Westinghouse
Savannah River Company

P.O. Box 616
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#36

MSD-STI-2000-00042

February ~~1~~ 2, 2000

Bruce Cadotte,
WSRC Public Relations Officer
Public Relations Department
Building 705-A

Dear Mr. Cadotte:

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Document No. DPE-2383

Document Title SRP Earthquake Study - 100 Areas

Author A. Poon (contact)

WSRC-PRD response due by February 8, 2000

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DPE-2383

WORK REQUEST 850891 - SAVANNAH RIVER PLANT

EARTHQUAKE STUDY - 100 AREAS

EARTHQUAKE CRITERIA FOR THE SAVANNAH RIVER PLANT

MARCH 1968

E. I. DU PONT DE NEMOURS & CO. (INC.)
ENGINEERING DEPARTMENT
WILMINGTON, DELAWARE

WORK DONE UNDER
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ATOMIC ENERGY COMMISSION

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53	E. E. Westbrook, Jr., Engineering
54-60	Engineering Department AEC File

TABLE OF CONTENTS

I. INTRODUCTION

At the request of the Atomic Energy Division (AED) of the Explosives Department, the Engineering Department undertook a study to determine (1) the vulnerability of the Savannah River production reactors to earthquake damage and (2) the modifications, if any, required to assure that the reactors would not become a hazard to the public under conditions of maximum earthquake. The earthquake criteria is based on analyses of the seismic history and geological structure of the area.

Since earthquake engineering is a highly specialized field, the Engineering Department contracted with Dr. George W. Housner, Professor of Civil Engineering at the California Institute of Technology in Pasadena, California, to develop the criteria to be used in the study and to serve as a consultant to Du Pont regarding the structural analysis of the reactor complexes. At Dr. Housner's recommendation, the Engineering Department also contracted with Dr. Jack Oliver of the Lamont Geological Observatory of Columbia University for a report on the seismicity of the area and with Dr. Vernon Hurst of the University of Georgia for a report on the geology of the plant site and the surrounding area.

This report transmits Dr. Housner's report of recommended criteria for the seismic analysis and the supporting reports by Dr. Oliver and Dr. Hurst. Also included is biographical material on the qualifications of each of the above in the discipline of his report.

The structural analysis of the reactor complexes is being made by John A. Blume & Associates, Engineers, of San Francisco, California, with review by Dr. Housner. A separate report will be issued about September 1968 covering their analysis and the details of any recommended modifications.

II. SUMMARY OF STUDY

In checking the capability of the reactor complexes for safe shutdown, Dr. Housner makes the following comments: "The strongest shaking experienced at the site was that produced by the Charleston earthquake of 31 August 1886. On the basis of the seismicity of the general area (Figure 2) and of the Hurst geology report it is concluded that the greatest likelihood of strong shaking in the future is a repetition of the 1886 shock near Charleston, or possibly west of Charleston somewhat closer to the site. Inasmuch as 5%g ground motion at the site was estimated for the 1886 shock, a 10%g ground motion might be a possibility if a similar earthquake were located somewhat farther west. The plant should, of course, have an appropriate factor of safety over and above such possibly expected ground motion to take care of unforeseen contingencies, etc. Accordingly, it is recommended the plant be checked for safe shutdown using the 20%g design spectrum shown in Figure 4. These spectrum curves have the same shape as those given in TID 7024 ("Nuclear Reactors and Earthquakes", published by the USAEC Division of Technical Information) but are reduced to 20%g maximum acceleration at zero period. Alternatively, where appropriate, detailed vibration analyses may be made using the accelerograms recorded at Taft, California 21 July 1952, (see Figure 5), scaled so that the spectrum curves for the ground motion are not below those of Figure 4 for periods less than one second and for damping of 0.5% of critical or greater".

Dr. Housner also makes recommendations for criteria to be applied to new installations and for the damping values and permissible stresses to be applied in the analyses.

The recommended criteria for the SRP reactors are similar to those proposed for the nuclear power plant to be built at Hartsville, S.C.

APPENDIX A

Recommended Seismic Design Criteria for Savannah River Facility - Dr. George W. Housner - November 1967.

APPENDIX B

Geology and Seismic History of the Savannah Plant Area, South Carolina - Dr. Vernon J. Hurst - August 1967

APPENDIX C

Seismicity and Seismic Effects at a Site in South Carolina Near Augusta, Georgia - Dr. Jack Oliver and Dr. Bryan Isacks - August 1967.

APPENDIX D

Biographical data:

Dr. George W. Housner
Dr. Jack Oliver
Dr. Vernon Hurst

APPENDIX A

RECOMMENDED SEISMIC DESIGN CRITERIA FOR SAVANNAH RIVER FACILITY

DR. GEORGE W. HOUSNER

NOVEMBER 1967

SEISMIC CRITERIA REPORT

FOR THE

SAVANNAH RIVER PLANT

PREPARED FOR E. I. DU PONT DE NEMOURS & COMPANY

WILMINGTON, DELAWARE

ON AXC 25930-1/2

DECEMBER 1967

Prepared By:

Dr. George W. Housner
California Institute of Technology
Pasadena, California

Approved By:

E. E. Westbrook, Jr.
Design Division
E. I. du Pont de Nemours & Co.,

GEORGE W. HOUSNER
1201 EAST CALIFORNIA BLVD.
PASADENA, CALIFORNIA 91109

November 30, 1967

E.I. DuPont de Nemours & Company
Wilmington, Delaware 19898

Attention: Mr. E. E. Westbrook, Jr.

RECOMMENDED SEISMIC DESIGN CRITERIA FOR SAVANNAH RIVER FACILITY

The Savannah River nuclear facility, located in southern South Carolina approximately 20 miles southeast of Augusta, Georgia, consists of a number of reactors and their appurtenances. The reactors are housed in separate reinforced concrete buildings. It is proposed to examine the earthquake resistance of the reactors and pertinent equipment, and the buildings housing the reactors and to take such measures as will ensure a safe shut-down in the event of future earthquake ground shaking. This report contains recommendations for the seismic safety of the facility. A visit was made to the site to inspect the facilities and the local geology. This report is based largely on the information contained in the following reports and publications:

a) Seismicity and Seismic Effects at a Site in South Carolina near Augusta, Georgia, by Jack Oliver and Bryan Isacks, August 15, 1967.

b) Geology and Seismic History of the Savannah River Plant Area, South Carolina, by Vernon J. Hurst, 1967.

c) Earthquake History of the United States, U.S. Coast and Geodetic Survey, 1965.

d) The Charleston Earthquake of August 31, 1886, U. S. Geological Survey Nineth Annual Report, 1887-88.

e) Nuclear Reactors and Earthquakes, A. E. C. TID-7024.

1. Buildings Housing the Reactors. Each reactor is housed in a large reinforced concrete building of very sturdy construction. A schematic cross-section through the central portion of a typical building is shown in Figure 1. The floor of the reactor room is approximately at grade level and the top of the penthouse is 150 feet above the reactor room floor. The building has massive walls, floor slabs and girders with relatively heavy reinforcement. The buildings were designed to resist external blast pressures. The quality of the concrete is good and the details of design are for the most part good. Preliminary investigation of the buildings indicates only a few places where strengthening is needed to resist ground shaking. Certain piping and equipment will require seismic bracing.

2. Foundation Material. As determined by bore holes, the pre-cambrian crystalline basement rock is approximately 1000 feet below ground surface. The material above the basement rock is firm and the design footing pressures for structures on the site are in the range of 7000 to 10,000 pounds per square foot. This firm material should have no adverse effect on earthquake ground motion.

3. Seismicity of the Area. The report by Oliver and Isacks lists 41 earthquakes originating within 200 miles of Augusta, Georgia, and having a maximum MM intensity of V or greater. These are plotted in Figure 2. They cover a period of 110 years, 1857-1967. Only one of these earthquakes centered within 50 miles of Augusta and that one was approximately

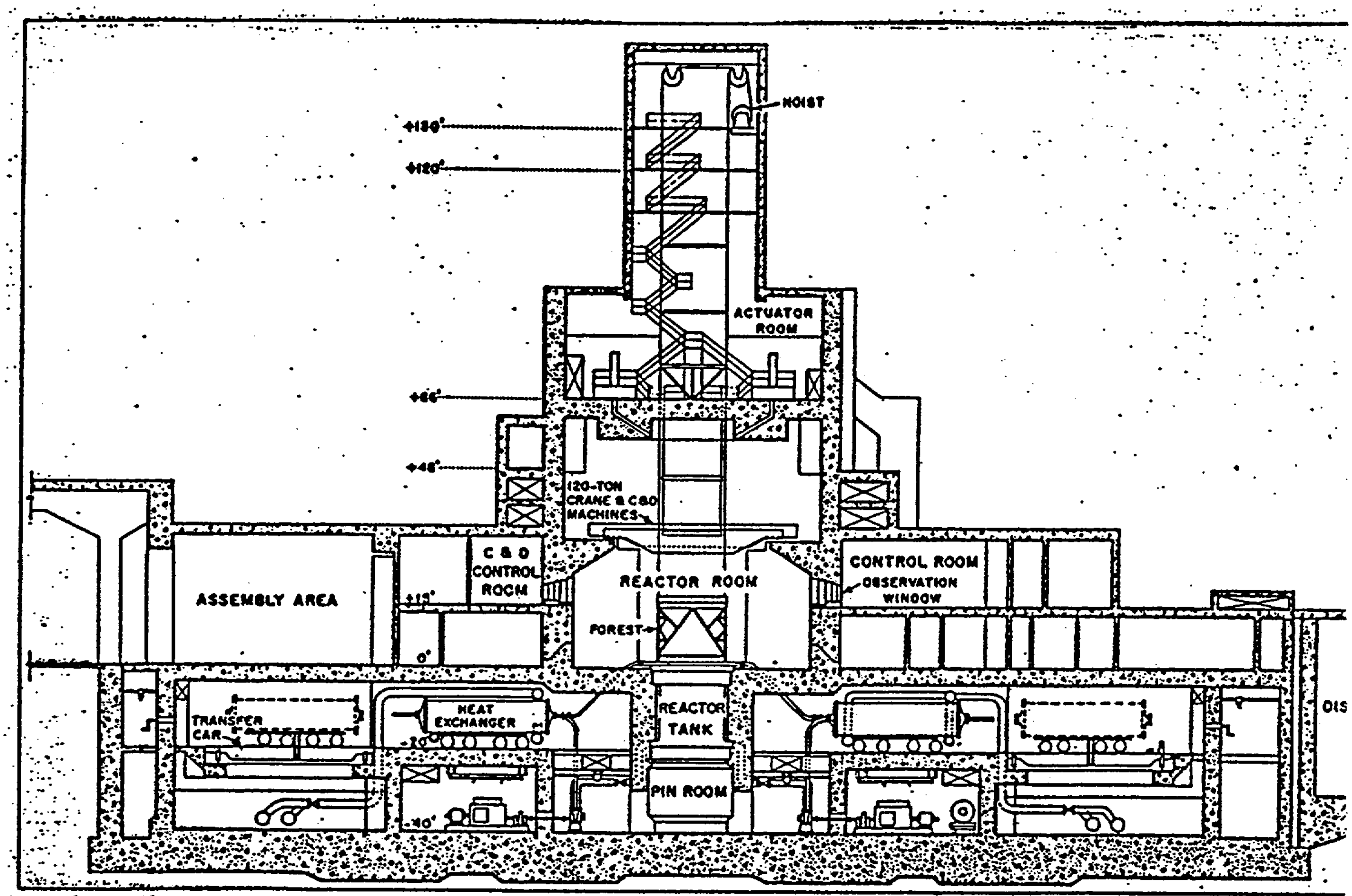


Figure 1. Schematic cross-section through central portion of typical building. Reactor room floor is at grade level. Top of penthouse is at elevation 150 ft.

50 miles northwest of the plant site. It was 35 miles from Augusta and the ground motion there was barely perceptible. The larger earthquake of February 21, 1916, in North Carolina was approximately 160 miles from the plant site. The motion at Augusta was perceptible only by most persons indoors and it did no damage.

On the basis of the area over which the motion was felt and the reported maximum intensity and knowing that, in general, the frequency of occurrence of earthquakes decreases exponentially with Magnitude it is possible to estimate the Magnitudes of the 41 shocks as follows:

M	No.
4.0 - 4.5	25
4.5 - 5.0	10
5.0 - 5.5	4
5.5 - 6.0	1
6.0 - 6.5	0
6.5 - 7.0	0
7.5	1

As shown in Figure 2, the site is on the southern edge of a cluster of epicenters which extends northward into the Appalachian Mountains. There is practically no seismicity south of the site. Approximately 100 miles east of the site there is a cluster of aftershock epicenters associated with the Charleston earthquake of 31 August 1886.

The strongest shaking at Augusta during the 110 year period was produced by the Charleston, South Carolina earthquake of 1886. Charleston is approximately 100 miles east of the site. No destructive ground motions have ever been recorded east of the Rocky Mountains so there is no firm data for determining the strength of shaking produced by the Charleston

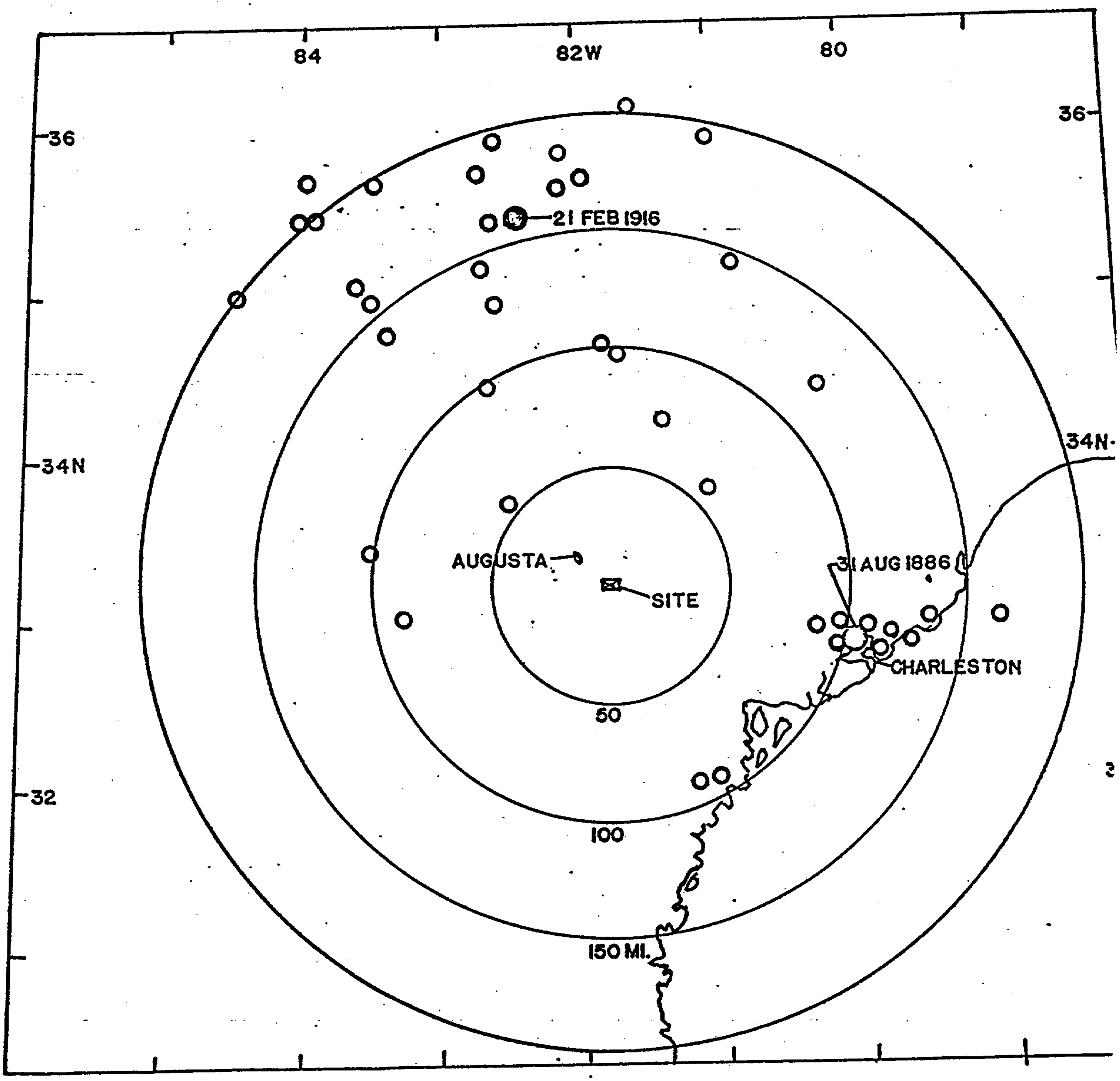
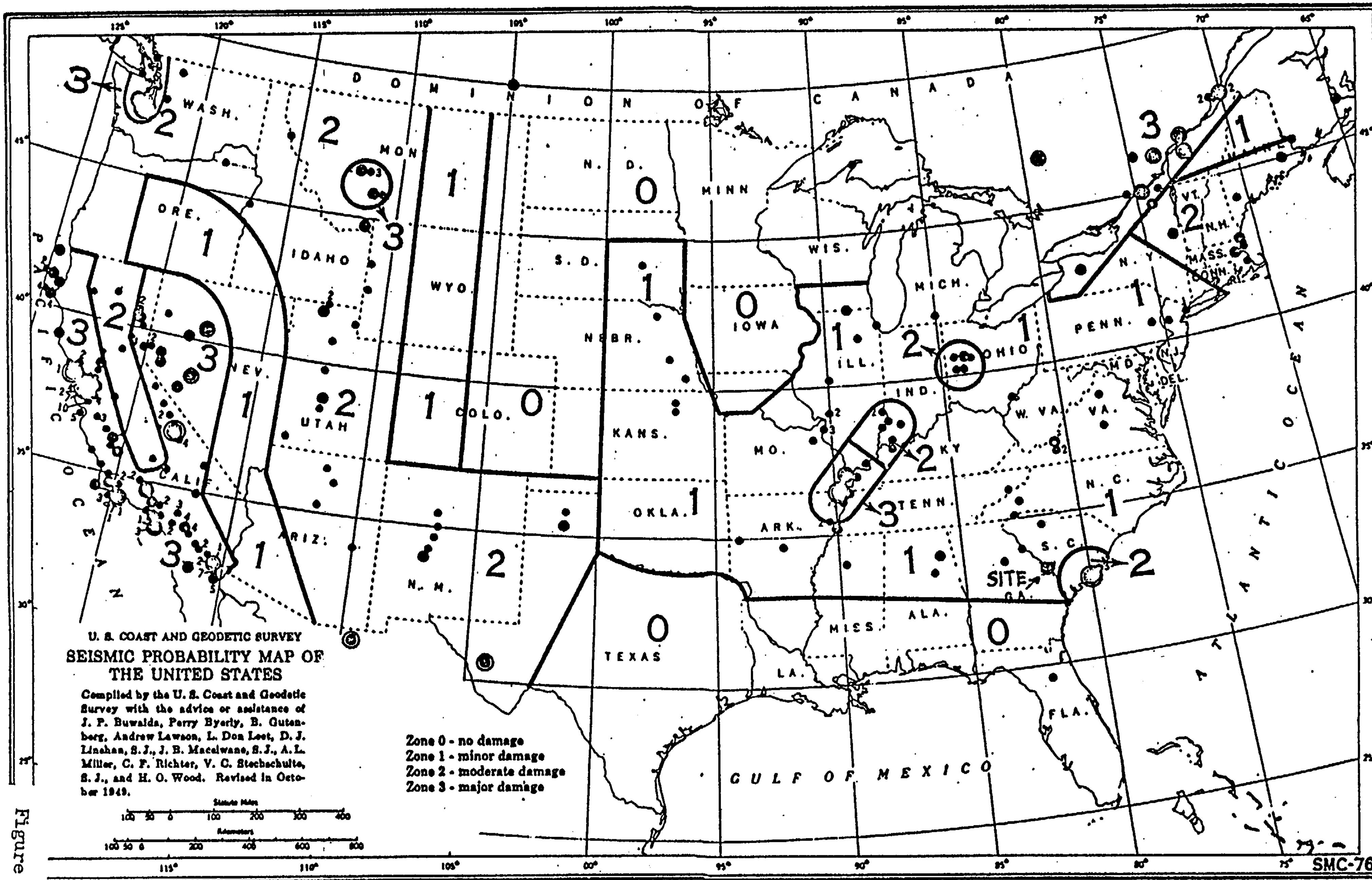


Figure 2. Epicenters of 41 earthquakes within 200 miles of Augusta, Georgia. All shocks occurring between 1857 and 1967 and having reported maximum intensities greater than or equal to Modified Mercalli V. (Oliver and Isacks).

earthquake. However, an estimate can be made on the basis of California data. The Magnitude 7.7 Arvin-Tehachapi earthquake of July 21, 1952 originated on a fault 65 miles north of Pasadena, California. The ground motion recorded at Pasadena had a maximum acceleration of 5%g, with the higher frequency components more attenuated than the low frequency components. The Charleston earthquake was at a greater distance from the site but on the other hand the attenuation of ground motion with distance is less rapid in the eastern United States than it is in California. In view of these factors it is thought that the ground shaking at the plant site in 1886 was approximately the same as at Pasadena in 1952.

