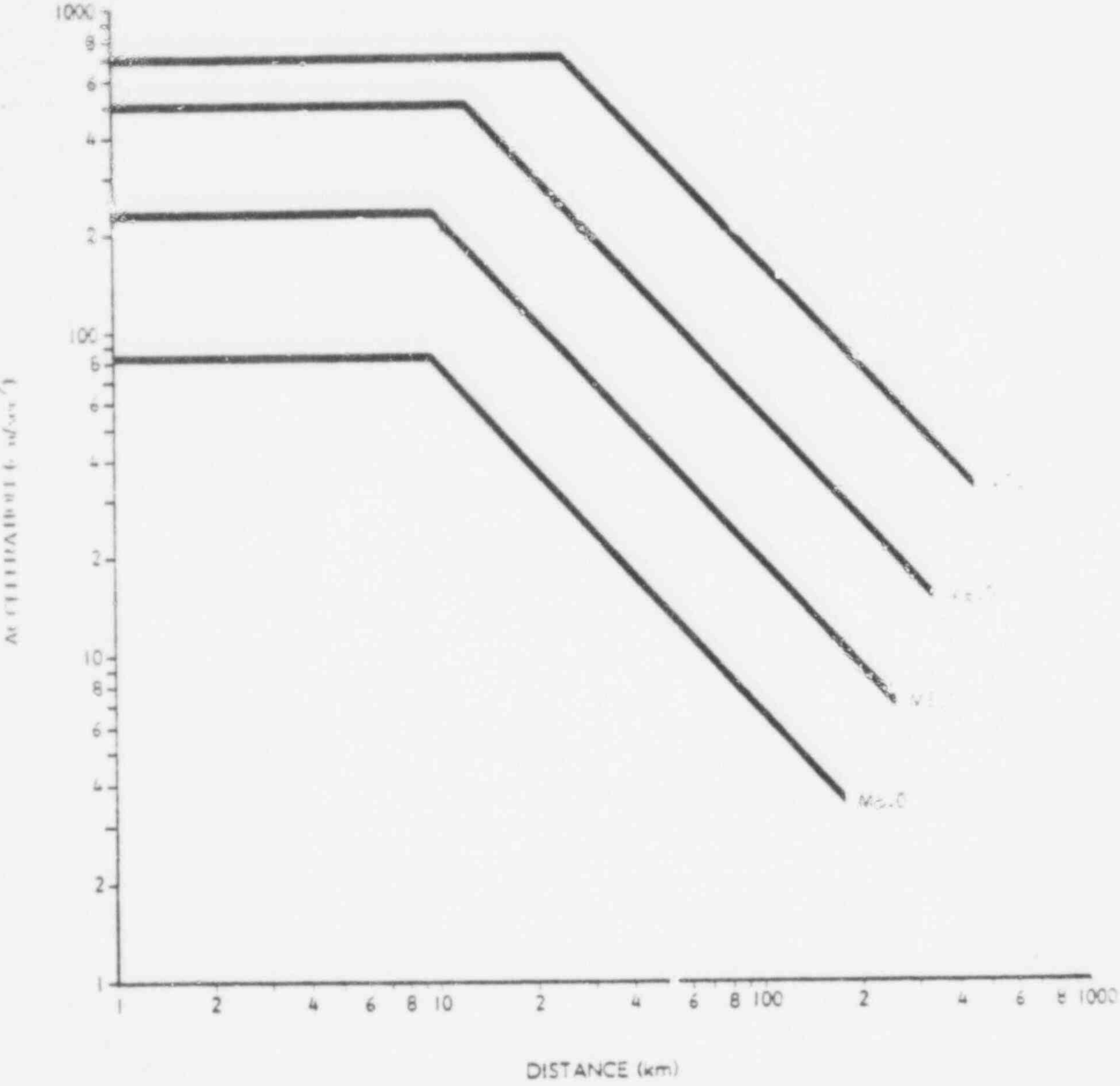

FIGURE 5-6

ATTENUATION RELATIONSHIP USED
IN THE ANALYSIS ( α =1.0)

