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**SEISMIC RISK ANALYSIS FOR
THE BABCOCK AND WILCOX FACILITY
LEECHBURG, PENNSYLVANIA**

Submitted to:

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A THREE DIMENSIONAL PLOT OF
HISTORICAL SEISMICITY AROUND THE SITE

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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 Babcock and Wilcox Plutonium Fuel Fabrication facility at Leechburg, Pennsylvania.

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, being 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.

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 adapted. Earthquakes as far from the site as 1,000 km were included, as were 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, three seismologists with particular expertise in the local and regional seismology:

Professor Shelton Alexander, Pennsylvania State University
Professor G.A. Bollinger, Virginia Polytechnic Institute and
State University
Professor R. Herrmann, St. Louis University

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 Babcock and Wilcox facility will experience 0.05 g every 220 years and 0.10 g every 1400 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.

Figure 1.1

RETURN PERIOD - PEAK ACCELERATIONS
FOR THE BABCOCK AND WILCOX 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 probabilistic Poisson model for the risk assessment at the Babcock and Wilcox facility.

There are generally two distinctly different approaches to seismic risk analysis; probabilistic 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 probabilistic 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 probabilistic 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 Babcock and Wilcox facility for two reasons. First, as will be shown below, the Pittsburgh 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 eastern United States is very diffuse and it 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 probabilistic 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), in the San Francisco Bay Area (Vagliante, 1973), in 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.

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 Babcock and Wilcox 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).

$$A = C_1 e^{C_2 M} (R+r_0)^{C_3}$$

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,

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

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

SITE DESCRIPTION

Location

The Babcock and Wilcox site is situated 0.5 miles southeast of the town of Leechburg, Pennsylvania, on the banks of the Kiskiminetas River about 8 river miles upstream from its confluence with the Allegheny River. The site lies just north of the southern boundary of the Leechburg Quadrangle (U.S.G.S. 7.5' topographic map series) at latitude $40^{\circ}37'35''\text{N}$ and longitude $79^{\circ}35'10''\text{W}$.

Topography

The site area lies within the east central part of the Allegheny Plateau physiographic province. The relatively flat surface of the plateau has been dissected into narrow, accordant ridges; and most of the land surface of the area is in slope. Maximum relief between the accordant ridges of the plateau and the floodplain of the Kiskiminetas River is approximately 500 feet. Local relief in the small valleys of the area ranges between 250 and 400 feet. Valley side slopes are often abrupt and steep with average slope angles ranging between 20 and 30 degrees.

The Babcock and Wilcox site is situated on the natural floodplain of the Kiskiminetas River. In this area the Kiskiminetas floodplain is a narrow discontinuous surface averaging less than 500 feet in width that is incised 100 to 150 feet below the level of adjacent upland valleys. This floodplain is generally widest and best developed on the concave sides of meander bends and in abandoned meander scars; and it is commonly bounded by steep valley side walls 150 to 400 feet high. The Babcock and Wilcox site is crowded onto a 400- to 500-foot wide segment of the floodplain between the river channel and a relatively gentle

strath terrace scarp. This terrace scarp is about 140-feet high, has an average slope of approximately 10 percent and a maximum slope of nearly 25 percent. Midway up this scarp, a 150-foot wide artificial bench has been cut by a now inactive coal strip mine.

Surficial Geology

The Babcock and Wilcox site is underlain by Holocene deposits of the modern Kiskiminetas River. Bore hole data indicates that these fluvial deposits are 40- to 50-feet thick in the site area (General Analytics, 1969a). They consist of complexly interbedded layers and lenses of brown to gray clay, silt, sand, and gravel. The uppermost 5 to 15 feet of these deposits are mostly silty sands and clayey silts, the next 10 to 20 feet are dominated by silty to clayey sand and gravel, and the lowest 10 to 20 feet are mainly sandy silt containing small amounts of gravel and clay (General Analytics, 1969a, 1969b).

The soils of the Kiskiminetas floodplain are mapped as Chavies and Whitwell soils by the U.S. Soil Conservation Service (1971). The Chavies soils are deep and well drained, and the Whitwell soils are deep but only moderately to poorly drained. Both soils are typically associated with high, infrequently flooded floodplain areas.