Oliver and Isacks conclude that the area around Augusta is somewhat more seismic than the state of Florida but distinctly less seismic than southern California, the central Mississippi Valley, or the upper St. Lawrence Valley. This assessment is consistent with the Seismic Probability Map, Figure 3, which shows the site located in Zone 1, Florida located in Zone 0, and southern California, the central Mississippi Valley and the upper St. Lawrence Valley all in Zone 3.

4. Geological Evidence. In his report, Hurst discusses the general geology of the region and describes the geologic formations underlying the Savannah River Plant area. He describes the past tectonic activity and concludes that the plant site is located in a region which throughout historic times has been one of the more stable regions of the United States. He also concludes that no geologic information portends any increase in seismic activity, and that available geologic information indicates that a majoy earthquake is not to be expected near the plant site.


U. S. COAST AND GEODETIC SURVEY
SEISMIC PROBABILITY MAP OF THE UNITED STATES
Compiled by the U. S. Coast and Geodetic Survey with the advice or assistance of J. P. Buwalda, Perry Byerly, B. Gutenberg, Andrew Lawson, L. Don Leet, D. J. Linehan, S. J., J. B. Macelwane, S. J., A. L. Miller, C. F. Richter, V. C. Stechschulte, S. J., and H. O. Wood. Revised in October 1949.
Zone 0 - no damage
Zone 1 - minor damage
Zone 2 - moderate damage
Zone 3 - major damage
D O M I N I O N O F C A N A D A
GULF OF MEXICO
ATLANTIC OCEAN
PACIFIC OCEAN
WASH.
ORE.
CALIF.
NEV.
IDAHO
MON
UTAH
ARIZ.
WYO.
COLO.
N. M.
N. D.
S. D.
NEBR.
KANS.
OKLA.
TEXAS
MINN
IOWA
MO.
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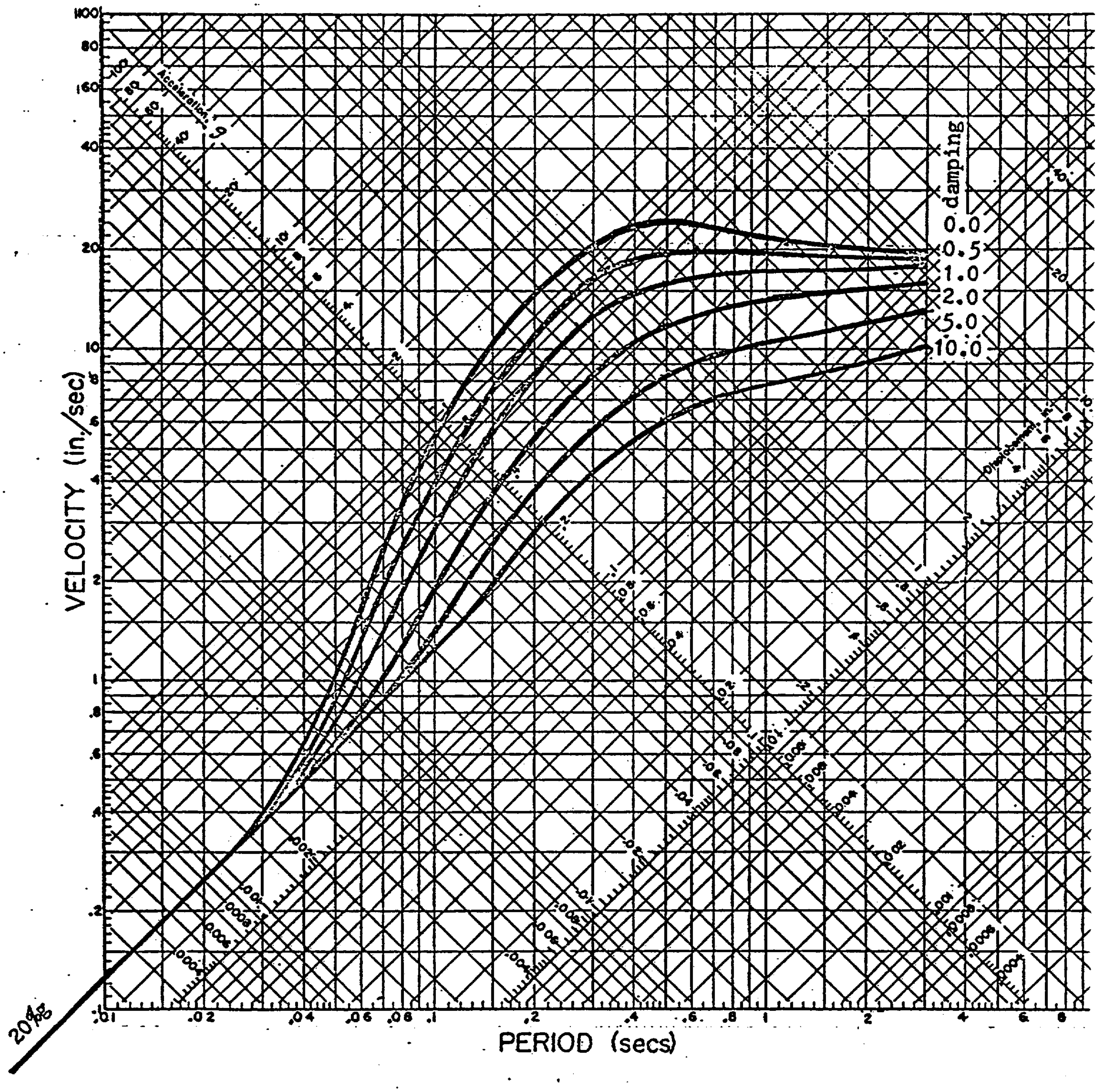
OHIO
W. VA.
VA.
N. C.
S. C.
GA.
FLA.
PENN.
N. Y.
MD.
N.J.
DEL.
VT.
N.H.
MASS.
CONN.
R.I.
SITE
SMC-76
M-2587-4

Figure

5. Recommended Earthquake Criteria. The strongest shaking experienced at the site was that produced by the Charleston earthquake of 31 August 1886. On the basis of the seismicity of the general area (Figure 2) and of the Hurst geology report it is concluded that the greatest likelihood of strong shaking in the future is a repetition of the 1886 shock near Charleston, or possibly west of Charleston somewhat closer to the site. Inasmuch as 5%g ground motion at the site was estimated for the 1886 shock, a 10%g ground motion might be a possibility if a similar earthquake were located somewhat farther west. The plant should, of course, have an appropriate factor of safety over and above such possibly expected ground motion to take care of unforeseen contingencies, etc. Accordingly, it is recommended the plant be checked for safe shut-down using the 20%g design spectrum shown in Figure 4. These spectrum curves have the same shape as those given in TID 7024 but are reduced to 20%g maximum acceleration at zero period. Alternatively, where appropriate, detailed vibration analyses may be made using the accelerograms recorded at Taft, California, 21 July 1952, (see Figure 5), scaled so that the spectrum curves for the ground motion are not below those of Figure 4 for periods less than one second and for damping of 0.5% of critical or greater. It is recommended that such a detailed analysis be made of the combined N-S, E-W, up-down vibrations of the penthouse on each building, in lieu of using the spectrum curves.

In the seismic analysis, when using the spectrum curves, the N-S, E-W, and up-down ground motions should be considered to occur simultaneously and the computed values of stresses, displacements, etc. for the three components should be combined by taking the square root of the sum of



DESIGN SPECTRUM

Figure 4. Design spectrum for safe shut-down criterion.

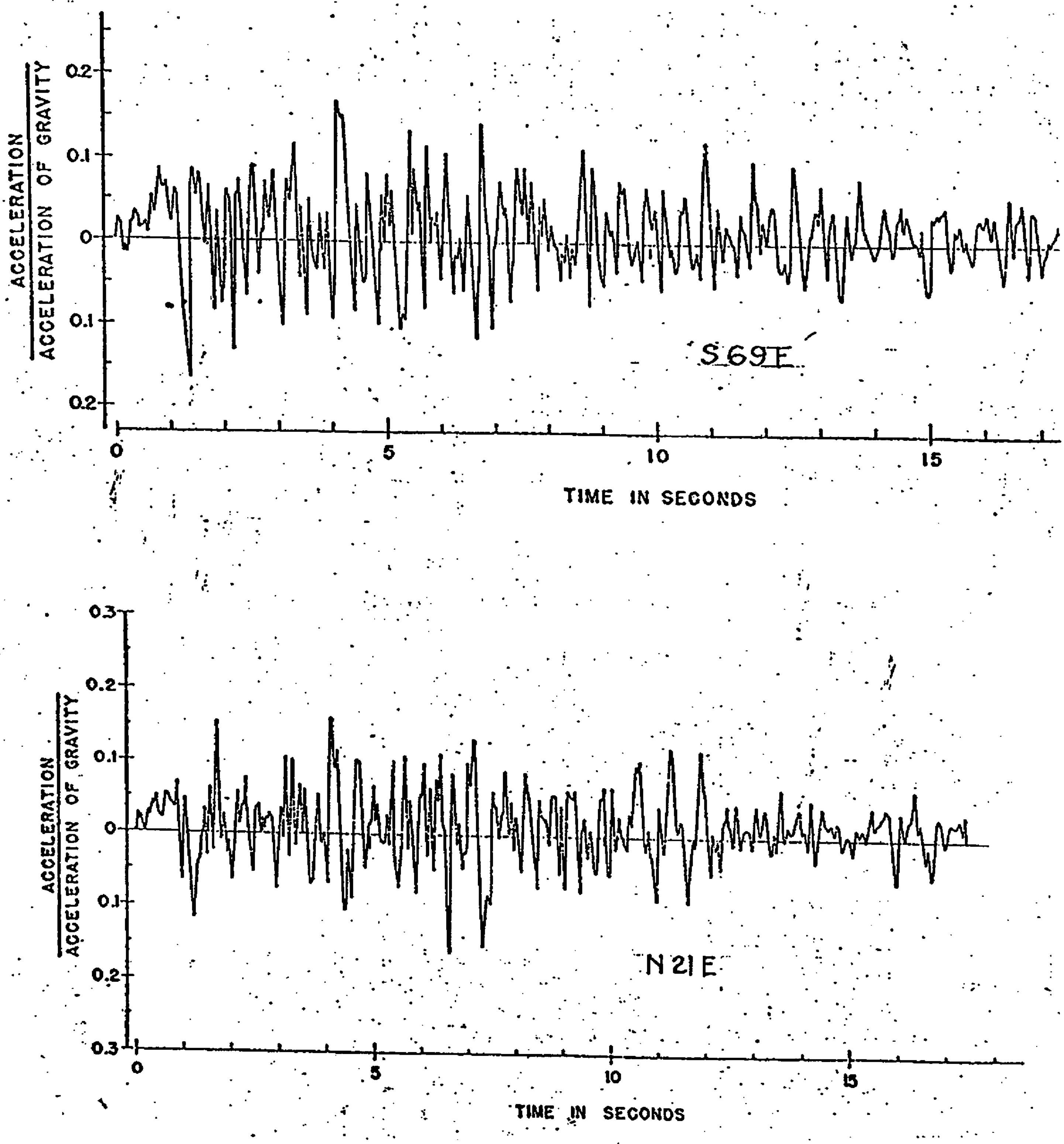


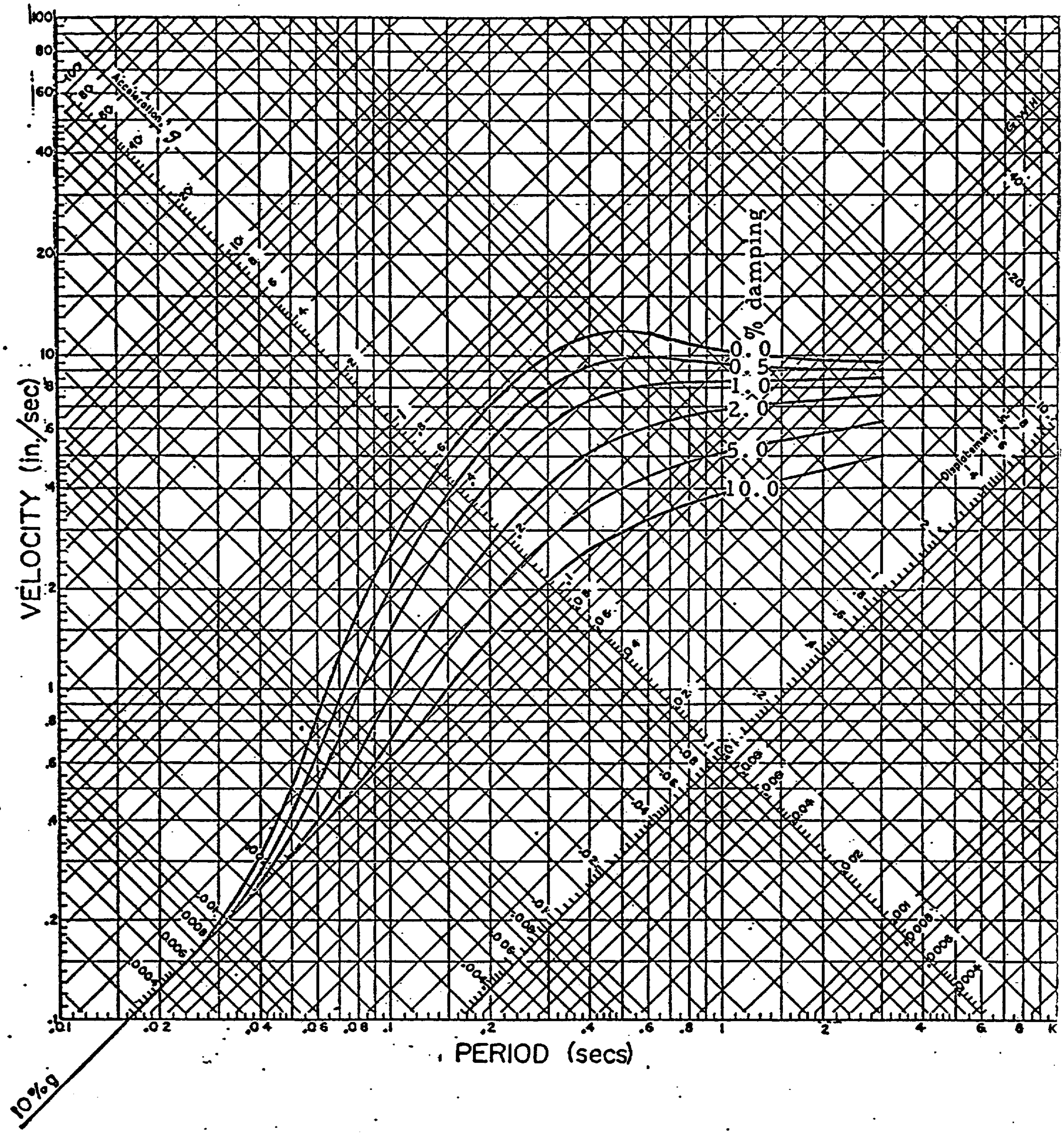
Figure 5. Horizontal components of ground acceleration recorded at Taft, California, 21 July 1952.

the squares. The design spectrum for vertical motion should have the same shape as Figure 3 but should be scaled down to have 10%g at zero period.

6. Method of Analysis and Design. a) For the seismic design of any new critical structures or equipment it is recommended to use an elastic analysis (see TID 7024) and ordinary allowable design stresses as specified by the applicable code (no 33% increase in allowable stresses for transient loading). The design spectra shown in Figure 6 (10%g at zero period) should be used. Reasonable values of damping should be used as exemplified by the following table:

Reinforced concrete shear wall building	5%
Reinforced concrete frame building	2.5%
Welded steel frame structure	1.0%
Steel pipes with rigid supports	1.0%

b) For analyzing the seismic resistance of existing critical structures and equipment the design spectra specified in Section 5 should be used. A safe shut-down should be possible during or after earthquake ground motion typified by the design spectra shown in Figure 4. It will be permissible for reinforced concrete to sustain minor cracking and for steel to be strained beyond the yield point by an amount equal to 100% of the yield point strain. However, major reinforced concrete beams should not be stressed in shear or torsion to the point of developing diagonal tension cracks. Reasonable values of damping should be used as exemplified by the following table:



DESIGN SPECTRUM

Figure 6. Design spectrum for new structures and equipment.

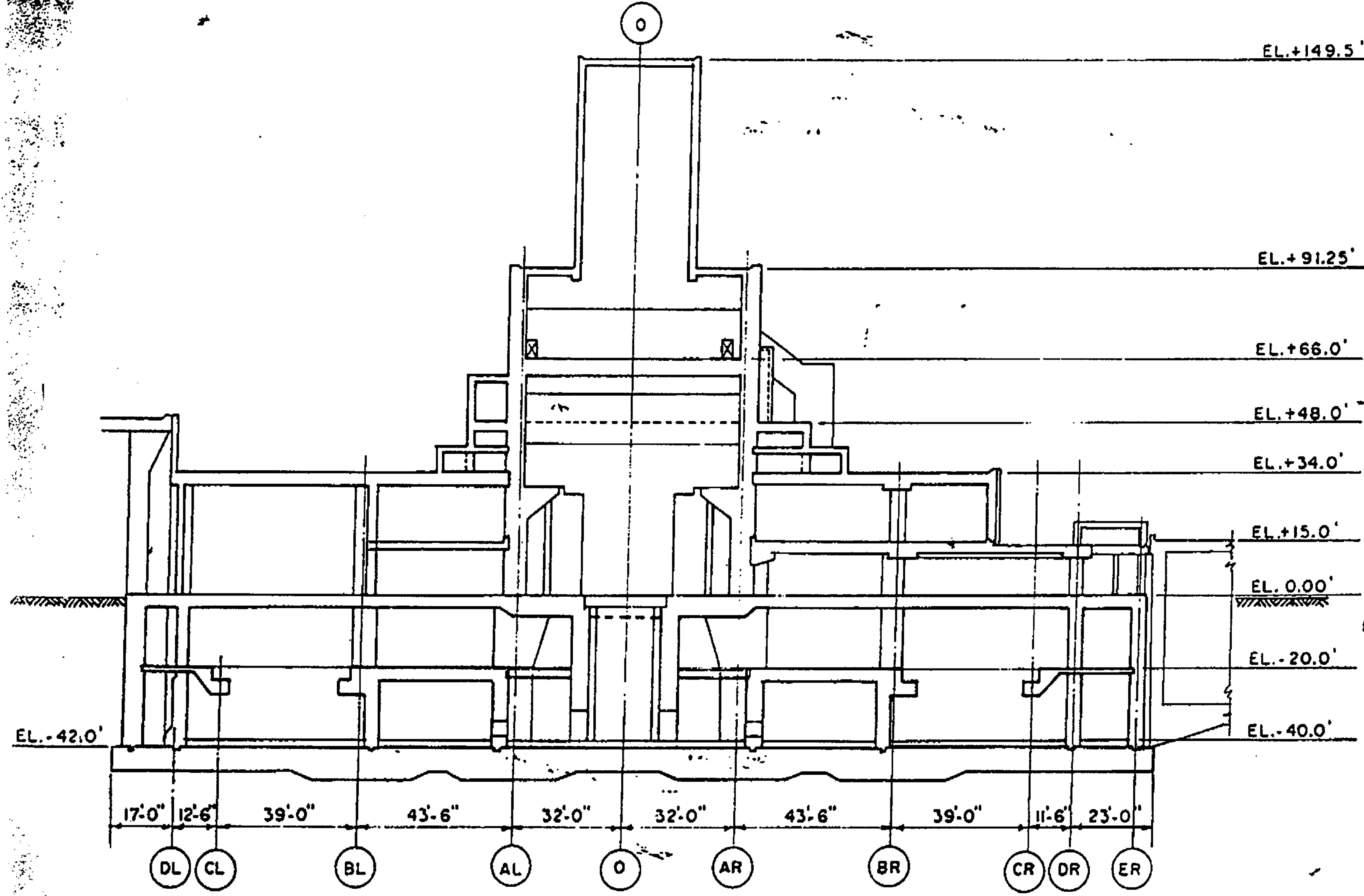
Reinforced concrete shear wall structures	[illegible].5%
Welded steel frame structures	2.0%
Steel pipes with rigid supports	1.0%

c) Structures and equipment not pertinent to the ability to achieve a safe shut-down need not be analyzed for the design spectrum shown in Figure 4. It is recommended, however, that these structures and equipment be checked for ground motion corresponding to the spectrum shown in Figure 6 with minor concrete cracking permitted, and, strain in steel equal to twice the yield point strain permitted.

d) It is recommended that structures and equipment critical to safe shut-down that do not meet the seismic requirements of Section 6d), and non-critical items that do not meet the requirements of Section 6c), be strengthened to meet these requirements.

<u>7. Underground Liquid Storage Tanks</u>. Existing critical storage tanks should be analyzed for earthquake motions represented by the design spectra of Figure 4. Minor cracking of concrete is permissible so long as the containment is not jeopardized. The analysis of the dynamic fluid pressures should be made according to the procedures described in TID 7024.