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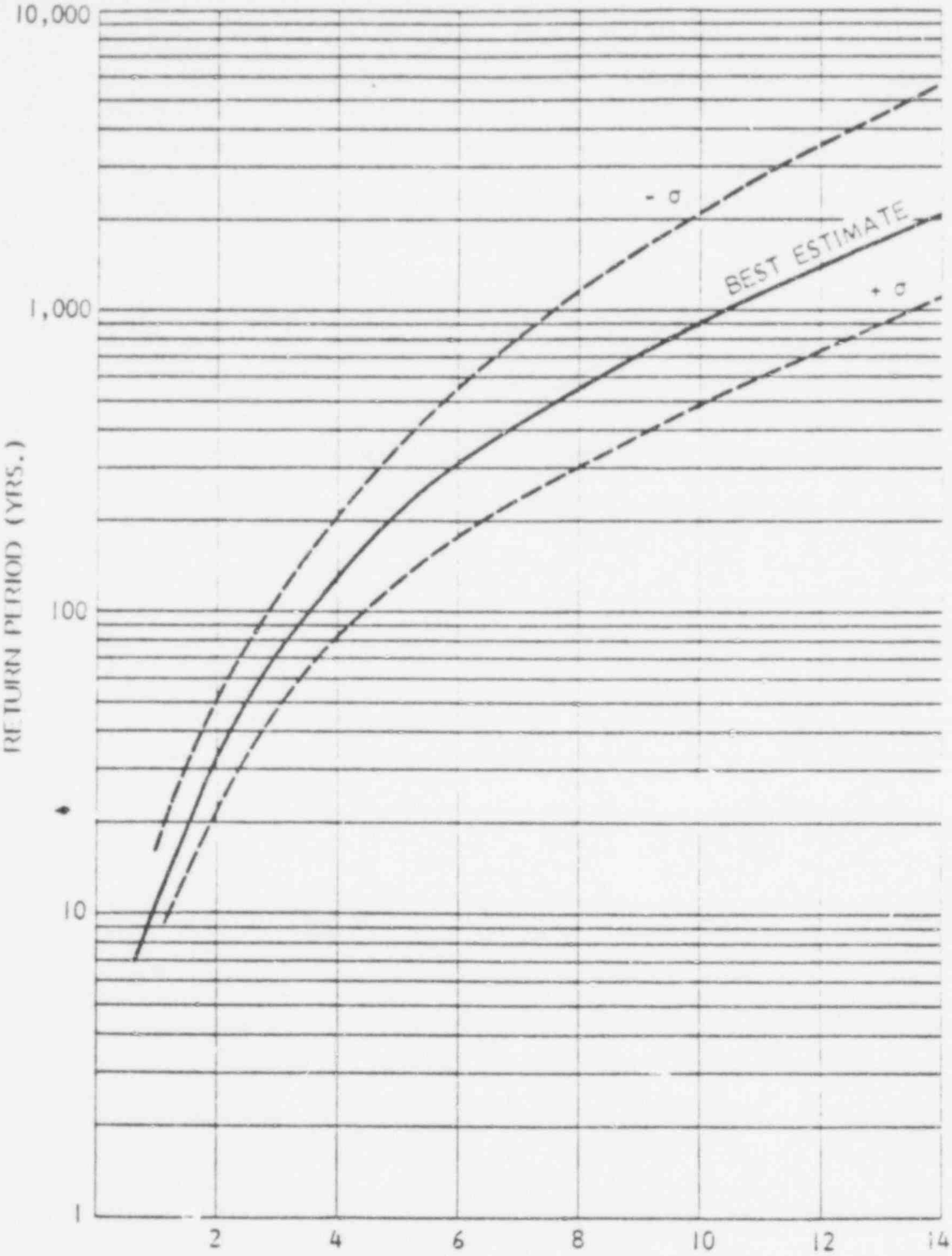

FIGURE 5-7

RETURN PERIODS FOR SEISMIC ACCELERATION
AT THE BMI WEST JEFFERSON FACILITY

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weighting of the six more conservative runs and similarly for the minus one standard deviation.

## RESPONSE SPECTRUM

These results define the peak horizontal acceleration at the facility for various return periods. We have also determined an appropriate response spectrum for the site since some structures and equipment at the BMI facility have sufficiently low fundamental frequencies to experience spectral amplification of the ground motion. The response spectrum for the site clearly cannot be developed in association with a specific earthquake; our return period accelerations represent an integrated effect at the site from an extraordinary variety of earthquakes and the response spectrum must reflect this. Accordingly, we judge that the <u>shape</u> of the spectrum should be similar to the Newmark-Blume statistically-based spectra from which Regulatory Guide 1.60 evolved. Because of an almost total lack of good data, the absolute level of spectral accelerations appropriate for design is very difficult to determine. For example, it is well known that attenuation in the Eastern United States is much less rapid than in the West (Alsup, 1972). Since the basis for Regulatory Guide 1.60 is exclusively western data, one might argue that the appropriate response spectral amplitudes should be in excess of the mean, perhaps the one standard deviation level, to account for the lesser attenuation. Alternatively, given the objective of best estimate results with minimum conservatism, it could be argued that the mean response spectrum for alluvium in WASH 1255 is most appropriate. There is, unfortunately, very little quantitative basis for choosing between these alternatives.

In our final consideration, we emphasize two points. First, the controversy surrounding the nature of attenuation (Q and its possible frequency dependency) and second, recent calculations at Lawrence Livermore Laboratory which show that the effects of straight line approximations of statistical spectra make Regulatory Guide 1.60 slightly more conservative than a one standard deviation spectrum. Accordingly, it is our judgment that the mean response spectrum for alluvium presented in WASH 1255 is the most appropriate for analysis of the BMI facility.