Bedrock Geology

The floodplain deposits of the Babcock and Wilcox site are underlain by a 16,000 foot sequence of Paleozoic sedimentary rocks. These rocks are only very gently folded, however, and only the top few hundred feet are significant to this study. These uppermost rock strata are Pennsylvanian age shale, claystone, sandstone, limestone, and coal of the Allegheny Group. These rocks are complexly interbedded and are dominated by the shale, claystone and sandstone. The limestone and coal make up only 25 feet out of the average 325-foot thickness of the group (Hughes, 1933; Poth, 1973).

The upper boundary of the Allegheny Group is defined as the top of the Upper Freeport coal. This thick, laterally continuous coal seam contains the bulk of the presently mineable coal reserves of the Pittsburgh area. Although this seam has been extensively mined in the general area of the Babcock and Wilcox site, this mining does not significantly impact the integrity of the site. The site lies below the level of the Upper Freeport coal and has not been undermined (Bushnell, 1975a; Wagner and others, 1975b; Craft and others, 1976). The Allegheny Coal does underlie the site but this group has not been mined anywhere in the vicinity of the site (Dr. A. Socolow, Pennsylvania State Geologist, personal communication, May 11, 1977). Furthermore, those coals within the Allegheny Group that do underlie the site are not of sufficient thickness or quality to be considered as an economically mineable resource at the present time (Wagner and others, 1970).

Bedrock Structure

The bedrock strata of the region surrounding the Babcock and Wilcox site are only very slightly deformed and nearly flat lying. Bedrock dips average approximately 100 feet per mile. These dips are associated with a series of gentle, northeast-southwest trending folds. The axis of the Leechburg-McFadden Anticline passes approximately one mile northwest of the site and the axis of the Duquesne-Fairmont Syncline passes about one mile southeast of the site. The structural relief on these two structures is less than 200 feet, and the average bedrock dip in the area of the site is about 80 feet per mile east southeast, into the high terrace scarp behind the site (Wagner and others, 1975b).

No faults are indicated on any geologic maps or in any other published literature describing the area. However, the drainage pattern of the region surrounding the site contains a strong angulate component indicating significant fracture control of erosion and drainage development in the area. Many stream valleys are strikingly linear and, although a detailed morphologic analysis of these valleys has not been made, generally northwest-southeast and northeast-southwest

trends predominate and locally many adjacent valleys exhibit striking parallelism. Gold and others (1974a) mapped a series of megalineaments throughout western Pennsylvania from the interpretation of Landsat imagery. The orientations of these megalineaments and the preferred orientations of the linear valleys in the region surrounding the site are similar, and both features may be generically related.

However, no historical earthquakes have been associated with these features and thus they are not considered in the seismic risk analysis. The seismic risk at the facility should be reconsidered, however, if data from the future Pennsylvania seismic network should establish a seismicity on one of these linears.

EVALUATION OF NON-TECTONIC GEOLOGIC HAZARDS

A preliminary evaluation of the non-tectonic geologic hazards associated with the Babcock and Wilcox site was made on the basis of:

- A thorough search for and review of existing maps, reports and other published and unpublished geologic data describing the region surrounding the site;
- Examination of 1:20,000 black and white aerial photographs of the site and adjacent areas; and
- A field examination of the geomorphic and surficial geologic characteristics of the site on May 12, 1977.

Slope Failure

The Babcock and Wilcox site is located on the nearly level surface of the Kiskiminetas River floodplain about 100 feet from the river's east bank. The channel of the Kiskiminetas River is about 25-feet deep in this area, and its channel banks are abrupt and steep-sided. However, the site is located on the concave side of the 50- to 60-degree bend in the stream channel and most of the unconsolidated floodplain deposits underlying the site consist of silty sands and gravels.

Moreover, no evidence of slumping or other modes of slope failure was detected along the stream channel in the area of the site. Therefore, the possibility of a slope failure in this channel bank that would be large enough to significantly impact the Babcock and Wilcox site is judged to be remote.

The Babcock and Wilcox site is also located at the foot of a 140-foot high bedrock and artificial fill slope. The average gradient of this slope is 10 percent. This slope consists of two moderately steep (25 percent) slope segments separated by a nearly flat strip mine bench 100- to 200-feet wide approximately midway up the slope. The upper steep slope segment is in bedrock on the lowermost part of the Glenshaw Formation and the lower segment is mostly in coal strip mine spoil. This slope is judged to be stable and is not considered to pose a significant landslide threat to the Babcock and Wilcox site because

- The average gradient of this slope is only 10 percent;
- The average dip on the bedrock is approximately 1° ESE (into the slope); and
- No evidence of slope failure was noted in the steeper slopes of the surrounding terrain.