Signed [signature]
George W. Housner



CROSS-SECTION -"R" REACTOR BUILDING

EXHIBIT "A"

APPENDIX B

GEOLOGY AND SEISMIC HISTORY OF THE SAVANNAH PLANT AREA, SOUTH CAROLINA

DR. VERNON J. HURST

AUGUST 1967

GEOLOGICAL HISTORY OF THE SAVANNAH RIVER PLANT AND THE SURROUNDING AREA

PREPARED FOR E. I. DU PONT DE NEMOURS & COMPANY,

WILMINGTON, DELAWARE ON AXC 25999½

SEPTEMBER 1967

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Approved by: George W. Housner
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Approved by: E. E. Westbrook Jr.
E. E. Westbrook, Jr.
Design Division
E. I. du Pont de Nemours & Co.

GEOLOGY AND SEISMIC HISTORY OF THE SAVANNAH RIVER PLANT AREA, SOUTH CAROLINA

Introduction

This geologic report has been prepared under contract with E. I. DuPont de Nemours and Company in connection with an earthquake study being made by Dr. George Housner, California Institute of Technology, for DuPont. The geology and seismic history of the Savannah River Plant area will be used in conjunction with existing information on engineering seismology and earthquake engineering to establish earthquake design criteria applicable to the area.

Location

The Savannah River Plant is in the state of South Carolina about 20 miles southeast of Augusta, Georgia, on a 315 square mile tract along and to the east of the Savannah River (Figure 1).

Physiography

The Plant area is on a broad gently rolling upland of the upper Atlantic Coastal Plain, 20 miles southeast of the Fall Line. Its average elevation is about 300 feet above mean sea level. Two physiographic units are distinguishable: (a) the Aiken Plateau ranging in elevation from 300 to 350 feet, and (b) the alluvial terraces of the Savannah River and its tributaries. The Aiken Plateau, about 80% of the Plant area, was relatively smooth, originally, and sloped gently to the southeast. It has been deeply eroded by the drainage tributaries, with relief now ranging up to 250 feet.

The Savannah River drains the entire Plant site except a small portion near the eastern boundary.

Regional Geology

South Carolina, Georgia and other states along the Atlantic Seaboard are divisible into 3 distinct geologic provinces. (1) The northwestern part of each state is underlain by consolidated and folded paleozoic sedimentary rocks. (2) The central portion of each state is underlain by metamorphic and igneous rocks ranging in age from pre-Cambrian to late Paleozoic, and even younger. (3) The southeastern portions are characterized by flat-lying, mostly unconsolidated sediments of Cretaceous age or younger of the Atlantic Coastal Plain. The boundary on the west between Paleozoic sediments and crystalline rocks is generally a thrust fault or a series of thrusts along which the crystalline rocks have been shoved westward. The boundary on the east between the crystalline rocks and younger sediments of the coastal plain is an erosional inconformity which dips gently seaward at the rate of 15-40 feet per mile.

Thus South Carolina and adjacent states are underlain by a stable basement of igneous and metamorphic rocks extending from the Blue Ridge Mountains on the west to the continental shelf on the east, a width greater than 200 miles, and trending NE-SW. The Savannah River Plant is near the midline of this basement, where the basement is overlapped by 900-1000 feet of Coastal Plain sediments. (see Figure 1).

The rocks constituting the basement were formed, folded, faulted, metamorphosed, and intruded during the pre-Cambrian and Paleozoic Eras. They underwent the last major metamorphism during upper Paleozoic time when the Appalachian Mountains were uplifted. During this orogeny, major faults developed in the Southern Appalachians and in what is now the Piedmont Plateau.

By Triassic time the areas which are now Piedmont Plateau and Coastal Plain had been reduced by erosion to subdued uplands and plains underlain largely by metamorphic and igneous rocks. The crust was then broken by large normal faults which developed basins in which Triassic sediments accumulated. Faulting continued to the end of the Triassic period while numerous diabase dikes and other basic rocks were intruded into the Triassic and older rocks. The dikes might have been intruded during the Jurassic period (de Boer, 1967).

Four major Triassic basins are known in the Southeast. One, the Deep River Basin, begins near Wadesboro, Anson County, N. C., and extends northeastward nearly to Oxford, Granville County. Another, the Dan River Basin, begins near Germanton, Stokes County, N. C., and continues northeast along Dan River into Virginia. A third strikes northeast from Allendale County, S. C., to Bladen County, N. C. A fourth extends from Florence to St. Charles, S. C. The latter two were located by seismic-refraction measurements. Deep wells in the upper coastal plain of South Carolina and Georgia are reported to have penetrated Triassic rocks in the underlying basement at several other places.

The eastern side of the crystalline basement began to warp down during the Triassic Period. Sediments might have accumulated locally on the eroded crystalline surface during the Jurassic and Upper Cretaceous periods, but deposition became widespread only during Upper Cretaceous time when the Tuscaloosa formation was laid down. Overlying the Tuscaloosa formation are the McBean formation, Barnwell formation and Hawthorn formation of Tertiary age.

Tectonically the region has been relatively stable since the Triassic Period. The sedimentary record does suggest differential movement of the Cape Fear arch, a prominent basement structure beneath the Coastal Plain sediments of North and South Carolina at least twice during Cretaceous and Tertiary time (Bonini and Woollard, 1960, p.310).

The earlier movement was Upper Cretaceous (pre-Black Creek). The later movement was Tertiary and Pre-Duplin Marl.

Summary of Coastal Plain Geology

The wedge of unconsolidated sediments, on which the Savannah River Plant is located, feathers out to the northwest along the Fall Line and thickens southeastward toward the coast at the rate of 15-40 feet per mile. The distance from the Fall Line to the coast, in South Carolina, is about 130 miles. The Savannah River Plant is southeast of the Fall Line about 20 miles where the sedimentary wedge is already 900-1000 feet thick. Along the coast the wedge is up to 4000 feet thick.

The crystalline rocks beneath the wedge of Coastal Plain sediments are known from hundreds of drill holes. They consist of schist, gneiss, granite, amphibolite, diabase, feldspathic sandstone, dark shale, sericite schist, and a variety of volcanic rocks, as basalt, rhyolite, and welded tuff. In Georgia these pre-Cretaceous rocks fall into four well defined zones whose boundaries are roughly parallel to the Fall Line. The zone nearest the Fall Line is characterized by gneiss and schist. In zone 2, to the southeast, deep wells bottom in "red beds" and diabase. In zone 3, farther southeast, deep wells bottom in volcanic rocks, while in zone 4, near the Florida-Georgia boundary deep holes bottom in feldspathic quartz sandstone or dark shale. (Hurst, 1960, pp. 12-13).

The sedimentary formation immediately overlying the crystalline basement is the Tuscaloosa formation of Upper Cretaceous age. The formation is predominantly arkosic sand and conglomerate, interbedded with lenses of clay and argillaceous sands. The sands and gravels usually are unconsolidated or semiconsolidated. The sands are angular to subangular, medium - to coarse-grained, and contain disseminated mica and clay. Lenses of clay are usually kaolinitic and contain varying proportions of sand and mica

The clay varies widely in color; white, tan, and gray are most common. Kaolin occurs in balls and boulders, especially in outcrops close to the crystalline contact, and in lenses, streaks and thin beds. Lenses of kaolin containing little or no sand and mica are found throughout the Tuscaloosa formation but appear to be larger and more numerous several miles south of the Fall Line, usually under cover of younger sediments.

In surface exposures the Tuscaloosa Formation is usually thin, under 50 feet, and no greater than 150 feet. It crops out along the Fall Line and along incised stream valleys where it extends for several miles into the younger coastal plain sediments. The formation thickens to more than 800 feet in the subsurface as shown by well logs to the southeast in the coastal plains.

Overlying the Tuscaloosa Formation are several formations of Tertiary age. The lowest is the McBean formation which unconformably overlies the Tuscaloosa formation and is in turn unconformably overlain and extensively overlapped by the Barnwell formation. In outcrop the McBean formation consists of fine - to medium-grained calcareous sands interbedded with semi-indurated gray limestone and shell beds in a matrix of marl or calcareous fullers earth. Due to groundwater leaching, the McBean formation commonly is pockety or cavernous, and is characterized by lime sinks where the overlying sediments have collapsed into the places where most calcareous material has been dissolved. Its pockety character and fullers earth layers render the McBean formation less stable, structurally, than the underlying and overlying non-calcareous units. The updip portions of the formation have been recognized as a "zone of weakness" insofar as structural foundations are concerned (Letter from A. N. Daniel and Z. E. Westbrook, Jr., 31 July 1967). In this respect, the McBean is like other calcareous units which have been subjected to copious groundwater. It differs in that it is more heterogeneous than most: the McBean rocks in the Plant area are a nearshore facies in which the marl beds vary both laterally and vertically within very short distances. The unconsolidated sands and clayey sands overlying the McBean formation collapse readily into the spaces left by the dissolution of calcareous material so that few, if any, large caverns remain open. It is therefore doubtful that the McBean behaves very different from the overlying sediments when seismically disturbed.

The Barnwell formation is typically red argillaceous sand. Chert beds are found in the upper part of the formation, and Irwinton sand and the Twiggs clay member are nearer the base. Most of the massive portions of the formation show little or no stratification and only local cross-bedding. The Barnwell formation grades down-dip into the Ocala limestone. Other limestones are found locally in the section, as the Cooper Marl and Suwannee limestone.

Overlying these units is the Hawthorne formation. It consists largely of mottled, compact, yellow, tan, and orange, argillaceous sands that are remarkably uniform over long distances. Much of this "sameness" is a consequence of saprolitization, in situ weathering in a subtropical climate. In most of the Hawthorne formation bedding is not distinct, though there are notable exceptions.

The most recent sediments are gravels, sands, and clays which have been deposited on the modern landscape. Recent gravels are common in the Fall Line area, both as stream deposits and as high level terraces resting directly on the Piedmont rocks. These gravels are derived from the weathering Piedmont surface and from pre-existing coarse sediments of the Tuscaloosa formation. Other gravels occur as thin sporadic deposits that have been let down from overlying units by erosion or washed downstream and superimposed on the modern landscape by earlier streams. All major stream valleys are lined by varying quantities and thicknesses of alluvial terraces. These are usually thin in the upland areas but are of significant thickness in the valleys of the Savannah river and some of its larger tributaries.

Much of the upper surface of the Hawthorne formation has leached to a fine-grained, gray to tan sand that thinly mantles large areas.

Geology of the Savannah River Plant Area

A geologic map of the Plant area and environs is shown in Figure 2. The geologic formations are listed in Table 1 (Christl, 1964, p. 15).

Seven deep borings drilled in the Plant area in 1961-62 reached the crystalline basement at 900-1000 feet below the surface. The basement rocks encountered are quartz-feldspar gneiss, hornblende gneiss, quartzite, schist and phyllite (Christl, 1964).

Past Tectonic Activity

Many large faults in southeastern United States have been reported. Figure 3 shows some which are better known. Because most of the area has been mapped only by reconnaissance methods, it is likely that many more faults will be revealed by future work. The faults that are shown are grouped readily into 4 types: (1) those associated with the folding of the Paleozoic sediments on the northwest; (2) the overthrusts separating the Paleozoic sediments from the metamorphic and igneous rocks of the Blue Ridge and Piedmont provinces; (3) the faults in the Blue Ridge and Piedmont provinces proper; and (4) the faults associated with Triassic graben.

The major faults associated with the folding of the Paleozoic sediments originated during Late Paleozoic time and were most active during the Appalachian orogeny. Intermediate and minor earthquakes have originated in the region during the last 300

Pages 10, 11, and 12 intentionally left blank. (NO INFORMATION IS MISSING.)

years, but the tectonic forces by which the Appalachian Mountain system evolved are now relatively inactive, and no major earthquakes are on record in historic time.

The overthrusts separating Paleozoic sediments from the Blue Ridge and Piedmont provinces likewise were active during the Appalachian orogeny. Considerable movement postdates the last period of metamorphism, about 250 million years ago, at the close of the Paleozoic Era, but no major movements have been recorded in historic time.

The major faults in the Blue Ridge and Piedmont provinces proper partly predate and partly post-date the Appalachian orogeny. Very little is known of these faults. Perhaps the largest is the Brevard fault zone which is shown on the Geologic map of Georgia, 1939, as extending northeast across the state from Heard County through North Atlanta, Gainesville, and on into North Carolina. The North Carolina portion of the fault was studied recently by Reed and Bryant (1964, pp. 1177-1196) who concluded that it is a strike-slip fault of great magnitude. They postulated right-lateral displacement of at least 135 miles occurring during late Paleozoic or Early Triassic time or both.

The Triassic graben are well dated. The locations of the larger known graben are given on page 5.

No major faults have been proven on the Atlantic Coastal Plain, though several have been postulated. It is highly probable that the Triassic rocks which have been encountered by drilling are bounded by major faults. From what is known of lithology and tectonic trend it is likely that major faults are as frequent in the basement underlying the Coastal Plain sediments as in the Piedmont province to the northwest.

Structure contours on the pre-Cretaceous basement are shown by Figure 4.

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Recent Tectonic Activity

The southeastern part of the United States is a region of considerable but moderate earthquake activity (Eppley, 1965). Earthquakes occur throughout the region, but not evenly. There is an axis of principal activity which roughly parallels the tectonic trend and the coast. The epicenters of most of the shocks within the region have been fixed by seismic stations outside the region or estimated from shock effects observed at the surface. Inaccuracies in fixing the foci of the quakes preclude an accurate correlation with specific tectonic elements.

The only major earthquake of historic time is the Charleston earthquake of August 31, 1886, whose epicenter was 15 miles northwest of Charleston, S. C. Taber (1914) concluded that the earthquake was due to movement along a fault in the crystalline basement, beneath a half-mile thickness of overlying unconsolidated sediments. Since the main quake of 1886, hundreds of lesser shocks (Taber compiled a list of more than 400) have followed in the same area, some as recently as 1959 (intensity V) and 1960 (intensity IV). This long continued localization of movement supports Taber's conclusion of faulting in the basement.

Recent tectonic activity along the Brevard fault zone has been postulated by Husted and Strahley (1960). They report the coincidence of epicenters of several recent intermediate and minor quakes and the trace of the Brevard zone. This suggests that the Brevard Fault still might be active.

Though several large faults are known in the Piedmont Province, just northwest of the Savannah River Plant area, and were active near the close of the Paleozoic Era, or earlier, only one, the Brevard fault, shows evidence of any recent activity. Even along this fault the evidence is not definitive, and any movements that might have taken place during historic times have been minor. The basement rocks east of the Fall Line, being covered by Coastal Plain sediments, are not known in sufficient detail for major faults to have been located. It would be expected, though, that major faults would be prevalent there, as in the Piedmont Province, and that they would be largely inactive. Certainly, only one basement fault under the Coastal Plain might have been the focus of major movement during historic time, the postulated fault in the Charleston area.

The Savannah River Plant is located in a region which throughout historic times has been one of the more stable regions of the United States. No geologic information portends any increase in seismic activity. The available geologic information indicates that a major earthquake is not to be expected near the Savannah River Plan

Seismic History of the Area

The geologic record shows that seismic activity in the southeastern part of the United States has been low since the Jurassic period (for about 200 million years).

Historic records show that seismic activity has remained low during historic times. According to Taber (1914, p. 116) "no severe earthquake shocks had their origin in the area from the time of settlement by white people in 1671 until the Charleston earthquake in 1886. The only shocks of any significance felt in the area during that 200 year period were those connected with the New Madrid disturbance of 1811-12. These shocks slightly damaged a few brick buildings at Columbia and elsewhere in the state (South Carolina). At Charleston they were severe enough to ring church bells, stop clocks and damage a few chimneys." Since Taber's report in 1914 the region has had 3 earthquakes of intensity VII, and lesser shocks.

The Charleston earthquake of August 31, 1886, had an intensity of X. The epicenter was at Woodstock, 15 miles northwest of Charleston. The area within a radius of 800 miles was affected. The shock was felt at Boston, Milwaukee, Cuba, and as far east as Bermuda, 1000 miles away. It was felt sharply at New York. A good des cription is in Earthquake History of the United States (Eppley, 1965, pp. 22-24).

A notable characteristic of earthquakes originating in the Charleston area, first pointed out by Taber, has been the great extent of the area affected, considering relatively low intensity in the epicentral region. A table of some of the greater earthquakes of historic time compiled by Tarr and Martin (1912, p. 128) shows the Charleston earthquake of 1886 first in the size of area affected, even though the maximum intensity in the epicentral region was low as compared with the other great earthquakes. The Charleston quake wrought only minor superficial chang The epicentral region was broken by many fissures through which water issued, but "the fissures seldom attained a width of more than an inch", according to Dutton (1889). In contrast, the California earthquake of 1906 opened fissures up to 5 fee wide, 15 miles from the fault, and within a few hundred yards of the fault vibratic were sufficiently violent to uproot oak trees 6 feet in diameter and break off limb 2 feet thick. Despite its greater intensity in the epicentral region, the 1906 Cal ifornia earthquake affected an area of only 373,000 square miles, while the 1886 Charleston earthquake affected 2.8 million square miles. This anomaly is consisten with Taber's idea that the Charleston earthquake was caused by movement along a fault in the basement, beneath a great thickness of unconsolidated sediments.

Since 1663 the southeastern part of the United States has had 49 earthquakes c intensity V, 30 earthquakes of intensity VI, 7 of intensity VII, 3 of intensity VII and 1 of intensity X. During the last 100 years the area within a 100-mile radius of the Savannah River Plant has experienced 9 shocks of intensity V, 4 shocks of in tensity VI, 2 of intensity VII, 1 of intensity VIII, and one of intensity X. The average period between shocks of intensity V or greater has been about 5 years. The frequency of tremors with intensity IV or less has been decreasing since 1886. Between 1886 and 1897 the frequency averaged 29 per year; between 1898 and 1913 the average was 6 per year. The present is about 1 per year. None of these shocks as felt in the Savannah River Plant area had an intensity greater than V except the Charleston shock.

Expected Seismicity

Good general clues to the relative seismicity of a region are (a) relief, (b) geologic structures, and (c) statistical information on past earthquakes.

The region within a 100-mile radius of the Savannah River Plant has low relief. To the southeast is the flat-lying Atlantic Coastal Plain, with the continental shel sloping beneath the sea for another 100 miles. To the northwest is the subdued topo graphy of the Piedmont province. Both beneath the Coastal Plain and within the Pied mont province are old crystalline rocks. While these are tightly folded and broken by major faults, there is no evidence of movement along most of them during historic time. The evidence presented for recent movements along the Brevard Fault, 150 mile northwest of the Plant, is inconclusive.