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In summary, we have combined the best available input data with the most credible tools of seismic risk analysis to determine the return period of acceleration at the BMI facility. The results, shown in Figure 5-7, account for the dispersion of the data about the functional relationships used in the model. Further, the results are insensitive to variations in the source zone geometries or seismic histories. Response spectral accelerations can be determined by scaling the mean response spectrum in WASH 1255 to the desired peak acceleration.

## 6.0 BIBLIOGRAPHY

Algermissen, S.T., 1969. Seismic Risk Studies in the United States. 4th World Conference on Earthquake Engineering, V. 1, p. 14.

Algermissen, S.T., 1974. Seismic Risk Studies in the United States. 5th World Conference on Earthquake Engineering.

Algermissen, S.T. and Perkins, D.M., 1976. A Probabilistic Estimate of Maximum Acceleration in Rock in the Contiguous United States: USGS Open File Report 76-416.

Alsup, S.A., 1972. "Estimation of Upper Mantle Q Beneath the United States from $P_n$ Amplitudes," PhD thesis, George Washington University.

Battelle Memorial Institute Revised FSAR for the Battelle Research Reactor Docket No. 50-6 March 26, 1974.

Bollinger, G.A., 1977. "Reinterpretation of the Intensity Data for the 1886 Charleston, South Carolina Earthquake." USGS Professional Paper 1028, in Press.

Bollinger, G.A., 1973. "Seismicity of the Southeastern United States." BSSA 63(5), p. 1785.

Bradley, E.A., and Bennett, T.J., 1965, "Earthquake History of Ohio": Seismol. Soc. America Bull., v. 55, p. 745-752.

Brazee, R.J., 1976. An Analysis of Earthquake Intensities with Respect to Attenuation, Magnitude and Rate of Recurrence. NOAA Tech. Mem. EDS N6SDC-2.

Chinnery, M.A. and Rodgers, D.A. 1973. "Earthquake Statistics in Southern New England," Earthquake Notes, Vol. 44, pp 89-103.

Cornell, C.A., 1968. "Engineering Seismic Risk Analysis," BSSA 58(5) p. 1583.

Cornell, C.A., and Merz, H.A., 1974, A Seismic Risk Analysis of Boston: Jour. Structural Div., A.S.C.E., 110, no. ST 10, Proc. Paper 11617, p. 2027-2043.

Cornell, C.A. and Mertz, H.A., 1974. "Seismic Risk Analysis of Boston." ASCE Annual Mgt, Preprint #2260. Cincinnati, Ohio.

Cornell, C.A. and Vanmarke, 1976. The Major Influences on Seismic Risk. 6th World Conference on Earthquake Engineering.

Docekal, J., 1970, Earthquakes of the stable interior, with emphasis on the midcontinent (Ph.D. dissert.): Lincoln, Univ. Nebraska, v. 1, 169 p., v. 2, 332 p.

688 201

Donovan, N.C., 1974. "A Statistical Evaluation of Strong Motion Data Including the February 9, 1971, San Fernando Earthquake," World Conf. Earthquake Eng., 5th, Rome 1973, Proc., v. 1, p. 1252-1261.

Esteva, L., 1970. "Seismic Risk and Seismic Design Decisions," in Hansen, R.J., ed., Seismic Design for Nuclear Power Plants; Cambridge, Massachusetts Inst. Technology Press, p. 142-182.

Evernden, J.F., 1970. "Study of Regional Seismicity and Associated Problems," BSSA 60(2) p. 393.

Fox, F.L., 1970. "Seismic Geology of the Eastern United States," Bulletin of the Assoc. of Engin. Geologists VII (1) p. 21.

Gupta, Indra N., and Nuttli, Otto W., 1975, Spatial Attenuation of Intensities for Central United States Earthquake: submitted to Seismol. Soc. America Bull.

Gutenberg, B. and Richter, C.F., 1956. Earthquake Magnitude, Intensity, Energy, and Acceleration, BSSA V.32, p. 163.

Herrmann, R.B., 1974, Surface Wave Generation by Central United States Earthquakes (Ph.D. dissert.): St. Louis, Saint Louis University, 263 p.

Herrmann, R.B., Fischer, G.W., Zollweg, J.E., 1977. The June 13, 1975 Earthquake and its Relationship to the New Madrid Seismic Zone, BSSA Vol. 67, No. 1, p. 209.

Howell, B.F., 1974. "Seismic Regionalization in North America Based on Average Regional Seismic Hazard Index," BSSA 64(5) p. 1509.