Differential Ground Subsidence

The Babcock and Wilcox site is not underlain by cavernous limestones or by presently mineable coal seams. The Upper Freeport coal crops out in the middle of the hillslope behind the site about 80 feet above the level of the site. Strip mining of this coal outcrop formed the prominent midslope bench on this slope, and an abandoned subsurface mine in this coal seam extends to within 400 feet of the site. However, the Upper Freeport coal does not underlie the site and the site has not been undermined for coal. Therefore, differential ground subsidence caused by coal undermining or by karst collapse is not a credible hazard at the Babcock and Wilcox site.

Flooding

The Babcock and Wilcox site is situated on the natural floodplain of the Kiskiminetas River. The topographic position and morphology of the site indicate a floodplain area, and the surface of the site is veneered with floodplain associated soils (U.S. Soil Conservation Service, 1970, 1971). Moreover, the site area was inundated by the March 18, 1936 flood of the Kiskiminetas River (Mr. Charles Woods, Babcock and Wilcox, Inc., personal communication; Speer and Gamble, 1965). However, the present flood hazard at the site cannot be assessed by a local site investigation and is beyond the scope of this report.

Since 1936, two large flood-control dams (the Loyahanna Dam and the Conemaugh River Dam) have been constructed upstream of the site and, consequently, evaluation of the present flooding hazard at the site is essentially a matter of appraising the effectiveness and safety of these two flood-control projects. A detailed evaluation of the risk due to flooding has been performed by the U.S. Army Corps of Engineers (1970).

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 the magnetic tape supplied by the U.S. Department of Commerce NOAA containing the earthquake history through 1975. 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 this data provided the most complete check and extension. The data through 1974 were checked against the USGS data, provided by D. Perkins. Finally, data obtained by Weston

Geophysical Research, Inc. for the Beaver Valley PSAR were examined as a final check. 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

Dr. Arthur Socolow
Pennsylvania State Geologist

The resulting integrated data base for the relevant area around Pittsburgh 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. When it is required to incorporate an estimate of the epicentral intensity in the data base, we use the Gutenberg-Richter relationship (1956)

$$M = 1.3 + 0.6I_e$$

to determine the equivalent magnitude. 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.

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 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, 180 miles northeast of the site, experienced an earthquake of intensity VIII (M.M.) (August 12, 1929) and two earthquakes of intensity VI (M.M.). In the Anna, Ohio area, approximately 200 miles west of the site, one earthquake of intensity VII-VIII (M.M.) (March 9, 1937) and three earthquakes of intensity VII (M.M.) have occurred. 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.

Another striking feature of the historical record is the absence of seismic activity in western Pennsylvania. It is apparent that the historical seismic risk in the Pittsburgh area has been due to earthquakes originating on distant structures. For example, the Attica Earthquake August 12, 1929 was felt with intensity IV at Pittsburgh, the Anna, Ohio Earthquake of March 8, 1937 resulted in intensity II, and the Cornwall-Moscona Earthquake (St. Lawrence Seaway Region—September 4, 1944) was felt with intensity III. Finally, as mentioned above, the New Madrid Earthquakes resulted in local intensities around Pittsburgh as high as V. These are very low intensities compared to those experienced in surrounding regions and thus serves to further demonstrate the consequences of local seismicity.

Figure 4.1

HISTORICAL EARTHQUAKES IN THE VICINITY OF THE SITE

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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 Babcock and Wilcox 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 Babcock and Wilcox facility analysis. Major contributions in this effort were made first by Professor G. A. Bollinger, (Virginia Polytechnic Institute and State University), Professor R. Herrmann (St. Louis University), and later by 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 were 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.