The geologic record for the last 200 million years shows the region to have bee relatively quiescent. Records kept during the last 3 centuries show the region has been one of the most stable in the United States. The only strong shock at the Sava nah River Plant area during the last 3 centuries was from the Charleston earthquake, 90 miles to the southeast, in 1886, for which the intensity in the Plant area has been estimated at VII-VIII. With this one exception in 300 years, the shocks in the Plant area have ranged from I to V with a frequency of one shock per 5-10 years. Ir struments at the Plant site have not alarmed at intensity II during the past 12 year:

The Savannah River Plant is in a region charactized by a relatively slow rate o1 crustal change. It is on the flanks of an ancient mountain system which is largely quiescent. Relatively frequent small tremors of low intensity appear to relieve stresses before there is any major accumulation. From geologic information as well as from seismic history a major earthquake near the Savannah River Plant is improbab]

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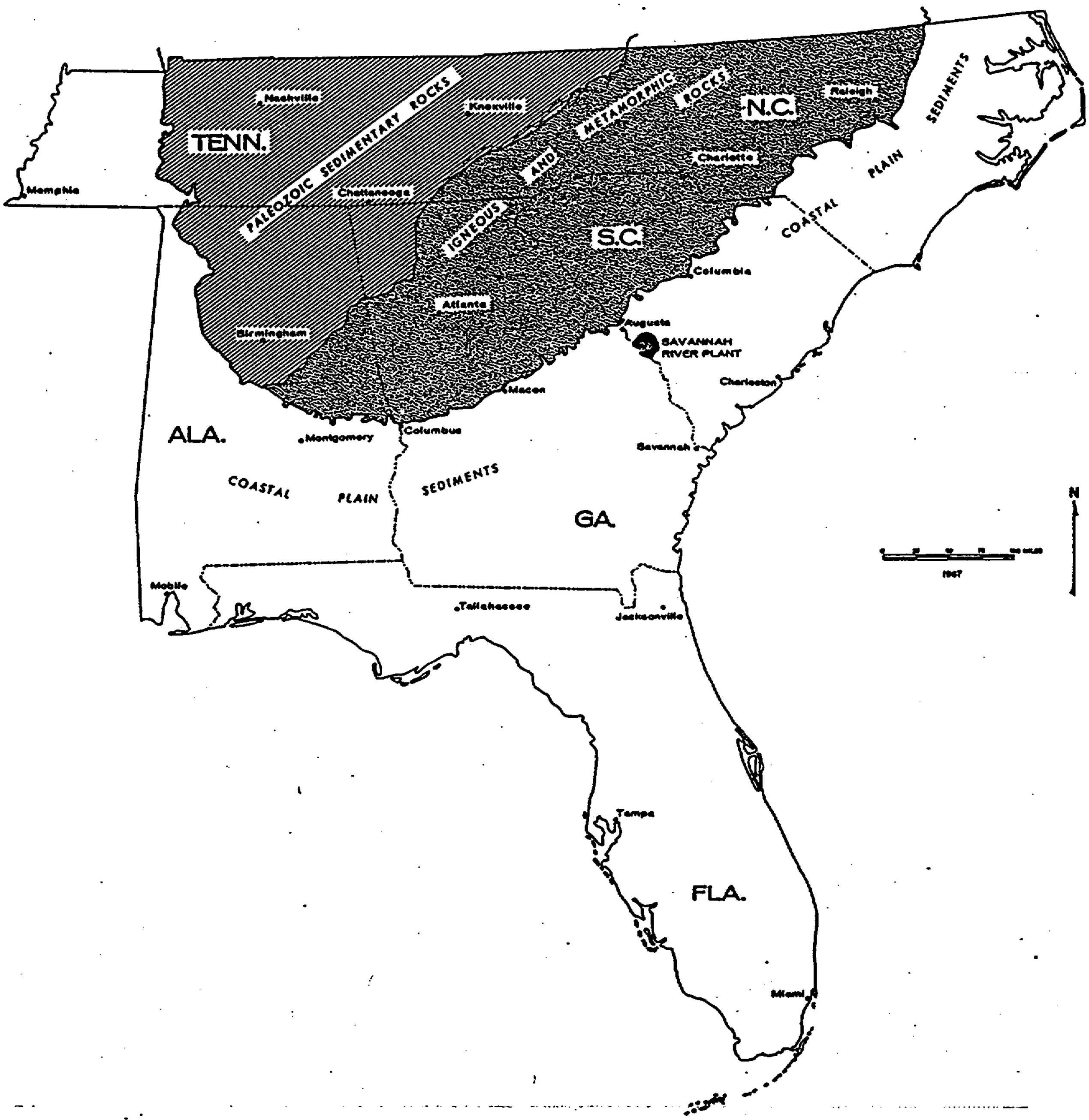


Figure 1. Location of Savannah River Plant with respect to major geologic provinces of Southeastern United States

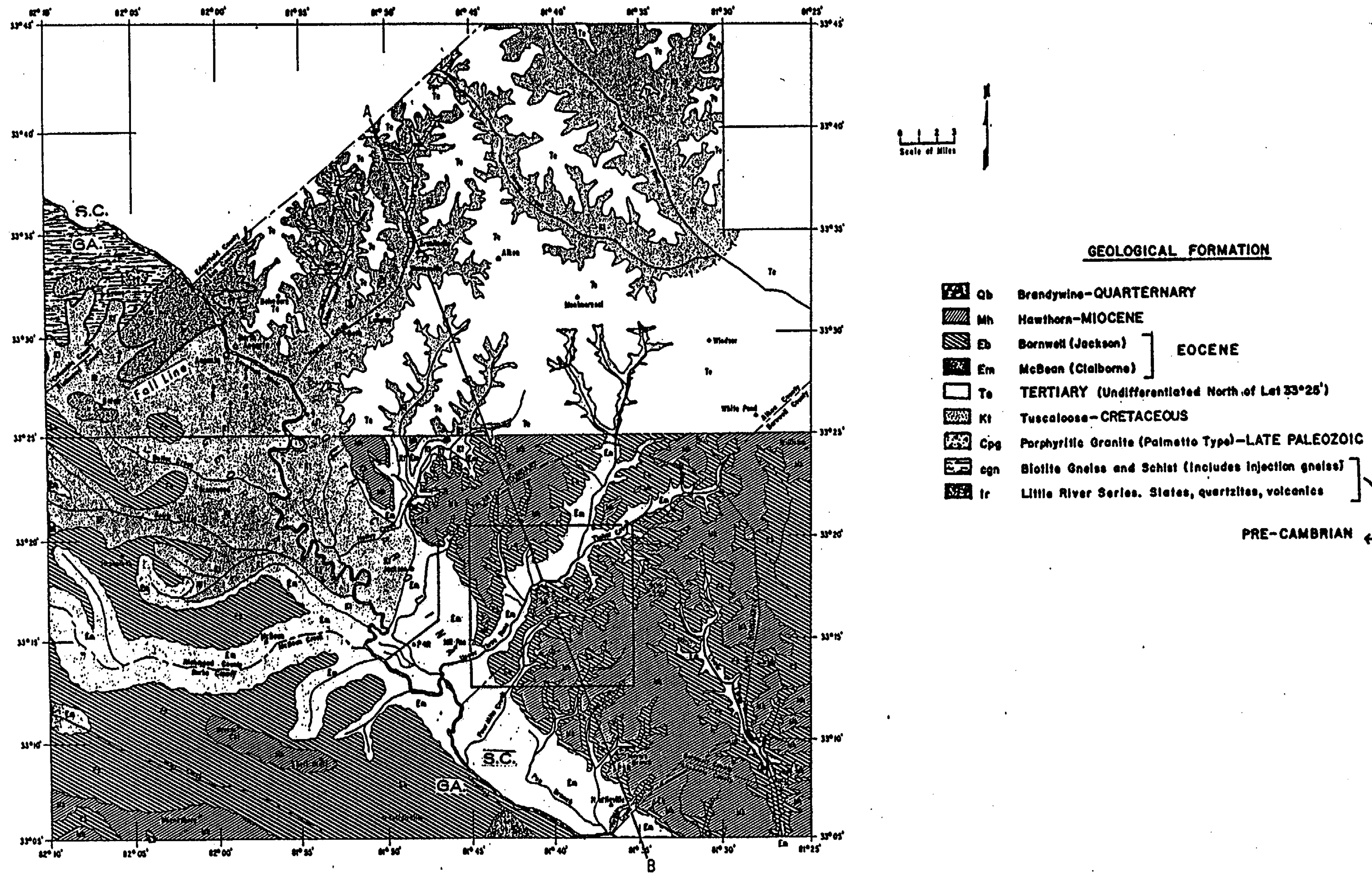


Figure 2. Geologic map of the Savannah River Plant area (rectangle) and environs

TABLE 1-Geologic formations underlying the Savannah River Plant Area.

Formation	Geologic Age	Exposure	Description	Water Content	Thickness, ft.
Alluvium	Recent		Fine to coarse sand, silt, and clay	Very little	0-30
Terrace Deposits	Pleistocene	Flood plains and terraces of stream valleys	Tan to gray sand, clay, silt, and gravel with blanket deposits of coarse gravel on higher terraces	Moderate to none	0-30
Alluvium	Pliocene		Gravel and sandy clay	Little or none	0-20
Hawthorne	Miocene	Large part of ground surface	Tan, red, and purple sandy clay with numerous clastic dikes	Small to moderate amounts	0-80
Barnwell	Eocene	Large part of ground surface near streams	Red, brown, yellow, and buff, fine to coarse sand and sandy clay	Limited quantities that are sufficient for domestic use	0-90
McBean Congaree	Eocene	In banks of larger streams	Yellow-brown to green, fine to coarse, glauconite quartz sand, intercalcated with green, red, yellow, and tan clay, sandy marl, and lenses of siliceous limestone	Moderate to large amounts. Quality likely to be harder and of higher iron than other ground water.	100-250
Ellenton	Upper Cretaceous	Not exposed on plant	Dark-gray to black sandy lignitic micaceous clay containing disseminated crystalline gypsum and coarse quartz sand	Moderate to large amounts. Higher sulfate and iron content than water from other formations.	5-100
Tuscaloosa	Upper Cretaceous	Not exposed on plant	Tan, buff, red, and white; cross-bedded, micaceous quartzitic and arkosic sand and gravel interbedded with red, brown, and purple clay and white kaolin	Large amounts available with up to 2,000 gpm yields from 8- to 12-inch gravel-pack wells. Soft and low in total solids	0-600
Newark Series "Red Beds"	Triassic	Not exposed on plant	Gray, dark-brown, and brick-red sandstone, siltstone, and claystone with included sections of fanglomerate containing gray calcareous pebbles. Rocks identified in only one piezometer and areal extent unknown.	Low yields typical of this type rock in other areas	Unknown
Basement Rocks of the Slate Belt and Charlotte Groups	Precambrian and Paleozoic	Not exposed on plant	Hornblende gneiss, chlorite-hornblende schist, lesser amounts of quartzite. Covered by saprolite layer 75 ft. thick derived from basement rock.	Small amounts	Many thousands

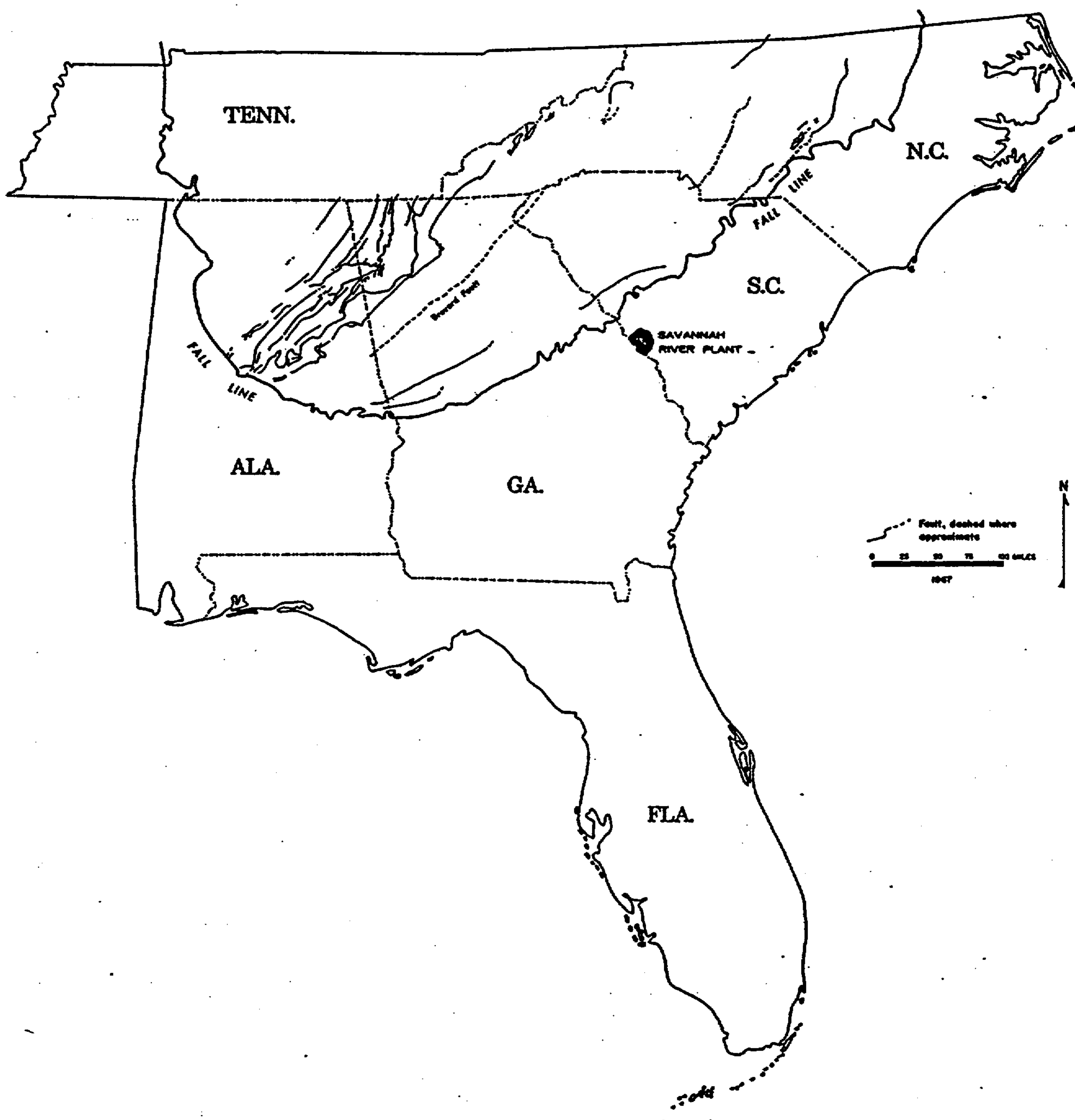
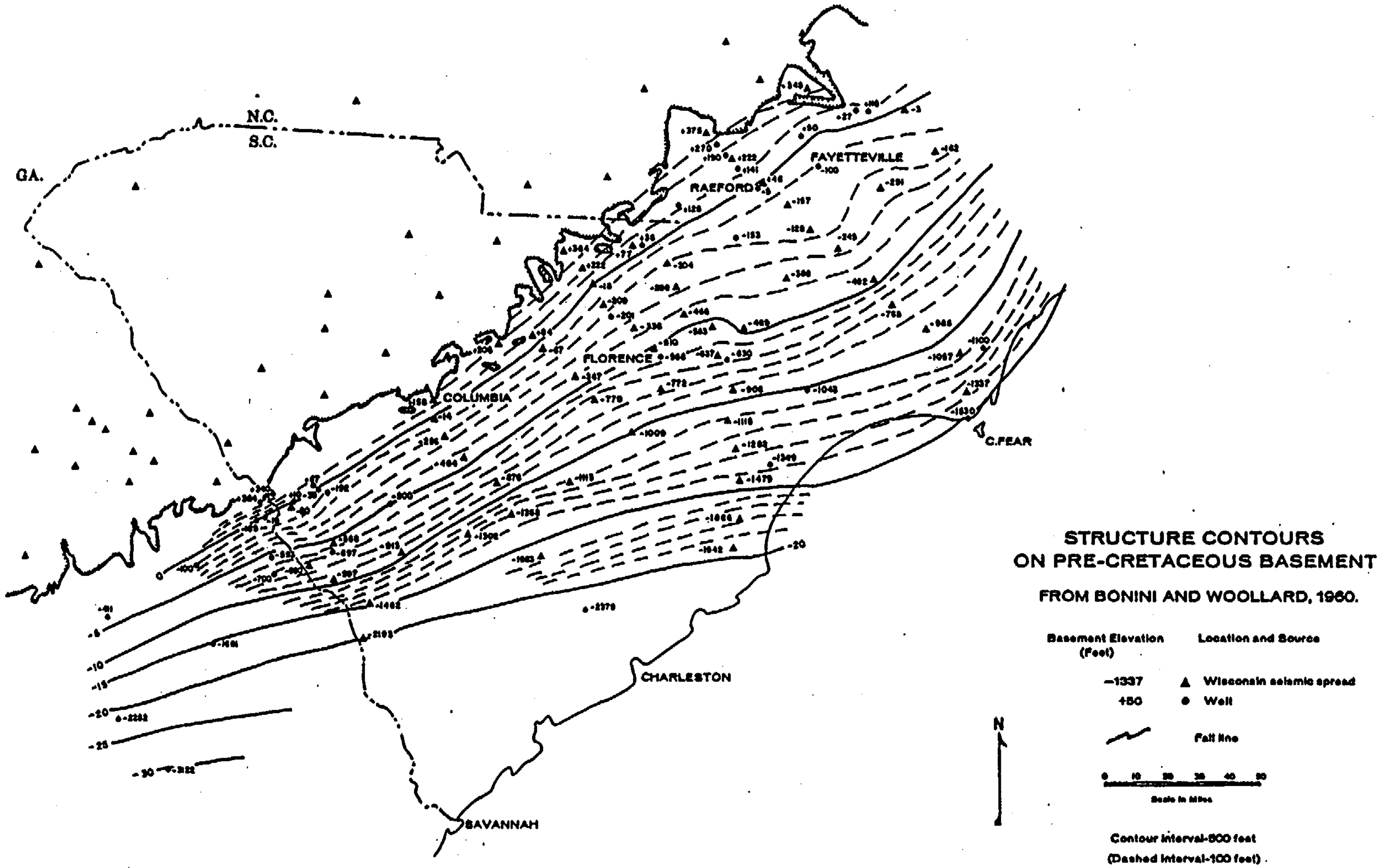


Figure 3. Major known faults in the region about the Savannah River Plant



STRUCTURE CONTOURS
ON PRE-CRETACEOUS BASEMENT
FROM BONINI AND WOOLLARD, 1960.
Basement Elevation (Feet)
Location and Source
−1337 ▲ Wisconsin seismic spread
+50 ● Well
Fall line
Scale in Miles
Contour interval-500 feet
(Dashed interval-100 feet)
N
N.C.
S.C.
GA.
FAYETTEVILLE
RAEFORD
FLORENCE
COLUMBIA
C.FEAR
CHARLESTON
SAVANNAH

Figure 4

APPENDIX C

SEISMICITY AND SEISMIC EFFECTS AT A SITE IN SOUTH CAROLINA NEAR AUGUSTA, GEORGIA

DR. JACK OLIVER AND DR. BRYAN ISACKS

AUGUST 1967

DPE-2383

WORK REQUEST 850891 - SAVANNAH RIVER PLANT

EARTHQUAKE STUDY - 100 AREAS

EARTHQUAKE CRITERIA FOR THE SAVANNAH RIVER PLANT

MARCH 1968

E. I. DU PONT DE NEMOURS & CO. (INC.)
ENGINEERING DEPARTMENT
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SEISMICITY AND SEISMIC EFFECTS AT THE SAVANNAH RIVER PLANT

PREPARED FOR E. I. DU PONT DE NEMOURS & COMPANY,

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Introduction

This report presents a study of the seismicity and seismic effects related to a site in South Carolina bordering on the Savannah River near Augusta, Georgia. No distinction is made here between these two locations, and data from Augusta for past earthquakes are assumed to apply equally to the site. In this report, the seismic history of an area included by a circle of radius about 200 miles centered on Augusta is presented and discussed in some detail and is compared with the seismicity of certain areas in other parts of the United States. An estimate of the seismic disturbances to be expected at the site in the future is given with a discussion of the reasons for and hence the reasonableness of these estimates.

Briefly, the situation is this. Within about 50 miles of the site only one earthquake with maximum intensity of at least V has been located. Its maximum intensity was VI. Within a circle of 200-mile radius, two general groups of earthquakes are of interest. To the north and west of the site there is moderate activity associated with the Appalachian Mountains and light activity in the Piedmont; such activity is characteristic of these provinces throughout most of their length. To the south and east of the site, on the coastal plain, activity is minor except for the large Charleston earthquake of 1886 and other activity in that region. The unusual, in fact, unique, 1886 event produced intensities at Augusta about three units higher than those from any other event that has affected that site. Subsequent events from the same area have produced many of the remaining cases of shaking at Augusta. Thus, the general outlook at the site, based on the seismic record, is one of light-to-moderate, relatively infrequent, shaking (Intensity rarely $\sim$ MM V, usually less) from events primarily in the Charleston area but also in the

Appalachian area and possibly from a rare event in the Piedmont or elsewhere in the coastal plain, with the reservation that there might be a large event similar to the Charleston earthquake that would cause more severe effects. The probability of such an event is difficult to assess in view of the limited information, which is that there has been one, and only one, such event in at least 300 years.

The sources of information used in this report are cited in the bibliography. Much of the basic information is found in the Earthquake History of the United States and in United States Earthquakes. Supplementary information comes from a variety of sources. The information is primarily of the intensity type; no good strong-motion instruments have been operated in the area to our knowledge, and even today the configuration of the network of sensitive seismograph stations is not adequate for very accurate determinations of epicentral locations, focal depths and magnitudes in spite of a general improvement of this network with time. The statements of this report are written so as to present reasonable estimates of the situation within the limitations of the less-than-ideal, but still fairly substantial, data.

For convenience of the reader, the Modified Mercalli (MM) scale of seismic intensities is reproduced in the appendix. This scale is used throughout this report. When conversion from the Rossi-Forel scale was required, the table found on page 651 of Richter's Elementary Seismology was used. One relation between maximum MM intensity and magnitude is that of Gutenberg and Richter, i.e., $M = 1 + 2/3\ I_o$. This point is discussed further in a later section comparing wave propagation in the eastern U.S. with that in the western U.S.

Seismic History of the Area

The seismic history of the area within 200 miles of Augusta is summarized in Figure 1, which shows a map of the area with epicenters superimposed, and Table 1, which lists relevant data on the corresponding events, as well as data on other large distant shocks felt at Augusta. The data cover an interval of about 300 years, at least for the larger shocks, but it must be remembered that intensity data are to some extent dependent upon population density, that the historical record is probably incomplete, particularly with regard to the smaller events, that seismographs were very sparse in North America prior to the San Francisco earthquake in 1906, and that for study of small earthquakes in the southeastern U.S. the distribution of seismographs has never been very good. Hence, even today locations of small events might be in error by some tens of kilometers and magnitudes of small events rarely and poorly determined. In spite of the limitations, however, there is a considerable quantity of informative macroseismic data for the area.

On the map of Figure 1 the maximum intensity is indicated by the diameter of the circular symbol according to the accompanying scale. Also indicated by a Roman numeral for the shocks for which such data are available is the intensity observed at Augusta as a result of that earthquake. The same information is given in Table 1a. If the seismic activity of the future is similar to that of the historical record, these intensities will provide the best information on what may be expected at that site in the future. With the exception of the three largest events, the aftershocks of the Charleston earthquake of 1886 are not listed in Table 1a. A large aftershock series was experienced, however, many of which were probably felt at Augusta. During the month following the earthquake at least ten shocks were felt in Augusta, probably none with intensity greater than IV.

The three largest aftershocks occurred in October and November and may have produced intensities as great as V in Augusta.