Howell, B.F., and Schultz, T.R., 1975. Attenuation of Modified Mercalli Intensity with Distance from the Epicenter: Seismol. Soc. America Bull., V. 65, p. 651-665.

Liu, S.C. and Fagel, L.W., 1972. Earthquake Environment for Physical Design: A Statistical Analysis. The Bell System Technical Journal, Vol. 51, No. 9, p. 1957.

McGuire, R.K., 1974. "Seismic Structural Response Risk Analysis, Incorporating Peak Response Regressions on Earthquake Magnitude and Distance," Massachusetts Inst. Technology, Dept. Civil Eng., Research Rept. R74-51, 371 p.

McGuire, R.K. 1976a. "The Use of Intensity Data in Seismic Hazard Analysis." 6th World Conference on Earthquake Engineering.

McGuire, R.K., 1976b. "FORTRAN Computer Program for Seismic Risk Analysis:" U.S.G.S. Open File Report 76 - 67.

McGuire, R.K., 1977a. "A Simple Model for Estimating Fourier Amplitude Spectra of Horizontal Ground Acceleration." Submitted to BSSA.

688 202

McGuire, R.K., 1977b. Effects of Uncertainty in Seismicity on Estimates of Seismic Hazard for the East Coast of the United States. BSSA Vol. 67 No. 3, p. 827.

Milne, W.G. and Davenport, A.G., 1969. "Distribution of Earthquake Risk in Canada." BSSA 59(2) p. 729.

Necioglu, A., and Nuttli, O.W., 1974. "Some Ground Motion and Intensity Relations for the Central United States:" Earthquake Engineering and Structural Dynamics, v. 3, p.111-119.

Nuttli, O.W., 1973. State of the Art for Assessing Earthquake Hazards in the United States, U.S. Army WES Misc. Paper S-73-1.

Nuttli, O.W., 1973a. "Seismic Wave Attenuation and Magnitude Relations for Eastern North America:" Jour. Geophys. Research, v. 78, p. 876-885.

Nuttli, O.W., 1974. "Magnitude-recurrence relation for central Mississippi Valley earthquakes": Seismol. Soc. America Bull., v. 64, p. 1189-1207.

Nuttli, O.W., 1978. "The seismicity of the central United States": to appear in Nuclear Geology published by the G.S.A.

Nuttli, O.W., and Zollweg, J.E., 1974. "The Relation between Felt Area and Magnitude for Central United States Earthquakes:" Seismol. Soc. America Bull., v. 64, p. 73-85.

Oliveira, C., 1974. "Seismic Risk Analysis," Earthquake Engineering Research Center Report EERC 74-1.

Schnabel, P.B. and Seed, H.B., 1973. Accelerations in Rock for Earthquakes in the Western United States, BSSA V. 63, p. 501.

Seismological Society of America, Seismological notes: published in the Seismol. Soc. America Bull. since 1911.

Stauder, W., and Nuttli, O.W., 1970. "Seismic Studies: South Central Illinois Earthquake of November 9, 1968:" Seismol. Soc. America Bull., v. 60, p. 973-981.

Stauder, W., Best, J., Cheng, S.H., Fisher, G., Kramer, M., Morrissey, S.T., Schaefer, S., and Zollweg, J., 1974-1976. Southeast Missouri regional seismic network quarterly bulletins Nos. 1-7: St. Louis, Saint Louis University.

Stepp, J.C., 1971. An Investigation of the Earthquake Risk in the Puget Sound Area by Use of the Type I Distribution of Longest Extreme. Ph.D. Dissertation Penn. State Univ. - Geophysics.

Stepp, J.C., 1974. "Analysis of Completeness of the Earthquake Sample in the Puget Sound Area and Its Effect on Statistical Estimates of Earthquake Hazard." Proceeding of Conf. on Microzonoticm, Seattle.

Street, R.L., Herrmann, R.B., and Nuttli, O.W., 1974. "Earthquake Mechanics in the Central United States": Science, v. 184, p. 1285-1287.

Trifunac, M.D. and Brady, A.G., 1975. "On the Correlation of Seismic Intensity Scales with the Peaks of Recorded Strong Ground Motion." BSSA 65(1) p. 139.

U.S. Department of Commerce, NOAA, 1973. Earthquake History of the United States. Edited by Coffman and Hake.

U.S. Geological Survey, Preliminary Determination of Epicenters, published annually by the National Earthquake Information Service, Denver, Colorado.

U.S. Geological Survey, 1976. Seismic Engineering Program Report, April-June 1976, Menlo Park, Calif.

U.S. Nuclear Regulatory Commission, 1977. The Correlation of Peak Ground Acceleration Amplitude with Seismic Intensity and Other Physical Parameters. NUREG-0143.

Vagliente, V., 1973. Forecasting the Risk Inherent in Earthquake Resistant Design. Ph.D. Dissertation, Civil Eng. Dept. Stanford University.

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