Figure 5.1

HISTORICAL EARTHQUAKES IN THE VICINITY OF THE SITE

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Figure 5.2 shows the appropriate source regions for the Babcock and Wilcox facility. The final determination of the most appropriate set of regions evolved from sensitivity studies. The regions are generally those contained in a 500-kilometer radius around the site, and with the exception of region 61, those regions more distant from the site did not contribute to the seismic risk. Region 61, which is the source region for the New Madrid earthquakes, was included because it has the low probability capability for large earthquakes that could contribute to the risk at the site. We have made two minor modifications to the Algermissen and Perkins source regions. First, for consistency with current NRC policy, we have extended the New Madrid source region (region 61) to the north, and second, we have truncated region 68 such that its outer boundary is 500 kilometers from the site. The seismicity of that region is allocated accordingly.

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.

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 indicated that there was no change in the earthquake statistics and therefore no basis for altering the Algermissen and Perkins statistical parameters. The maximum magnitude earthquake is a very uncertain parameter, particularly in the less seismic areas that we are

Figure 5.2

SEISMIC SOURCE REGIONS
USED IN THE ANALYSIS

(Source Region Numbers From
Algermissen and Perkins, 1976)

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Table 5.1
ALGERMISSEN AND PERKINS (1976)
EARTHQUAKE PARAMETERS

<u>Zone No.</u>	<u>Maximum Historical Earthquake</u>	<u>No. of MM Maximum Intensity V's per 100 Years</u>	<u>b</u>
61	X	84.5	.50
62	VIII	22.0	.50
63	VIII	22.1	.64
66	VIII	13.0	.59
67	VII	7.8	.59
68	VIII	69.1	.67

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 also used here to relate historical intensity to magnitude. To account for uncertainty in not only this relationship, but also the physical arguments leading to a specific maximum upper bound earthquake, we also consider in our calculations, described below, the possibility for upper bound cut-offs of plus and minus one-half magnitude unit about this maximum upper bound earthquake. 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.

Note that Table 5.2 includes a background zone of seismicity; these parameters describe the earthquake parameters for the region in Figure 5.2 containing the site. Although this area, as noted by Algermissen and Perkins, is very aseismic, the inclusion of a reasonable seismicity model is essential for proper estimation of the risk within the region. The indicated parameters are based on the data and on the advice of Perkins (personal communication, July 7, 1977). As above, the upper cut-off corresponds to one magnitude unit greater than the largest historical earthquake.

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
EARTHQUAKE PARAMETERS USED IN THE RISK CALCULATIONS

<u>Zone No.</u>	<u>Lower Cut-off Magnitude</u>	<u>Upper Cut-off Magnitude</u>	<u>Number of earthquakes greater than lower cut-off magnitude per year</u>	<u>b</u>
61	4.0	8.0	2.24	0.50
62	4.0	6.5	.59	0.50
63	4.0	6.5	.63	0.64
66	4.0	6.5	.36	0.59
67	4.0	6.0	.21	0.59
68	4.0	6.5	.70	0.67
Back- ground	5.0	5.5	.004	0.70

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

Δ = epicentral distance (km)

Figure 5.3 compares several of Bollinger's fractile relations with other recently published attenuation functions.

Figure 5.3

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

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

A_H = peak horizontal acceleration

M = earthquake magnitude

γ = region-specific parameter.

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

$$M = 1.3 + 0.6I_e$$

Combination of these three correlations results in

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

The effect of the Δ term is small (it results in less than one percent g reduction at 500 km), and for convenience the term is neglected in the calculations.

The value of γ 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 fortuitously very similar to the Babcock and Wilcox site, we allow for the possibility for some site response amplification in these data by considering three different fits to the data. We judge that the most appropriate fit to the data is for $\gamma = 0.9$, while consideration of possible site effects, particularly for data point 2, indicates that $\gamma = 0.8$ and $\gamma = 1.0$ are possible alternative fits. These three relationships are compared to the data in Figure 5.4.

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		

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

Figure 5.4

COMPARISON BETWEEN
ATTENUATION FUNCTION AND DATA

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Figure 5.5
ATTENUATION RELATIONSHIP USED
IN THE ANALYSIS

As Figure 5.4 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 sets used in 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 (Esteve, 1970) with a median value close to the value of 0.707 determined by Donovan (1974). We judge, therefore, that the value of 0.707 is a reasonable best estimate of the one standard deviation dispersion on acceleration.