Table 2 summarizes the intensity data at or near the site (with the exception just noted). If an estimate of seismic effects in the future were to be based entirely on the history of seismic effects at the site, such data would suffice, for, although a few small events from the past may have been omitted, there is little likelihood that enough events have been left out so that the statistics would be changed significantly. There is virtually no chance that a major event occurring over the last 300 years or so has been omitted.

Some further information bearing on the problem may be obtained, however, by considering seismicity of adjoining and similar regions and by considering the geological record of the area. In the case of the seismicity of the Appalachians, including the Piedmont, the evidence (see, for example, Figure 2) suggests that the seismicity indicated in Figure 1 for the area near the site is essentially typical of that throughout most of the length of the Appalachians. Shocks of moderate intensity are not unusual, but very large shocks are unknown. Furthermore, the geologic record in the Appalachians does not indicate any large-scale recent faulting or other evidence of large-scale recent tectonic movements such as are observed in the tectonically active parts of Alaska, California and Nevada, for example.

On the other hand, the Charleston earthquakes present an anomaly in the seismic pattern of the coastal plain. Other shocks of such magnitude are unknown throughout the length of the coastal plain along the east coast of the United States and as far north as the site of the Grand Banks earthquake that occurred off Newfoundland on 18 November 1929. The seismic record thus suggests that such shocks will rarely be experienced. The geological record, on the other hand, suggests that the area, although not highly active, is not quiescent. The authors of this paper are not expert in the geology of the coastal plain, but merely point out that it is generally thought that the coastal plain is emerging in a section known as the Cape Fear Arch and subsiding in the adjacent section to the south known as the Sea Islands Downwarp. Charleston lies near the boundary between these two sections of the coastal plain and hence the Charleston earthquake may be a manifestation of the contrast in motion between these two elements, one positive, one negative. In both cases there is geomorphic evidence near the sea coast for very recent movement, although probably not at such a great rate as might be found in very active seismic areas.

Only a few earthquakes with epicenters outside the 200-mile circle of Figure 1 have been felt at Augusta. These are listed in Table 1b. They include the famous New Madrid earthquakes in Missouri in 1811-12 and some subsequent activity in that region, two events in Virginia about 300 miles from Augusta, and possibly a large event in the West Indies in 1843. In no case does the intensity at Augusta from these events appear to have exceeded V, and that was in the case of the largest shocks in Missouri.

The Charleston Earthquakes

The large Charleston earthquake of 1886 had a maximum intensity of X. This earthquake apparently marked a change in the overall level of seismicity of the area. From 1671 to 1886 no severe shocks were felt in the area. Between 1754 and 1886 eight small shocks are reported to have been felt; an average of about one per sixteen years. In the year following the 1886 main event, a series of some 86 aftershocks was felt, with the rate gradually falling off with time as is characteristic of aftershock series.

The main Charleston shock was rated at intensity 8 to 8-1/2 on the Rossi-Forel scale, which corresponds to VII to VIII on the MM scale, at Augusta. The three largest aftershocks were rated at intensity VII for one and VI for two at Charleston and hence probably had intensities of about V or less at Augusta. Following the rapidly decreasing aftershock series, the level of activity has apparently remained somewhat higher than it was prior to 1886. Between 1935 and 1964, 19 earthquakes were reported in Charleston, a rate of more than one every two years. Of the 19 events two were felt at Augusta, and these had intensities of IV and V, respectively, although the report of intensity V appears anomalously high in the isoseismal pattern of this event.

Propagation of Seismic Waves in Eastern vs. Western U.S.

It is well known that, in general, an earthquake of a given maximum intensity in the eastern United States will be felt at much greater distances than a shock of the same maximum intensity in the western U.S. Some exceptions to this statement have occurred, but, in general, it is rather well supported by most data. The radius of perceptibility is increased by roughly a factor of four in the eastern U.S. over that in the western U.S. For many years it was felt that this effect was observed because the depths of the shocks in the east were greater. Now it appears more likely that the effect is due to the more efficient propagation of certain seismic waves, primarily the Sg or Lg phase, in the more uniform crustal structure of the east. Thus, a simple relation between magnitude and maximum intensity such as that given earlier could not be expected to apply with great accuracy to earthquakes in a variety of environments. The effect has not been well studied quantitatively. For this reason, in this report the emphasis is placed on the observations, and reliance on theory or on empirical relations based on data for other areas is avoided, insofar as possible. The point is made, however, as a precaution for those who may be unfamiliar with this phenomenon.

Comparison with Seismic Effects in Other Areas

Florida: Florida is a state of relatively infrequent seismic activity. Only two earthquakes of intensity V or greater are reported for Florida in Earthquake History of the United States. Both of these, one with maximum intensity VI, one with maximum intensity V, occurred in northern Florida. Florida has also been shaken by events centered in areas outside the state. The northern part of the state experienced intensity VI during the Charleston earthquake of 1886. The southern part of the state, particularly Key West, experienced "severe shocks" from the Cuban earthquakes of 1880. Other shocks in the West Indies, Missouri and elsewhere have been felt in Florida, but probably the largest intensity ever experienced anywhere in Florida was about VI. In order to make a more detailed comparison with the site near Augusta, a specific location in Florida would have to be chosen, but it appears that no site in Florida has experienced the intensity level observed in Augusta from the Charleston earthquake.

Central Mississippi Valley: Activity in the central Mississippi Valley is dominated by the seismicity of the site of the New Madrid earthquakes of 1811-1812 and the surrounding area. Three major shocks with maximum intensity XII occurred in 1811-12 and since then many earthquakes have occurred in that region, at least two of which had maximum intensities of VIII. These shocks were felt over large areas, two million square miles in the case of the larger ones. There have been many smaller shocks. Over the interval between 1873 and 1963, 31 shocks with maximum intensity equal to or greater than VI (4 with maximum intensity VII) were experienced, about one every three years. In Charleston, events with maximum intensity VI or greater have been experienced about once every thirty years or so. This figure excludes the main shock of 1886 and its aftershocks and hence is comparable to the figure of one per three years given above for the New Madrid area. The main shocks in New Madrid were greater in every way than the main shock in Charleston. Subsequent activity has also been greater in the Missouri area. A more detailed comparison of some site in the central Mississippi Valley with the site near Augusta would depend upon the location of the particular site chosen.

St. Lawrence Valley: For the purpose of discussing seismic activity, the active region of the St. Lawrence Valley may be conveniently divided into two parts. One is a zone of concentrated activity northeast of the city of Quebec; the other is a zone of more diffuse activity trending northwest across the St. Lawrence Valley between Ottawa and Montreal. Both of these areas have been more active in historic time than the region near Augusta shown in Figure 1.

In the zone northeast of Quebec, five shocks with intensity about IX or over were experienced in about 425 years, a much greater rate of activity than indicated for the Augusta region shown in Figure 1 and Table 1a. Numerous earthquakes of lower intensity have been felt in the Canadian zone. For shocks of lower intensity, however, two prime sources of data, Earthquake History of the United States and Earthquakes of Eastern Canada and Adjacent Areas, give results that appear to be somewhat in conflict with the above statement, i.e., the rate of occurrence of shocks of a given intensity in the intensity range of about VII or less is less in the Canadian area than in the area of Figure 1. It is our opinion that this difference probably represents a different point of view in assigning intensity values and that the apparent difference may not be real. A detailed study of the basic data would be required to resolve this difficulty. We believe it is clear from the total number of large shocks and the total number of shocks of all sizes that the seismicity of the St. Lawrence Valley northeast of Quebec is far greater than that of the area of Figure 1.

For the Ottawa-Montreal portion of the St. Lawrence Valley a comparison of the literature indicates that the activity is about the same as that of the area of Figure 1. One shock of maximum intensity IX and one of maximum intensity VIII have been felt in about 400 years. However, the number of reported shocks is greater in the case of the St. Lawrence Valley and it appears that the difficulty cited above applies here as well. Probably this portion of the St. Lawrence Valley is more active than the area of Figure 1, but it is less active than the section of the St. Lawrence Valley to the northeast of the City of Quebec.

Southern California: Data were accumulated for an area of Southern California of size comparable to that of the circle of Figure 1. The statistics for this part of California are shown in Table 4, which may be compared with Table 3. It is clear that earthquakes of a given maximum intensity occur much more frequently in California, i. e., that the seismicity of California is considerably greater. What the seismic effects might be at a given site in California, of course, depends on other factors such as the propagation effects cited above, and a simple comparison of the seismicity is not adequate for more than a general assessment of the situation.

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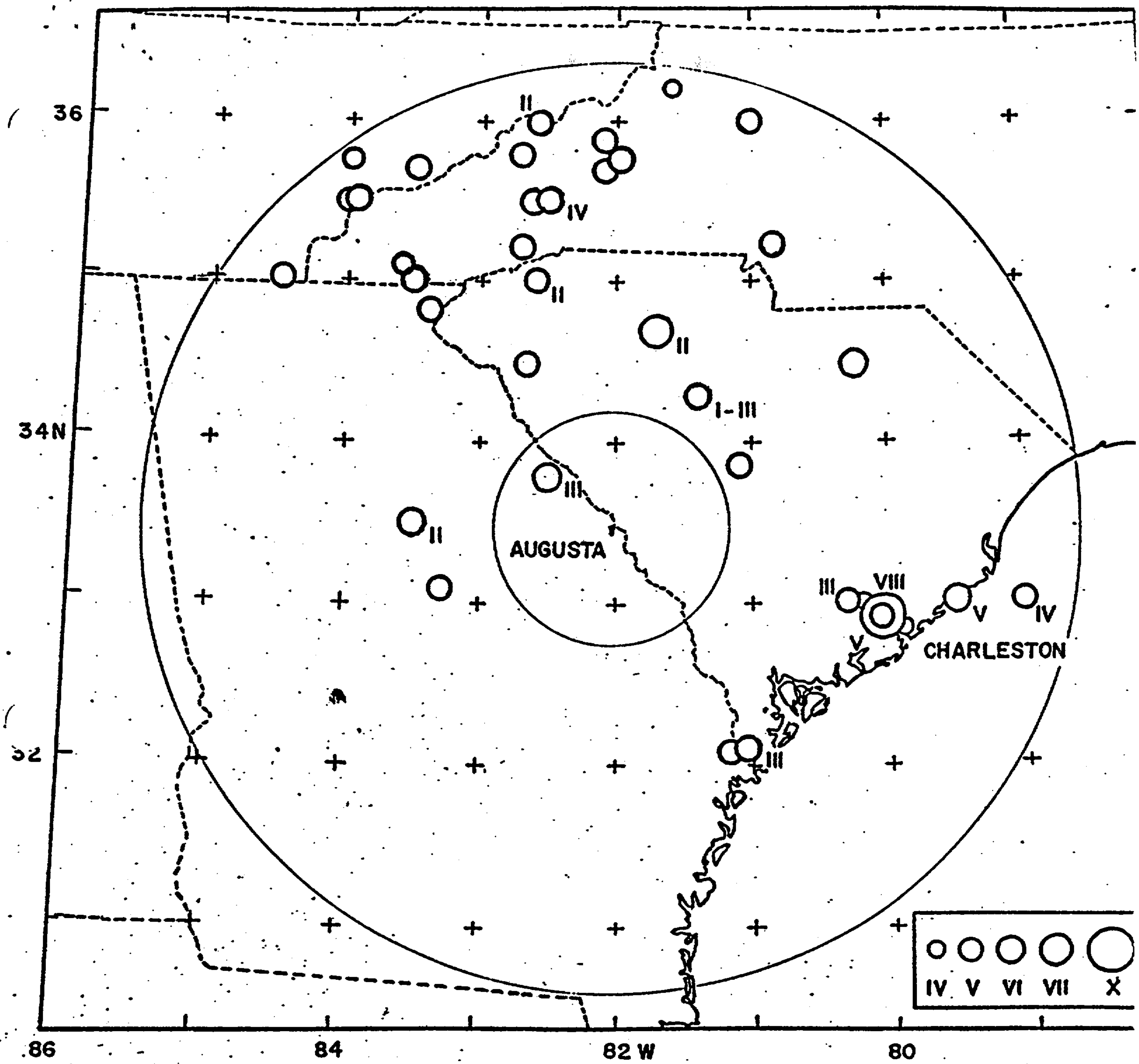
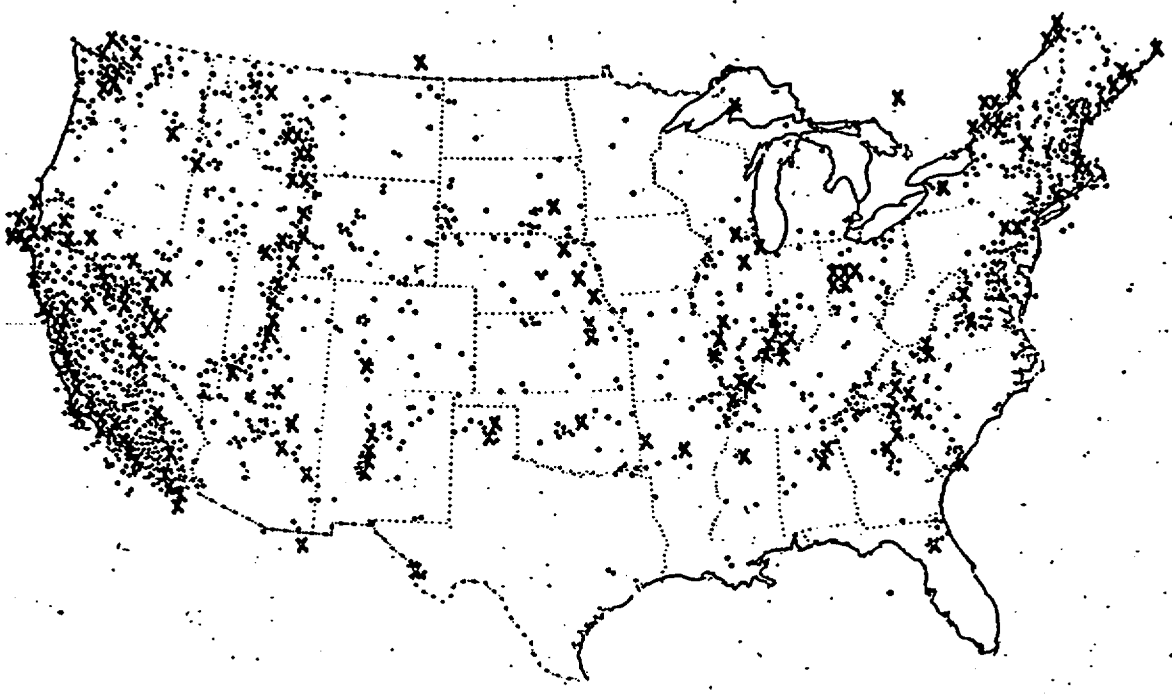


FIGURE I

Earthquakes with maximum intensity greater than or equal to V. The large circles indicate distances of 50 and 200 miles from Augusta, Georgia. A Roman numeral shown near an epicenter is the intensity felt at Augusta.



X Destructive and near destructive earthquakes (after C and GS)

• Minor earthquakes (after American Geophysical Union)

Figure 2. Epicenters of earthquakes in and immediately adjacent to the United States. X = destructive and near-destructive earthquakes. (After Coast and Geodetic Survey.) • = minor earthquakes. (After American Geophysical Union.)

Table 1a. Earthquakes located within 200 miles of Augusta, Georgia.

Date				Location			Max. Inten- sity	Area felt sq. mi.	Dist. from Augusta	Intensity at Augusta[1]
Year	Mo.	Day	Hr.		Lat. N	Long. W				
1857	Dec	19	09	Charleston, S. C.	32.8	79.8	?	?	130	-
1872	Jun	17	15	Milledgeville, Ga.	33.1	83.3	V	?	80	-
1874[2]	Feb	10-Apr	17	McDowell Co., N.C.	35.7	82.1	V	25	155	-
1875	Nov	1	21	Northern Georgia	33.8	82.5	VI	25,000	35	(III)[3]
1879	Dec	12	19	Charlotte, N. C.	35.2	80.8	V	?	140	-
1885	Aug	6	08	North Carolina	36.2	81.6	IV-V	Local	190	-
1886	Aug	31	21	Charleston, S. C.	32.9	80.0	X	2,000,000	110	VIII
1886	Oct	22	05	Charleston, S. C.	32.9	80.0	VI	30,000	110	(IV)
1886	Oct	22	14	Charleston, S. C.	32.9	80.0	VII	30,000	110	(V)
1886	Nov	5	12	Charleston, S. C.	32.9	80.0	VI	30,000	110	(IV)
1903	Jan	23	20	Ga. and S. C.	32.1	81.1	VI	10,000	110	III
1904	Mar	4	19	Eastern Tenn.	35.7	83.5	V	5,000	175	-
1907	Apr	19	03	Southeastern S. C.	32.9	80.0	V	10,000	125	-
1911	Apr	20	?	N. C.-S. C. border	35.2	82.7	V	600	100	-
1912	Jun	12	05	Summerville, S. C.	32.9	80.0	VII	35,000	110	V
1912	Jun	20	?	Savannah, Ga.	32	81	V	?	110	-
1913	Jan	1	13	Union Co., S. C.	34.7	81.7	VII-VIII	43,000	85	II
1914	Mar	5	15	SE of Atlanta, Ga.	33.5	83.5	VI	50,000	85	(II)
1914	Sep	22	02	Summerville, S. C.	33.0	80.3	V	30,000	105	III
1915	Oct	29	01	Marshall, N. C.	35.8	82.7	V	1,200	165	-
1916	Feb	21	17	Western N. C.	35.5	82.5	VI	200,000	145	IV
1916	Aug	26	14	Western N. C.	36	81	V	3,800	185	-
1924	Oct	20	03	Pickens Co., S. C.	35.0	82.6	V	56,000	110	II
1926	Jul	8	04	Mitchell Co., N. C.	35.9	82.1	VI	Local	165	-
1928	Nov	2	23	Western N. C.	36.0	82.6	VI	40,000	160	II

Table 1a (Continued)

Date				Location			Max. Intensity	Area felt sq. mi.	Dist. from Augusta	Intens at Augus
ear	Mo.	Day	Hr.		Lat. N	Long. W				
33	Dec	19	09	Summerville, S. C.	33.0	80.2	IV-V	Local	110	-
33	Jan	1	03	N. C.-Ga. border	35.1	83.6	V	7,000	145	-
15	Jun	13	22	Cleveland, Tenn.	35	84.5	V	?	180	-
5	Jul	26	06	Murray Lake, S. C.	34.3	81.4	VI	25,000	65	I-II
2	Nov	19	?	Charleston, S. C.	32.8	80.0	V	?	125	-
5	Sep	7	08	Eastern Tenn.	35.5	84.0	VI	8,300	180	-
	May	13	09	Western N. C.	35-3/4	82	VI	8,100	160	-
	Jul	2	04	Western N. C.	35-1/2	82-1/2	VI	?	145	-
	Nov	24	15	N. C.-Tenn. border	35	83-1/2	VI	4,100	135	-
	Oct	20	01	Anderson, S. C.	34-1/2	82-3/4	V	Local	80	-
	Aug	3	01	Southeastern S. C.	33	79-1/2	VI	25,000	150	V
	Oct	26	21	Northeastern S. C.	34-1/2	80-1/4	VI	4,800	125	-
	Mar	12	07	Coast of S. C.	33	79	V	3,500	180	IV
00	Apr	15	05	Eastern Tenn.	35-3/4	84	V	1,300	195	-
1960	Jul	23	22	Charleston, S. C.	33	80	V	Local	125	-
1964	Apr	20	14	Gaston, S. C.	34.0	81.0	V	?	55	-

(1) A dash indicates that the earthquake was probably not felt at Augusta.

(2) A swarm of 50-75 shocks.

(3) An intensity in parentheses is estimated from consideration of the maximum intensity an the distance between the shock and Augusta; otherwise, the intensities at Augusta are estimated from reports of effects at Augusta.

Table 1b. Large earthquakes felt in Augusta and at distances greater than 200 miles

Date			Location			Max. Intensity	Area felt sq. mi.	Intensity at Augusta
Year	Mo.	Day		Lat.	Long.			
				N	W			
1811	Dec	16	New Madrid, Mo.	36.6	89.6	XII	2,000,000	V
1812	Jan	23	New Madrid, Mo.	36.6	89.6			V
1812	Feb	7	New Madrid, Mo.	36.6	89.6			V
1843	Jan	4	Western Tennessee	35.2	90.0	VIII	400,000	(II-III)
1843	Feb	8	West Indies	16	32	?	?	(II) ?
1861	Aug	31	Virginia	?	?	VI	300,000	(II-III)
1895	Oct	31	Charleston, Mo.	37.0	89.4	VIII	1,000,000	(II-III)
1897	May	31	Giles Co., Virginia	37.3	80.7	VIII	280,000	(II-III)

Table 2. Intensities observed at Augusta over the interval 1873-1964 (excluding aftershocks of the Charleston earthquake occurring in 1886).

Intensity greater than or equal to	Cumulative number of events	Average interval between events (years)
II	15*	6*
III	9*	10*
IV	5	18
V	3	31
VI	1	main Charleston earthquake, only one in at least 300 years.
VII	1	
VIII	1	

* Data are probably far from complete at these intensities.

Table 3. Summary of maximum intensity data of Table 1a and Figure 1.

Intensity greater than or equal to	Cumulative number of events in table	Average interval in years between events for interval 1873-1964
IV	39*	--
V	36	2 1/2
VI	16	6
VII	3	31
VIII	2	46
IX	1	main Charleston earthquake, only one in at least 300 years.
X	1	

* Data are probably far from complete at this intensity.

Table 4. Summary of maximum intensity data for a region of Southern California for the years 1812-1961.

Intensity greater than or equal to	Cumulative number of events	Average interval in years between events
VI	107	1 1/2
VIII	31	5
IX	12	12 1/2
X	5	30

APPENDIX

Modified Mercali Scale, 1956 Version

I. Not felt. Marginal and long-period effects of large earthquakes.

II. Felt by persons at rest, on upper floors, or favorably placed.

III. Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.

IV. Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV wooden walls and frame creak.

V. Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate.

VI. Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knickknacks, books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D cracked. Small bells ring (church, school). Trees, bushes shaken (visibly, or heard to rustle).

VII. Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices (also unbraced parapets and architectural ornaments). Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.

VIII. Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.

IX. General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. (General damage to foundations) Frame structures, if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated areas sand and mud ejected, earthquake fountains, sand craters.

X. Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.

XI. Rails bent greatly. Underground pipelines completely out of service.

XII. Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

Masonry A. Good workmanship, mortar, and design; reinforced, especially laterally, and bound together by using steel, concrete, etc., designed to resist lateral forces.

Masonry B. Good workmanship and mortar; reinforced, but not designed in detail to resist lateral forces.

Masonry C. Ordinary workmanship and mortar; no extreme weaknesses like failing to tie in at corners, but neither reinforced nor designed against horizontal forces.

Masonry D. Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.

APPENDIX D

BIOGRAPHICAL DATA

DR. GEORGE W. HOUSNER

DR. JACK OLIVER

DR. VERNON HURST

Experience Record
of
George W. Housner

Education	B. S., University of Michigan, 1933 Ph.D., California Institute of Technology, 1941
Publications	Author of 65 technical papers and three engineering textbooks.
1934-38	Practicing engineer in Los Angeles
1939-41	California Institute of Technology
1941-42	U. S. Army Engineer Corps
1943-45	Chief, Operations Analysis Section, Fifteenth Air Force, ETO
1945 —	Professor of Engineering at the California Institute of Technology
1955-66	President, Earthquake Engineering Research Institute
1957-60	Member, Senior Advisory Panel on Titan Missile Bases, U. S. Air Force
1959-64	Member, Advisory Panel on Public Safety During Underground Tests, Atomic Energy Commission
1960 —	Member of Board of Directors of International Association of Earthquake Engineering
1963 —	Member of Advisory Committee on Earthquake Problems for California Department of Water Resources
1963 —	Member of Board of Directors of International Institute of Seismology and Earthquake Engineering
1964-65	Member of Office of Science and Technology Committee on Earthquake Prediction
1965 —	Member of National Academy of Engineering
1965 —	Chairman, California State Geological Hazards Committee

Consultant on numerous projects, such as:

Design of Trans-Arabian Pipeline.
Design of San Francisco Bay Area Rapid Transit System.
Design of Suspension Bridge over Tagus River in Lisbon, Portugal.
Earthquake design of California State Water Project.
Preparation of AEC Handbook of Nuclear Reactors and Earthquakes.
Earthquake design of Nuclear Reactors for Japan Atomic Power Company.
Earthquake design of Jersey-Central Nuclear Power Project.
Earthquake design of Niagara-Mohawk Nuclear Power Project.
Earthquake design of City of Los Angeles Malibu Nuclear Power Project.
Earthquake design of So. California Edison San Onofre Nuclear Power Project.
Earthquake design of Los Angeles nuclear power-water desalinization project.
Earthquake design of Standard Oil Co. of New York Nicaragua Oil Refinery.
Etc.

Biographical Data for Jack E. Oliver

Born: September 26, 1923 - Massillon, Ohio

Education: Graduated Washington High School, Massillon, Ohio, 1941
B. A. Columbia College 1947
M. A. (Physics) Columbia University 1950
Ph. D. (Geophysics) Columbia University 1953

Positions Held:
Professor of Geology, Columbia University - 1961-present
Associate Professor of Geology, Columbia University - 1959-61
Assistant Professor of Geology, Columbia University - 1958-59
Instructor of Geology, Columbia University - 1955-58
Terrestrial Physicist, Air Force Cambridge Research Laboratories - 1951
Scientist's Aide, U. S. Naval Research Laboratory - 1947

Military Service:
U. S. N. R. 1943-46 - Served in Pacific Theater with 129th Naval Construction Battalion

Societies: Seismological Society of America
American Geophysical Union
Society of Exploration Geophysicists
American Physical Society
Acoustical Society of America
Geological Society of America
American Association for the Advancement of Science
Sigma Xi

Offices Held:

Seismological Society of America
President, 1964-65
Vice President, 1962-64
Member, Board of Directors, 1961-present
Member, Editorial Committee, 1957-61

Eastern Section, Seismological Society of America
Chairman, 1959-60
Vice Chairman, 1958-59

Biographical Data of Jack E. Oliver (continued)

American Geophysical Union, Section on Seismology
President, 1964-68
Vice President, 1961-64
Member, Committee on Fellows, 1964-present
Member, Special Committee on Geological and Geophysical Studies, 1964-present

Member, Carnegie Institition Advisory Committee on Awards for the Grove Karl Gilbert Fund and the Harry Oscar Wood Fund, 1964-present

Committees, Panels, etc.:

President's Scientific Advisory Committee Panel on Seismic Improvements, 1958-59
Ad Hoc Panel on Seismology, Department of Defense (Advanced Research Projects Agency), 1959-63
National Academy of Sciences, Committee on Polar Research, 1959-present
National Academy of Sciences, Committee on Seismology (previously Committee on Seismological Stations), 1960-present
National Academy of Sciences, Advisory Committee to U. S. Coast and Geodetic Survey, 1962-1966
National Academy of Sciences, Panel on Solid Earth Problems, 1962-present
National Academy of Sciences, National Committee for Upper Mantle Program, 1963-present
National Academy of Sciences, Site Selection Committee for New Accelerator, 1965
Air Force Office of Scientific Research, Contractor's Research and Evaluation Panel (formerly Advisory Committee for Geophysics), 1961-present
Air Force Scientific Advisory Board, 1960-63; 1964-present
UNESCO Consultative Committee on Seismology and Earthquake Engineering, 1965-present
International Seismological Summary Committee of the IASPEI, 1963-present

Consultant to:

Advanced Research Projects Agency, 1963-present
U.S. Arms Control and Disarmament Agency, 1962-present
U.S. Air Force Technical Applications Center, 1958-present

Biographical Data of Jack E. Oliver (continued)

Special Tasks:

Scientific advisor to political discussions on a nuclear test ban treaty - Geneva, Switzerland, 1958 and 1959.

UNESCO Seismological Symposium - Santiago, Chile, 1961.

UNESCO Working Group on the Earth's Crust - Paris, 1962.

VELA-UNIFORM-TABOR PLUTO Conference - London, 1962.

VESIAC Special Study Conference on Problems in Seismic Background Noise - Clearwater, Florida, 1962.

UNESCO Intergovernmental Meeting on Seismology and Earthquake Engineering - Paris, 1964.

Leader U.S. delegation to Conference on Research-Related to Earthquake Prediction - Japan, 1964.

VESIAC Special Study Conference on Seismic Signal Anomalies - Beaugency, France, 1964.

Meeting of the Consultative Committee on Seismology and Earthquake Engineering - Tbilisi, Georgia SSR, 1965.

U. S. Coordinator, Second U. S. -Japan Conference on Research Related to Earthquake Prediction - Palisades, New York, 1966.

Special Geophysical Field Work:

1947-49 - Exploration of the upper atmosphere by acoustical methods - New Mexico, Florida, Alaska.

1950 - Seismic exploration of Hudson River and Long Island Sound.

1951 - Geophysical study of Arctic ice pack - First U. S. plane landings on ice pack for scientific purposes.

1954 - Installation of seismic and barometric instruments in South Africa.

1964 - Survey of sites for seismograph stations - Ivory Coast and Chad.

1964 - Geological field trips throughout New Zealand

1964-65 - Installation of seismographs in Fiji-Tonga area of Pacific.

1965 - Study of microearthquakes in Nevada.

1965 - Study of microearthquakes in Alaska.

1966 - Study of microearthquakes in Nevada and Alaska.

Biographical Data of Jack E. Oliver (continued)

Research Summary (see publications for details):

Past research includes exploration of the upper atmosphere by acoustical methods; participation in first U. S. aircraft landings on Arctic ice pack for scientific purposes; marine seismic refraction measurements; research in seismology, including model seismology, earthquake and explosion-generated seismic waves.

Recent research includes analysis of long period seismic data from Lamont Geological Observatory's worldwide seismograph network; study of phase velocities of Rayleigh waves across tripartite arrays; moon seismograph program; strainmeter program; Arctic ice pack investigations; study of mechanisms of sources of seismic waves using earthquake and model seismographic methods; study of propagation of elastic waves from nuclear explosions; study of ultralong period microseisms; study of leaking modes; study of deep earthquakes; study of microearthquakes.

Awards:

Carnegie Institution Harry Oscar Wood Award, 1964
Society of Exploration Geophysicists Award - Author of Classic Paper in Geophysics, 1960
Fellow Member, American Geophysical Union, 1963
Fellow Member, Geological Society of America, 1965

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Publications of Jack Oliver, Principal Investigator

Air-coupled flexural waves in floating ice, with F. Press, A. P. Crary and S. Katz, Amer. Geophys. Union Trans., 32, 166-172, 1951.

Geophysical investigations in the emerged and submerged Atlantic coastal plain: Part VI, Long Island area, with C. L. Drake, Bull. Geol. Soc. Am., 62, 1287-1296, 1951.

Two-dimensional model seismology, with F. Press and M. Ewing, Geophysics, V. XIX, 202-219, 1954.

Elastic waves in Arctic pack ice, with A. P. Crary and R. Cotell, Amer. Geophys Union Trans., 35, 282-292, 1954.

Seismic model study of refractions from a layer of finite thickness, with F. Press and M. Ewing, Geophysics, 19, 388-401, 1954.

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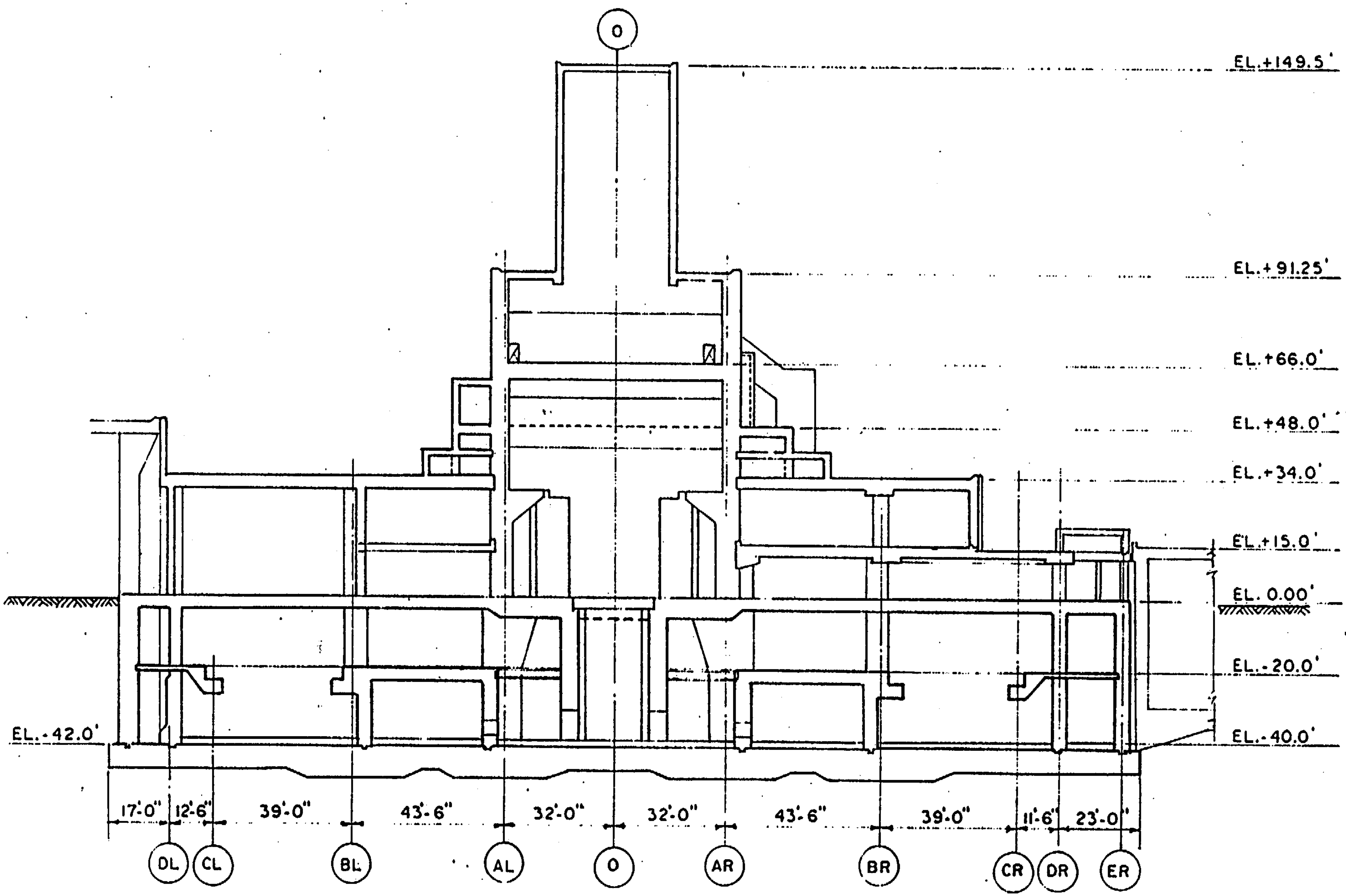

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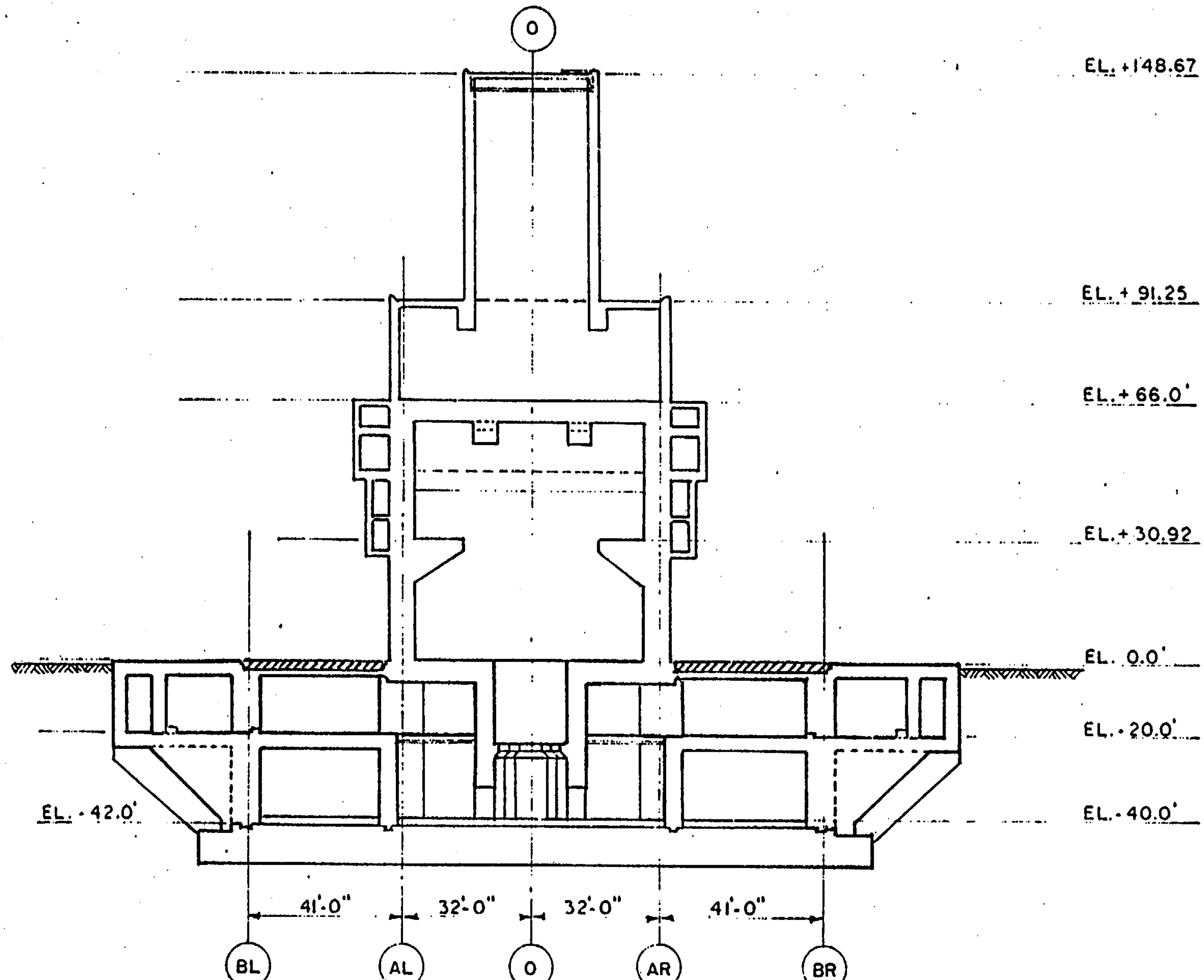

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WSRC-TR-94-0528
DECEMBER 1994

Update of H-Area Seismic Design Basis-Rev 1 (U)

Westinghouse Savannah River Company
Savannah River Site
Aiken, SC 29808

Prepared for the U.S. Department of Energy under Contract No. DE-AC09-89SR18035

Disclaimer

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Update of H-Area Seismic Design Basis (U)

R. C. Lee

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Update of H-Area Seismic Design Basis

Summary

This report supports the history and development of the seismic design basis for the In-Tank Precipitation (ITP)/H-Area Tank Farms. Related documents are the Justification of Continued Operation (JCO) (letter from A. Scott to S. Richardson) and the JCO support document (WSRC-TR-94-0369) for the ITP. The tasks described in this report follow the ITP/H-Area Task Technical work plan (Morin, 1994). This report is also supplemented by a summary report that highlights the conclusions developed in this report (Lee, 1994). Although the report describes data and ground motions that pertain to H-Area, all shallow geotechnical parameters were specific to the ITP, which is a subsection of H-Area.

At the request of DOE oversight groups, this report contains background material that outlines the history and basis for spectra developed for SRS. In particular, both the URS/Blume (1982) (hereafter referred to as the Blume report or spectra) and the Geomatrix (1991) report (hereafter referred to as the Geomatrix report or spectra) are summarized. This report includes a discussion for the application of these spectra for the Replacement Tritium Facility (RTF) and the ITP, both of which are in the H-Area.

The ITP Task Technical work plan (Morin 1994) specifies parametric studies to determine the appropriateness of using the RTF earthquake spectra (derived from spectra developed for K-Reactor) as the ITP evaluation basis earthquake (EBE) for geotechnical evaluations. This report describes parametric studies to compare distant event design basis motions between H-Area, RTF, and K-Reactor. These comparisons are used to understand the sensitivity of derived site spectra to earthquake source parameters, crustal, and soil structure assumptions.

The EBE spectra consist of "local" and "distant" spectra. The "local" spectrum was derived from a deterministic-type Nuclear Regulatory Commission (NRC) Standard Review Plan (SRP) approach and then scaled to probabilistically derived values contained in DOE-STD-1024 (2×10^{-4} annual probability of exceedance). The "distant" spectrum was also derived per NRC SRP guidance but remained unscaled. The primary issue this report addresses, is the adequacy of the distant event spectrum. Following Tank Seismic Expert Panel (TSEP) guidelines, the adequacy of the distant EBE spectrum is judged by comparison to site specific 84th percentile deterministic rock spectrum. Comparisons were also made to

SRS uniform hazard spectra, and some published eastern U.S. ground motion attenuation regressions.

Based on H-Area data, application of the EBE "distant" earthquake spectrum at H-Area provides motions that are more conservative than median. This judgment is based on assessments of deterministic "distant" event spectra using H-Area specific properties for the 50th and 84th percentile expected motions. These spectra indicate that the EBE "distant" spectrum is in excess of the 50th percentile and less than the 84th percentile of deterministic ground motions.

EPRI and LLNL rock and soil UHS were also reviewed for applicability to H-Area. It was determined that the applicability of the LLNL rock and soil UHS were limited until improvements are made in the LLNL seismicity model. The 84th deterministic rock spectra is "close" to the EPRI $1x10^{-4}$ rock UHS in the 1–2.5 Hz range (Figure 40). The EBE spectra together with the 84th percentile deterministic spectrum meet the acceptance criteria as defined by DOE-STD-1024 with the TSEP recommendations for the distant event spectrum. These criteria are considered temporary until specific guidance on the LLNL UHS are developed by the DOE.