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. Because of the aseismicity of the host region and the distance from the site to significant sources, the details of this near field response are inconsequential. This complete attenuation relationship is presented in Figure 5.5 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

$$\text{risk} = 1.0 - \exp(-\text{total expected number}).$$

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 five individual calculations. The five calculations represent a base case and four perturbations of input parameters about this base. The perturbations are weighted by subjective estimates of their probability of occurrence and thus their weighted combination can be considered a Bayesian estimate.

The parameters that are considered uncertain and which are included in the Bayesian estimate of the risk are the maximum earthquake in each source zone and the intercept of the attenuation relation expressed through the value of γ .

The base case is considered to consist of the following input:

- maximum earthquake = largest historical plus one-half magnitude unit
- attenuation intercept, $\gamma = 0.90$

We characterize the uncertainty in these data by considering that it is roughly 70 percent probable that the maximum earthquake is as specified above, and that it is 15 percent probable that the maximum earthquake is respectively one-half magnitude unit larger and one-half magnitude unit smaller.

Similarly, we consider 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. The best estimate in Figure 5.6 is the weighted summation of these five calculations. The plus one standard deviation is derived from 50 percent-50 percent

Figure 5.6

RETURN PERIOD - PEAK ACCELERATIONS
FOR THE BABCOCK AND WILCOX FACILITY

TERA CORPORATION

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

We have further examined the sensitivity of the results to possible uncertainty in other elements of the input and have established that the return period accelerations are relatively insensitive to reasonable variations in

- The slope of the attenuation function;
- The boundaries of the source zones; and
- The historical earthquake statistical parameters within each zone.

For example, when the slope of the attenuation function was varied 25 percent to reflect the use of the simpler and less refined relation (USNRC, 1977)

$$\log A_H = 0.25 + 0.25I$$

in place of the $\log A_H$ relation above, the peak accelerations at a given return period increased only 10 percent. The insensitivity of the results to source zone geometry and earthquake recurrence intervals can be established through a parametric survey, but this can also be concluded from a careful examination of the results of a single run. It turns out that generally each source region (including the host region) contribute equally to the risk at the site up to the 500-year return period earthquakes. The risk above the 500-year return period is increasingly dominated by the New Madrid Seismic Zone but for shorter return periods, the contributions to the risk are about the same for nearby small earthquakes and distant, large earthquakes. Since no single zone dominates, small changes in the geometry and earthquake statistics for any single zone do not significantly change the risk.

COMPARISON WITH OTHER DESIGN CRITERIA

A better perspective of the methodology and these results can be obtained through comparison with other seismic design standards.

A commonly cited design standard is based on the analysis of Algermissen and Perkins (1976). This analysis, which was probabilistic and used the same seismic zonation as our analysis, determined that the site could experience up to 4 percent g with a return period of 475 years. This is roughly one-half the 475-year acceleration that our analysis predicts. The difference results principally from the manner in which dispersion is included in the analysis. Our analysis allows for one standard deviation acceleration of a factor of two over the mean whereas Algermissen and Perkins neglect this dispersion. When we neglect dispersion in our model, we calculate a 3 percent g peak acceleration, a result quite consistent with the Algermissen and Perkins result.

Finally, it is interesting to compare our analysis against the standards for nuclear power plants. The design methodology for nuclear power plants is deterministic, requiring identification of the largest credible earthquake which is assumed to occur either at the nearest provincial boundary, or at the site. As such, this methodology is incapable of expressing the criteria in terms of a return period acceleration. It is, therefore, virtually impossible to quantitatively compare results for specific sites. Typical values of the SSE acceleration for Eastern United States plants range from 10-20 percent g and our results indicate that this corresponds to return periods from 1,000 to 10,000 years.

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 Babcock and Wilcox 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 shape of the spectrum should be similar to the Newmark-Blume

statistically-based spectra from which Regulatory Guide 1.60 evolved. This intuitive judgment is supported by a separate analysis we performed in which the risk is assessed through peak velocity. This calculation, which used McGuire's velocity attenuation relation (1976a), shows that the ratio of peak velocity to peak acceleration is very close to the ratio developed in WASH 1255 for alluvial sites. 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 (Aisup, 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 (β) 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 Babcock and Wilcox facility. The uncertainties in this judgment are, however, large; there is probably a 20 percent probability that the spectral accelerations could exceed the 75 percentile accelerations in WASH 1255.

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 Babcock and Wilcox facility. The results, shown in Figure 5.6, 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.

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