Additional direction is required from facilities for the performance and hazard goals. The acceptance criteria of DOE-STD-1024 anchors the local median spectral shape to the pseudo-mean of the LLNL and EPRI hazard curves at the 2×10^{-4} annual probability of exceedance. This hazard level falls between that required for PC3 and PC4 facility levels described in DOE-STD-1020 (i.e., corresponding hazard levels of 5×10^{-4} & 1×10^{-4} respectively). This investigation uses a hazard annual probability of exceedance of 2×10^{-4}, corresponding to the highest hazard category of DOE-STD-1024. Until the performance/hazard guidelines are issued, engineering evaluation of foundations should use the scaled local and 84th percentile deterministic spectra in their evaluation. Evaluations of structures should use an envelope of the scaled local and 84th percentile deterministic spectra.

Introduction

The H-Area engineering analysis requires design basis motion be specified for determination of the liquefaction potential of foundation soils and structural integrity. In order to proceed with the engineering evaluation at H-Area, a decision was made to conduct the analysis using the local and distant spectra developed for the RTF. The RTF spectra (Stephenson et al. 1993) was derived from DOE-STD-1024 and work conducted by Geomatrix for K-Reactor (Geomatrix 1991). Until site specific spectra are developed, the RTF spectra will be used and called the evaluation basis earthquake (EBE) spectra. In a parallel investigation with the engineering and geotechnical analysis of H-Area, WSRC reviewed the H-Area site-specific data and developed 50th and 84th percentile spectra for comparison to the distant EBE spectrum.

At the ITP facility, EBE local and distant spectra were utilized to evaluate the foundation for settlement response as opposed to the Blume envelope spectrum used for the structural analysis of the tanks. The use of the EBE spectra is more appropriate in the non-linear evaluation of the foundation condition. The structural analysis was based on the need to have a broad-banded spectrum to cover the uncertainties in the structural response and to assure that the structural response is maximum, the envelope spectrum is used.

DOE Order 1024 provided the basic guidance for this investigation. Recommendations from the Tank Seismic Expert Panel (TSEP) were also incorporated into the approach. TSEP requested: (1) a brief description of the technical basis and rational for the EBE spectra and its application to H-Area; and (2) an 84th percentile distant event spectrum for H-Area to use for foundation analysis in lieu of the distant EBE spectrum.

The sections below summarize background material to the development of deterministic and probabilistic hazard assessments for the SRS. Following that, parametric studies describing some ground motion prediction uncertainties, response spectra comparison for K-Reactor, RTF, and H-Area are shown, and development of site-specific median and 84th percentile spectra for H-Area are described.

Scope

The scope of the seismology effort for the H-Area/Tank Farm area is:

- Review background material relative to past deterministic and probabilistic hazard studies conducted for the SRS (see sections Deterministic estimates of Ground Motion; Probabilistic Hazard Assessments; and Disaggregated Spectra Applied to Replacement Tritium Facility (1993)).
- Review and follow DOE guidance on seismic design basis earthquakes contained in DOE STD-1024 (see section Seismic Design Criteria).

- Conduct parametric studies for ground motion prediction using available H-Area soil properties (see section on Evaluation Basis Earthquake Spectra of H-Area).
- Review the basis for use of the EBE for the H-Area facility (see section on Evaluation Basis Earthquake Spectra of H-Area).
- Develop site-specific 50th and 84th percentile spectra for H-Area using the best available soil properties (see section on H-Area Site-Specific Deterministic Ground Motion Studies).
- Estimate probability of exceedance of the spectra (see section Electric Power Research Institute and Lawrence Livermore National Laboratory Hazard Spectra).

Summary of Criteria

Design basis criteria for H-Area are DOE STD-1020 and STD-1024. DOE STD-1020 develops the facility specific hazard categories and specifies that a median spectral shape be anchored to the assigned PGA. Specific direction for eastern U. S. (EUS) DOE facilities that have Electric Power Research Institute (EPRI) and Lawrence Livermore National Laboratory (LLNL) hazard curves are contained in STD-1024. That standard provides criteria that constrain the "local" event spectrum to 0.19g for SRS. This is based on the geometric mean of EPRI and old LLNL median hazard soil curves scaled to a pseudo mean. The local spectrum is median scaled to the STD-1024 design PGA at $2x10^{-4}$ (the distant event spectrum was determined to be adequately conservative and was applied unscaled, Stephenson et al., 1993).

Criteria for scaling lower frequency components of the design basis spectra to probability derived values are contained in DOE-STD-1024-92 (Appendix B). STD-1024 recommends a procedure to scale deterministically derived median spectrum to the maximum spectral velocity having the appropriate annual probability of exceedance. However, STD-1024 does not give correction factors for the averaged EPRI and LLNL spectral velocities, nor does it account for the large differences in the two hazard studies.

As discussed below, the RTF spectra were applied to H-Area (called the EBE spectra). As an alternative to developing a scaling factor for the maximum spectral velocity, adequacy of the distant EBE is assessed on the basis of comparison to H-Area specific median and 84th percentile deterministic ground motions (following TSEP recommendations).

Deterministic Estimates of Ground Motion

Estimates of ground motion for SRS critical facilities have generally adopted USNRC (NRC) regulatory guidance provided in 10CFR100, Appendix A. This guidance has been applied at K-Reactor. The RTF facility evaluation employed the results of the K-Reactor investigation together with the probabilistic guidance contained in DOE-STD-1024.

Because potential causative fault structures within the Coastal Plain, Piedmont, and Blue Ridge provinces are not delineated by low-level seismicity or geomorphic features, regulatory guidance prescribes the use of an assumed local earthquake. The magnitude/intensity is conservatively controlled by assuming a repeat of the largest historic event in a given tectonic province to occur closest to the site. Application of this guidance has resulted in two controlling earthquakes for the seismic hazard at SRS. One earthquake is a local event comparable in magnitude and intensity to the Union County earthquake of 1913 but occurring within a distance of about 25 km of the site. The other controlling earthquake represents a potential repeat of the 1886 Charleston earthquake having a similar magnitude and location. Selection of these controlling earthquakes for design basis spectra has not changed significantly in over twenty years. However, the assumed maximum earthquake moment and magnitude estimates have increased in the most recent assessment of the 1886 Charleston earthquake (Geomatrix 1991). Also, the assumed distance to a repeat of the 1886 Charleston-type earthquake has decreased.

Until the late 1980's, investigations performed for the NRC focused on the uniqueness of the location of the Charleston earthquake. Due to a lack of knowledge of a positive causative structure at Charleston, at issue was the possibility of a rupture on any one of the numerous northeast-trending basement faults throughout the eastern seaboard. Further, there were no obvious geomorphic expression that might suggest large repeated faulting.

Prior to recent detailed paleo-liquefaction investigations conducted along the southeastern coast, evidence to define the Charleston seismic zone (CSZ) have depended on the following:

- The detailed analyses of isoseismals following the 1886 Charleston earthquake (Dutton 1887, 1890).
- Instrumental locations and focal mechanisms of seismicity defining the 50 km long Woodstock fault lineament which closely parallels the north-northeast trending Dutton isoseismals.

- The remote sensed 2.5 m high, 25 km long lineament that also parallels the Woodstock fault (Talwani 1982, 1986).

Recent paleo-liquefaction investigations along the Georgia, North and South Carolina coasts (Obermeir et al. 1990; Amick et al. 1990) have identified and dated multiple episodes of paleo-liquefaction that have constrained the latitude of the episodes. Crater frequency and width, are maximized in the Charleston area and decrease in frequency and width with distance along the coast, away from Charleston. This evidence led the NRC in 1992 to its position that a repeat of the Charleston earthquake was constrained to the Charleston, Middleton Place region. NRC guidance for the nearby commercial nuclear power plant (Plant Vogtle) has, therefore, been based on an assumed recurrence of the 1886 Charleston earthquake in the Summerville-Charleston area (Geomatrix 1991).

Sporadic and apparently random low level seismicity is prevalent in the Coastal Plain and Piedmont geologic provinces (excepting clusters of seismicity in Bowman and Middleton Place). Regulatory guidance has prescribed a design basis local event to occur at a random location within a specified radius of the site. Recent geologic investigations, to determine and limit the age of deformation of known basement faults at SRS (Stieve and others 1994), indicate ages no more recent than Eocene. Consequently, deterministic analyses assumed source properties for a random local event, with on-site faults considered not capable.

The following sections contain brief summaries of the important deterministic and probabilistic seismic hazard investigations that have been conducted at SRS.

Housner, 1968

The earliest spectra used at SRS was developed by Housner (1968) who used a 5% damped response from the 1952 Taft earthquake (Stephenson 1990). For a repeat of the Charleston earthquake, Housner predicted 0.1g at SRS and recommended 0.2g for the Design Basis Earthquake. This spectra was used in an early evaluation of the seismic adequacy of production reactors at the site.

Blume, 1982

Recommended site acceleration and spectra in the Blume analysis were based on conservative assumptions for the occurrence of specific earthquakes. The anticipated ground motions from those events were developed from recorded earthquakes and synthetic seismograms for those postulated events. A probabilistic hazard evaluation was also done.

Two hypothetical earthquakes consistent in size with earthquakes that have occurred in similar geologic environments were found to control SRS spectra and peak ground motion: (1) hypothesized site intensity VII (Modified Mercalli Intensity (MMI)) local earthquake of epicentral intensity VII causing an estimated site PGA of 0.10g; and (2) a hypothetical intensity X (1886 Charleston-type), occurring at a distance of 145 km causing an estimated site PGA of <0.1g. For added conservatism, the site PGA was increased to 0.2g that corresponded to a site intensity of VIII (Figure 1). The probabilistic hazard assessment indicated that the mean annual rate of exceedance of $2x10^{-4}$, corresponding to 0.2g, was comparable to those probabilistic hazard studies developed for nearby nuclear power plants. The spectra also compared well to LLNL report UCRL 53552.

Table 1 describes the seismic source parameters developed to describe potentially controlling SRS earthquakes (URS/Blume 1982).

Table 1. Blume-derived Earthquake Source Parameters

Event	Mag (m_b)	r (km)	M (dyne-cm)	h (km)	rise-time (sec)
Charleston	6.6	145	$3x10^{26}$	10	3.0
Bowman (hypothetical)	6.6	95	$3x10^{26}$	10	3.0
Local	5.0	10	$1x10^{23}$	5	1.0

In the Blume study, the following three seismogenic source regions were considered for ground motion assessment:

- Appalachian mountain including the Piedmont and Blue Ridge geologic provinces assessed at a maximum intensity VIII
- Atlantic Coastal Plain at VII
- The Charleston seismic zone (CSZ) with intensity X. A hypothetical Charleston event was assumed to occur at Bowman for the purposes of estimating the distance dependence on ground motion.

The length of the 1886 Charleston seismogenic zone was estimated to be 50 km based on the elongation of the highest intensity Dutton isoseismal and on the similar length and location of the Woodstock fault (Talwani

1982) as determined by instrumental location and mechanisms of earthquakes. A displacement of 200 cm was estimated for the Charleston source based on the source dimension and the seismic moment. The source mechanism was argued to be similar to the mechanisms recorded along the Woodstock fault: steeply dipping right lateral strike-slip fault oriented N10°E

The estimated PGAs for postulated maximum events were based on the following:

- a local earthquake of MMI VII as a maximum credible earthquake (MCE) for the Atlantic Coastal Plain
- a Fall line event, MMI VIII with distance > 45 km, is a MCE for the Piedmont
- a Middleton Place event of MMI X, a repeat of the Charleston 1886
- a Bowman, MMI X, a postulated and considered extremely unlikely occurrence of a 1886 type-event at closest credible distance of 95 km

These parameters are summarized in Table 2.

Table 2. Blume (1982) Estimated Site Motions for Postulated Maximum Events

Location	Intensity (epicentral)	R (km)	Intensity (site)	PGA (%g)
Local	VII	0-10	VII	0.10
Fall Line	VIII	45	VI	0.06
Bowman	X	95	VII	0.10
Middleton	X	145	VI-VII	0.075

Blume applied a confidence margin of one intensity unit to the estimates above, resulting in a site intensity of VIII with a corresponding doubling of the estimated PGA (to 0.2g). Using the probabilistic hazard analysis (PHA), they note that a doubling of the PGA results in an approximate order of magnitude smaller probability of exceedance.

Synthetic seismograms were a third means used by Blume to estimate ground motion (in addition to observed intensity and attenuation functions). Generalized ray-theory using point source models were used to generate ground motion values that appeared to be higher than the other prediction schemes while underestimating duration. With the tabulated source values, a PGA of 0.08g for the Charleston earthquake, and about 0.1-0.26g for the local event were estimated depending upon source distance. Because ground motion model PGA scales with the inverse-cube of source rise-times (RT), and because there was easily a factor of 2 or 3 for acceptable values of RT, PGA was not acceptably constrained.

Strong motion duration was only briefly addressed in the Blume report, and that was based on the synthetic seismogram analysis. Strong motion duration was estimated to be 1–1.5 seconds for the local, and 3–7 seconds for the Charleston-type earthquake. Those calculations assume all energy arrives solely by minimum path and that velocity structures are half space (four layer for distant event), i.e., the estimated durations are a minimum value. Therefore, the durations should not be used because they do not contain mantle post-critical reflections and crustal scattering so apparent in local and regional seismic recordings.

Local and distant earthquake response spectral shapes were derived from statistical analysis of primarily western U.S. (WUS) data. The recommended response spectra was computed from the envelope of the mean spectral shapes. Table 3 summarizes the data used by Blume to compute the spectra for the local and distant earthquakes.

Table 3. Blume (1982) Empirical Data Parameters

EVENT	Eqkes (n)	Components (n)	Mag. (ML)	R (km)
Local	7	16	4.5-5.5	5 - 12
Distant	5	18	6.5-7.2	90-126

All records were recorded on deep soil (> 60m) in California; the local event was derived from moderate sized earthquakes in central and northern California; the Charleston-type distant event was based on records from the Kern County and San Fernando California earthquakes. Because the local and distant event spectral shapes are similar in character, the report states that "for most applications, the two sets of spectra are sufficiently similar in the band of engineering interest that separate structural analyses for the two events would not be warranted."

This conclusion, of course, is not considered appropriate to those responses controlled by nonlinear behavior (e.g., liquefaction).

Geomatrix, 1991

In a manner similar to Blume, Geomatrix (1991) performed a deterministic analysis following NRC SRP 2.5.2 for K-Reactor. The resulting spectra to be used were for a Charleston source (distant source) and a local source. The Charleston source of moment magnitude (Mw) 7.5 uses a Random Vibration Theory (RVT) model and site-specific data. The local source of Mw 5 uses WUS deep soil strong motion data corrected for EUS soil and rock conditions. The 5% damped spectra for the two hypothetical earthquakes are illustrated in Figure 2. Other derived source parameters for the Geomatrix ground motion calculations are listed in Table 4.

Table 4. Geomatrix (1991) Derived Source Parameters (RL is rupture length, RW is rupture width, and DU is displacement.)

Event	Mag (M_w)	r (km)	M (dyne-cm)	h (km)	RL (km)	RW (km)	DU (cm)
Charleston	7.5	120	2.75×10^{27}	15	110	20	400
Bowman (hypothetical)	6.0	80		15			
Local	5.0	<25					

The primary uncertainty related to the moment estimate was the interpretation of intensity (Bollinger 1977), derived from Dutton's damage patterns. The fault rupture width was estimated to be 20 km based on a range of deepest Coastal Plain hypocenters (Geomatrix 1991). The rupture length was determined from regressions of world-wide M_o vs. rupture area. The derived rupture length is more than twice the length from other data compiled for the Woodstock fault. From the rupture dimensions and moment, Geomatrix estimated a stress-drop of 65 bars and an average displacement of 400 cm.

The Bowman seismicity zone, located in the Coastal Plain Province, consists of M3.5-4.0 events occurring along a NW trend from Charleston. Because of the timing and mechanisms of events, they are not believed to be associated with the CSZ. The largest historical earthquake in the Piedmont Province was the 1913 Union Co.

earthquake having an epicentral intensity of VI-VII. Based on Johnston (1990) isoseismal areas, that earthquake was estimated to be Mw 4.5. The largest Appalachian Province earthquake was the 1875 Central Virginia event of MMI VII and Mw = 4.8. These earthquakes suggest Mw_{max} of 5.0 for Bowman, but because it was part of a diffuse northwest trend, Geomatrix used 6.0 for conservatism.

For the local earthquake, the occurrence of a random earthquake within 25 km of K-Reactor was assumed. With the largest site vicinity events limited to magnitude range 2–3, regulatory guidance suggests using largest historical events in the Piedmont Province:

$$M_{wmax} = 5.0$$

Numerical Ground Motion Modeling Scheme

Geomatrix used the Band Limited White Noise/Random Vibration Theory (BLWN/RVT) model (Hanks and McGuire 1981) to estimate ground motion for the distant Charleston-type event. This approach also allowed Geomatrix to correct WUS strong motion data to the EUS. This model is widely accepted and with proper parameterization, is found to predict ground motion as successfully as empirically derived relationships. Because of the models simplicity, computational speed, ability to parameterize source, geometrical spreading, crustal attenuation, and site response (including kappa) make it ideal to quantify ground motion. The RVT methodology appears to be well suited in geologic environments where empirical strong motion data may not exist in the earthquake magnitude and distance ranges of interest. Nonlinear wave propagation within the soil column is accounted for by using a one dimensional equivalent linear approach (Silva 1989).

Soil Conditions Used At K-Reactor

The K-Reactor site soil shear-wave velocity (Vs.) conditions and assumptions used in the Geomatrix analysis are described as follows:

o h < 200' GEI Vs 1991 recommended profile from in-situ SCPT measurements

o 200' < h < 900' use trend in Vp/Vs. ratio, and velocity logger p-wave profile

o 900' < h < 10,000' Vs. = 8,000 fps using measured Vp in Triassic and assuming a Poisson solid (Poisson's ratio of 0.25)

- h > 10,000' Vs. = 11,000 fps using measured Vp in crystalline and assuming Poisson model

The K-Reactor strain-compatible modulus reduction and damping curves were used (GEI, 1991).

Charleston Source Constraints

Somerville et al. (1987) showed that the median stress drop for the EUS was about 100 bars and, therefore, similar to the WUS. Because of the large variability in stress-drop (as great as 300%), the selected "median" value recommended by Geomatrix was 150 bars with a test at 300 bars to judge sensitivity.

At about the time of the Geomatrix investigation, there were other programs related to the development of site-specific spectra for a New Production Reactor (NPR) at SRS. A workshop was convened in 1992 on the size of the Charleston earthquake (Ebasco 1992). In the workshop, magnitude estimates were made based on the following:

- 1886 earthquake intensity data
- Liquefaction and related data for evidence of magnitude six and greater earthquakes recurring in the Charleston vicinity every 500–600 years
- Historical and instrumental seismicity
- North American correlations between earthquake moment and MMI area for selected intensities (Hanks and Johnston 1992).

Using the isoseismal data and peak ground motion predictions, a suite of magnitude and stress-drop trade-offs was established that satisfied the isoseismal data:

- Mw 6.5 and 500 bars
- Mw 7.0 and 300 bars
- Mw 7.5 and 100 bars

A preferred value of Mw 7.5 and stress-drop of 100 bars was selected because the group felt that those estimated ground motions were most consistent with the available liquefaction data (the NPR and K-Reactor ground motion studies by Geomatrix used a "conservative median value" of 150 bars).

For geometrical attenuation, a plane layered crustal model approximation by Ou and Herrmann (1990) was used that accounts for the post critical reflection. The crustal model is based on a surface wave study conducted between Bowman and Atlanta (Herrmann 1986). The effect of the approximation is to decrease the attenuating loss between about 80–120 km. Using a point source and the local crustal structure for the Charleston event, the attenuation model predictions were found to be sensitive to source depth and distance source depth and distance. The modeled Charleston point source had a local peak in the predicted PGA at a distance of 110 km (Figure 18). For added conservatism, Geomatrix scaled the predicted 120 km distant spectrum to the peak PGA at 110 km.

Geomatrix developed 5% damped response of the horizontal component from a Mw 7.5, 150 bar Charleston-type earthquake using the parameters described above (Figure 2). The vertical component of motion was estimated to be half the horizontal. The standard error for the predicted spectral values were judged to be about the same as that measured in empirical ground motion data. That is about 0.5 in natural log of ground motion. The "spectra ... represent median or average levels of ground motion" (Geomatrix 1991). As will be shown below in the section on conservatisms, the Geomatrix source assumptions (primarily the assumed Mw, stress drop, and distance) are more than median predicted motions for a repeat of the 1886 Charleston earthquake.

Geomatrix, like Blume, considered an earthquake at 80 km with a stress-drop of 100 bars to correspond to a hypothetical Bowman source. That source gave considerably lower motions than the Charleston event and was not considered further in the design basis recommendation.

Local Event Statistics

Statistics for the Geomatrix local earthquake were selected following Kimball (1983) using earthquakes of Mw =5.0 +- 0.5 within 25 km. Events used in the analysis are summarized in Table 5.

Table 5. Western U.S. Earthquakes Used by Geomatrix (1991)

Event	Eqkes. (n)	Components (n)	Mag. (ML)	R (km)	Mech*
Port Hueneme (1957)	1	3	4.7	3	SS
Imperial Valley (1979)	1	36	5.2	8-18	SS
Coalinga (1983)	6	27	4.9-5.3	8-15	Rev & Thrust

* where SS denotes a strike-slip mechanism

A weighting scheme was applied to account for bias in the non-uniformity of areal distribution and to account for the bias of the Imperial Valley earthquake. A correction was also applied to account for the fact that only certain records have been processed to response spectra. To correct for differences between EUS and WUS soil and rock, the RVT model was used to derive a transfer function between the average soil and rock properties at the western sites and assumed the K-Reactor profile. In both cases, an Mw 5.0 is assumed to occur 15 km from the site, and source characteristics are assumed to be identical for both the EUS and WUS (stress drop, source scaling). Table 6 (Geomatrix 1991) summarizes these parameters.

Table 6. Comparison of Eastern and Western U.S. Earthquake Source, Path, and Site Parameters

	WUS	EUS
Stress-Drop	50-100 bars	50-100 bars
Vs	3.2 km/sec	3.5 km/sec
density	2.7 gm/cc	2.5 gm/cc
Kappa	0.03-0.04 sec	0.006 sec
Q	$150f^{0.6}$	$500f^{0.65}$
M_o	1.5M + 16.1	1.5M + 16.1
M_W	5.0	5.0

Spectral ratios for this comparison are reproduced in Figure 3. The same correction was applied to vertical motions. Figure 2 shows the corrected 5% damped horizontal motions for the local event. As seen in Figure 3, the EUS (local) predictions exceed the WUS (Blume 1982) results above 5 Hz.

Probabilistic Hazard Assessments

Considerations for uniqueness of the Charleston seismic zone has resulted in evolution of the southeastern U.S. seismic hazard for the past 25 years. Following a ten year investigation by the USGS to determine (unsuccessfully) the causative structures of the 1886 Charleston earthquake (Gohn 1983) emphasis was placed on updating the characterization of the seismic hazard for the Eastern United States. Further investigations were funded by the NRC and EPRI for EUS nuclear power plants. The NRC funded investigations of 69 nuclear power plants by a national laboratory (LLNL 1989), while EPRI evaluated 49 nuclear power plants using private contractors (EPRI 1989). Summaries and comparisons of the approaches and methodologies are described by Savy (1993), DOE-STD-1024, and in work conducted by Risk Engineering (1990) and Jack Benjamin and Assocs. (Wingo 1992).

Blume, 1982

Probabilistic hazard was calculated for the SRS for the purposes of estimating probabilities of exceeding PGA of 0.10g and 0.20g, the deterministically derived values of PGA. The calculation also provided relative likelihoods for the design motion earthquake source contributions.

The following three source regions were used:

- Atlantic Coastal Plain Province
- Appalachian Mountain Province
- Two hypothetical configurations for the Charleston seismic zone.

The Charleston zones were: (1) a 3,000 km^2 zone centered about Middleton Place to represent recurrence of the 1886 Charleston earthquake; and (2) an 8,500 km^2 zone that extends from offshore through Bowman to the Orangeburg scarp to assess the sensitivity of a floating Charleston-type event. The activity rate prescribed for the Charleston zone was based on the 1754-1975 earthquake catalog after removing the 1886 main shock and 10 years of aftershocks. The 1886 main shock and aftershocks were considered unrepresentative of two-to-three centuries of Charleston seismicity. A b-slope of 0.54 was used for the three sub-regions. The adopted recurrence relation yields 11 events of MMI V or more per century, and 0.024 events of MMI X per century. The intensity X event occurs about every 4000 years.

The Coastal Plain and Appalachian Mountain province rates were constrained by counting MMI VII events, presumed complete in catalogs for the last two centuries. The Appalachian Mountain province contained ten events in the last century and the Coastal Plain yields about three per century. Maximum epicentral intensity was VII, VIII, and X respectively. Intensity attenuation with distance together with correlations between PGA and intensity were used with the recurrence rates to compute probabilities of exceedance.

When the exceedance rates for the two Charleston source configurations are compared, the difference in rates for the two sources is negligible (Figure 4). This is probably a result of keeping the overall rate in the two zones constant. Exceedance rates contained in the report shows that at 0.10g (MMI VII) the exceedance rates are within about 20% for the three zones. At 0.20g the Charleston and Coastal Plain zones are about the same and more than 100% greater than the Appalachian Mountain zone.

Lawrence Livermore National Laboratory (1988, 1993)

Three hazard investigations have been conducted relative to the SRS by LLNL over the past 10 years. All of the studies conducted by LLNL (and EPRI) reflect enhancements to the methodology from the earlier Cornell (1968) type approaches in several ways. The hazard curve itself becomes a statistical distribution by

- o treating alternative source zone configurations and activity rates as a probability model
- o selecting alternate attenuation functions with specified uncertainty
- o selecting a variety of different experts to insure completeness in the population of models

In the LLNL investigations, a Monte Carlo type approach was used to explore the possible combinations of derived hazard curves, while EPRI uses logic trees to quantify the uncertainty.

The LLNL EUS PHA took the standard approach of identifying the spatial and temporal earthquake process as a Poisson process. The distribution of earthquake magnitudes was modeled as a truncated exponential distribution. Standard attenuation functions for PGA (or other frequency dependent peak motion parameter) were used as a function of earthquake magnitude and distance. That process was extended to include uncertainty in characterizing source zones and the variability of diverse expert opinion (Savy 1993). The purpose of the investigation was to estimate seismic hazard at commercial nuclear power plants located east of the Rocky Mountains. Separate seismicity and ground motion attenuation teams were formed and then solicited independently for input to the study (Bernreuter et. al. 1989, Savy 1988). For application to SRS, the compiled database contained no site-specific data but was complete in a regional context in terms of seismicity and attenuation models. In this context a calculation was conducted for SRS. The hazard curves contain no site-specific data and site conditions were treated generically (deep or shallow soil, and rock). LLNL (1993) reported hazard curves for SRS at a deep soil site location central to the plant site that included magnitudes 4.0 and greater (Figure 5).

Concerns about the accuracy of quantifying the seismic hazard uncertainty led to additional investigations by LLNL. A 1993 review of work done previously indicated the following areas of improvement in the elicitation process for application to SRS (Savy 1993):

- A revised seismicity model elicitation that would request specific magnitude events rather than "a" and "b" values.

- A new ground motion expert elicitation was suggested to improve the ground motion standard deviation and ground motion prediction methodology.

- An improved documentation of the elicitation process.

Results from the latest ground motion portion of the elicitation are illustrated in Figure 6 (Savy 1994), however, the revised seismicity portion of the elicitation remains to be completed. The updated LLNL analysis used a site specific soil model. The SRS soil model was derived from data collected at the SRS NPR site prior to Jan. 1992 (Savy 1993). The data consisted of in-situ shear-wave velocity data to depths of approximately 270 ft, K-Area dynamic properties, and velocity extrapolation to basement depths. Based on our review, the updated LLNL work still has issues associated with uncertainty of the local earthquake source.

Electric Power Research Institute (1986)

EPRI (1986) conducted a parallel investigation to the NRC funded study for the EUS. Methodologies were similar between the two studies and were both tested with identical input data to show consistency. Instead of elicitation's from individual experts as used in the LLNL study, six individual teams were employed from several consulting companies to provide input. To develop results specifically for SRS, Jack Benjamin and Associates (JBA) conducted a PHA for SRS using EPRI methodology and seismic and ground motion inputs (McCann 1989). Figures 7 and 8 show the SRS results for rock and soil conditions. The EPRI soil model for SRS was a generic soil model that did not use site-specific data (E. Wingo, personal communication). Even comparing the most robust estimator, the median, significant differences are seen between the EPRI and LLNL investigations by comparing Figures 6 and 7.

Discussion and documentation of differences between the EPRI and LLNL results are summarized in detail in DOE-STD-1024-92, Wingo (1992), and Risk Engineering (1990). Expert opinion diverged between the two studies in the following areas:

- seismic zonation
- ground motion attenuation
- uncertainties associated with activity rates
- selection of maximum magnitude of host zone

Disaggregated Spectra Applied to Replacement Tritium Facility (1993)

For liquefaction studies at RTF, a design basis envelope spectra such as that recommended in the Blume report was not recommended because the spectra were not representative of a specific earthquake (Stephenson et al. 1993). As pointed out by the National Research Council's 1988 report, the results of PHAs and deterministic methods may be different because of low recurrence rates. For this reason, the Council recommended that the results of a PHA be disaggregated or decomposed to determine which seismic sources dominate the hazard at a site. This was done for SRS by JBA and LLNL to identify the sources controlling the hazard at the site. The following steps were used for decomposing the probabilistic seismic hazard at SRS (Stephenson et al. 1993):

1. Using either the LLNL or EPRI probabilistic hazard result, select ground motion parameters of interest (e.g., PGA, 5Hz spectral velocity (SV), 1Hz SV, etc.).

2. Select a probability of exceedance (e.g., 10^{-4}/yr.).

3. Compute probability, retaining results at discrete magnitude and distance interval.

4. Determine the mean magnitude and distance that controls the ground motion at the selected probability of interest.

Two analyses were developed using the LLNL and EPRI matrix of results showing the hazard contribution percentages. Figure 9 shows contribution to hazard (for PGA) by magnitude and distance for SRS. The results show that the seismic hazard can be characterized by local events with R<30 km, controlling PGA. Larger events, at some distance from the site, controlled peak ground velocity (PGV) at SRS (Stephenson et al. 1993). These results compared favorably with the deterministic analyses performed for the site by Blume and Geomatrix.

The controlling earthquakes used in the liquefaction study at RTF (Stephenson et al. 1993) were selected to be consistent with the DOE probabilistic acceptance criteria (DOE-STD-1024). A spectral shape was taken from the local event spectra developed for K-Reactor (Geomatrix 1991). The distant event spectra was recommended unscaled. The results were then compared to the past deterministic study of Blume and the disaggregated LLNL and EPRI hazard analyses. Induced stresses were calculated for the liquefaction analysis based on the two controlling earthquakes. Separate analysis is warranted based on the difference in shape of the two spectra.

Seismic Design Criteria

This section contains a brief description of DOE orders as they relate to seismic hazard issues for nonreactor facilities at SRS. Descriptions are limited to criteria related to topics affecting input motions for design (e.g., hazard exceedance probabilities, DBE, response spectra) and do not include topics such as seismic structural analysis, load factors, and capacities.

Seismic design criteria for nonreactor DOE facilities are contained in DOE Order 5480.28 and 6430.1A, DOE-STD-1020 and 1024. Additionally, criteria can be found in the DOE STD-1022 and the Seismic Hazard Systematic Evaluation Program (SEP). Order 6430.1A identifies site characterization studies to be conducted that could influence the design or operation of facilities that may be subject to ground failure, surface faulting, liquefaction, vibratory ground motion, and site amplification.

DOE Order 5480.28 provides a consistent approach to natural hazards mitigation, that includes seismic hazards. Performance goals are defined:

		Performance Category	Hazard Goal	Performance Goal
o	PC1	1	2×10^{-3}	1×10^{-3}
o	PC2	2	1×10^{-3}	5×10^{-4}
o	PC3	3	5×10^{-4}	1×10^{-4}
o	PC4	4	1×10^{-4}	1×10^{-5}

DOE-STD-1020 defines the seismic hazard goals. PGAs are prescribed from site-specific seismic hazard exceedance rates that are developed for each facility type based on the determined performance category.

DOE STD-1020 and DOE-STD-1024 requires the use of median input response spectra determined from site-specific geotechnical studies, and anchored to PGAs determined for the appropriate facility-use annual rate of exceedance. Guidance regarding the specific characterization of seismic hazard is found in the SEP guidance and DOE-STD-1022.

A mandatory list of important geologic factors will include

- o determining existence of Quaternary faults within 25 miles radius of the site

- o determining whether any magnitude six earthquake is associated with an active Quaternary fault within a 200 mile radius of the site

- o identifying all faults with length greater than 1000' within 5 miles of the site and determine whether there is evidence of any Quaternary movement on the fault

- o determining potential for site-specific amplification of vibratory ground motion

Both deterministic and probabilistic methodologies for hazard evaluation need to be used. The guidelines for probabilistic hazard analyses are: sites can use a combined EPRI and LLNL result if applicable, or complete a new estimate using site-specific data; definition of source zones, earthquake recurrence rates, ground motion attenuation, and computational methodologies are spelled out in the SEP.

Specific guidelines are provided for deterministic assessments including estimates of median, mean, and mean plus one-standard deviation level. Median estimates should not fall above selected probabilistic motions; Faults with slip rates lower than about 0.1 mm/yr. should have a maximum credible earthquake consistent with the low slip rate. Geotechnical studies should be used to assess influence of local site conditions on ground motions.

DOE-STD-1024-92

DOE-STD-1024-92 was developed for EUS DOE sites, supplementing UCRL-15910. STD 1024 addresses variability in the probabilistic hazard investigations conducted by EPRI and LLNL for SRS and eastern nuclear power plants.

In particular, DOE-STD-1024 describes how to combine the LLNL and EPRI hazard results. STD-1024 gives specific PGA values at assigned probability of exceedances (POEs) for SRS. The guidance uses hazard curves developed from the LLNL and EPRI methodologies and applied to the central SRS. The geometric means of the median hazard curves are computed at three hazard category levels, and a factor is applied that accounts for hazard uncertainty.

DOE-STD-1020-94

The DOE-STD-1020 is an extension of UCRL-15910 that accounts for the DOE site to site variability in the slope of the hazard curve that could tend to under- or overestimate the seismic performance goals for Performance Category 3 and 4 (PC3 or PC4) facilities. To correct for the hazard slope, 1020 recommends that a DBE factor (0.45) be applied to the ground motion at 1×10^{-5} (for PC4 facilities), and a factor (0.50) be applied to the ground motion at 1×10^{-4} (for PC3 facilities). The DBE motion for a PC3 or PC4 facility is then the larger of the factored value or the assigned PGA at the hazard exceedance probability assigned by performance category.

DOE-STD-1020 differs from DOE-STD-1024 in the definition of the annual rate of exceedance of the high hazard levels. STD-1024 uses 2×10^{-4} vs. the 1 or 5×10^{-4} annual probability of exceedance specified in STD-1020.

Evaluation Basis Earthquake Spectra for H-Area (1994)

To support initial engineering evaluations for H-Area the EBE spectra were used until site-specific spectra could be developed to judge adequacy. The EBE spectra, which accounts for local and distant earthquakes, are consistent with DOE criteria, and will be used in the interim for engineering and geotechnical evaluation. The H-Area EBE spectra position consists of the following: (1) Geomatrix (1991) median local spectral shape scaled to 0.19g per DOE-STD-1024; and (2) Geomatrix (1991) median Charleston spectral shape (uses Mw 7.5, distance of 120 km, and stress drop of 150 bars) (Salomone 1994). The time histories for a Charleston-type event were 25 seconds in total duration with 15 seconds strong motion duration. The local time history was 10 seconds total duration with 6 seconds of strong motion.

Geotechnical Properties for Ground Motion Assessments

In this section, comparisons are made between some of the geotechnical properties at H-Area, and K-Reactor, the site where the original spectral estimate for the local and distant earthquakes were made. Sensitivity studies were completed to better understand the assumptions on source parameters and effects of path and soil. These comparisons, supplemented by parametric studies, form the basis for assessing the appropriateness of using the EBE at H-Area. More specifically, these comparisons establish whether the distant EBE spectrum, when applied at the H-Area, would constitute a median or 84th percentile motion.

Site Properties Summary for H-Area Tanks

H-Area/H-Tank Farm site geological and geotechnical properties are described in the ITP JCO support document (WSRC-TR-94-0369). The H-Area model shallow soil properties derived from the geotechnical program data include the geologic unit thickness, elevations, estimated values of Poisson's ratio, and mean and uncertainty (+- one standard deviation) (Figure 10). These unit thickness and velocities are used in the ground motion comparisons. The nearly uniform average shear velocity and variability from ground surface to elevation 120 ft (above the Congaree) are evident in the Vs(h) as measured by SCPT's in the H-Area Geotechnical Programs (Figure 11 and 12).

The H-Area modulus reduction parameters, as determined from laboratory testing of soil samples (WSRC-TR-94-0369) are shown in Figure 13 and material damping vs. strain curves are shown in Figure 14. For comparison, corresponding curves that were derived for K-

Reactor are included on the figures. The ITP curves are applicable to the depth range (< 200') over which soil samples were taken.

Comparison of H-Area and K-Reactor Soil Properties

Because the EBE spectra for H-Area was based on the soil profile for K-Reactor, we compare in this section the site properties and ground motion response for these facilities. Figure 15 compares shallow Vs. at the sites. All facility sites display differences in mean velocity, especially in the near surface. Although the mean Vs(h) appears to converge somewhat with depth, the variability below about 200' is not as well constrained and may have large uncertainties because most site measurements are limited to about that depth. At SRS, there are two, closely spaced, down-hole measurements of Vs. to basement, that were taken in the vicinity of the NPR (Agbabian 1992) using an Oyo shear-wave velocity logger. Figure 16 compares the complete H-Area soil column profiles; two hypothetical profiles previously assumed for K-Reactor (Geomatrix 1991), and the measured Confirmatory Drilling (CFD) profile of the Pen Branch fault Confirmatory program (Agbabian 1992). At depths exceeding about 500', the CFD velocity profile significantly exceeds the previously assumed deep soil velocity models (Figure 16). The increased deep soil velocity effect on site response will be to decrease the site fundamental period.

Earthquake Source Parameters

This section discusses the earthquake source parameter uncertainty affecting ground motion prediction for H-Area. Much of what is described here builds on other investigations conducted for SRS, especially the Geomatrix, 1991 report for K-Reactor. As described above, the local and distant earthquake spectra were developed by URS/Blume (1982) and refined later by Geomatrix (1991). "Local" earthquake hypocentral distances have been specified as a random occurrence within 25 km of the site in question (Kimball 1983). This accounts for the possible recurrence of the largest historic earthquake in the geologic province to occur in the site vicinity.

The "distant event" or Charleston-type earthquake was discussed in detail by Geomatrix (1991). Figure 17 shows the SRS site center to 1886 Charleston MMI X isoseismal contour is approximately 120 km. This 120 km distance was conservatively used by Geomatrix. The SRS center to the southern end of the Woodstock fault is approximately 130 km. The center of SRS to the center of the 1886 MMI X isoseismal, close to Middleton Place and central to Dutton's isoseismals, measures approximately 145 km. URS/Blume (1982) used 145 km distance for the

SRS center to the 1886 Charleston earthquake epicenter. Because the MMI X isoseismal subtends an angle that is almost perpendicular to a line connecting K and H-Areas, the difference in epicentral distance for each of these facilities to the assumed 1886 Charleston earthquake epicenter is insignificant. For H-Area ground motion analysis a reoccurrence of the 1886 event at a distance of 120 km, has been used. For estimates of median ground motions for a recurrence of the 1886 earthquake, a source distance of 120 km is conservative since the center of the isoseismal zone is approximately 145 km distant.

The Geomatrix (1991) RVT models of ground motion use a simplification of point seismic sources, and with the Ou and Herrman (1990) approximation, selection of the source depth makes the site response somewhat sensitive to the selected crustal structure. The Charleston source distance and point source focal depth effects on the RVT predicted rock PGA is shown in Figure 18. The source is a Mw 7.5 event with a stress-drop of 150 bars. Predicted peak ground motion is shown for a suite of point source local depths ranging from 10 to 20 km. These RVT calculations illustrate the important affect that structure has on the point source results, particularly the effects of the post-critical reflection (seen at approximately 110 km). The effects of focal depth alone, assuming the Herrmann (1986) crustal structure, results in variations of peak predicted motion of nearly 50% at the epicentral distances of interest for the Charleston event. For the application at K-Reactor the selection of the PGA value at 110 km (Geomatrix 1991) was conservative because a more appropriate finite source model would tend to average the effects of focal depth.

The distance and stress drop effects on rock motion predictions for a Charleston Mw 7.5 event with a point source depth of 15 km is shown in Figure 19. Shown are the 5% damped response spectra for rock outcrop motions for distances of 100-145 km and stress-drops of 100–150 bars. The 100–150 bar range in stress-drop is a probable range for the median value of an EUS earthquake. Sommerville et al., (1987) found a value of 100 bars as the median stress-drop for EUS earthquakes; the EPRI (1993) guidelines report estimated a value of 120 bars as a median for stress drop, from data with reported stress-drops in the range of 20–600 bars.

Prior ground motion studies for SRS have reported expected or median stress drops of 100 bars for a Charleston-type event (Geomatrix 1991) and subsequently used a "conservative" value of 150 bars. Geomatrix noted that a doubling of stress drop for the Charleston-type event resulted in an approximate 60% increase in peak ground motion. It is clear from the rock spectra (Figure 19) that selection of stress drop, source distance, and focal depth are critical to analysis of ground motion. For comparison at H-Area, a median value of 100 bars for stress drop is assumed in the ground motion calculations.

Ranges in moment and moment magnitude have also been described in the studies conducted for the NPR site at SRS (Geomatrix 1992, Appendix A). It was concluded that the 1886 isoseismal data is consistent with ground motion models with reduced earthquake moment magnitude from the Mw 7.5, but with a corresponding increase in stress-drop. The trade-off of best estimate values expressed in that report were as follows:.

- o Mw 6.5 and SD=500 bars
- o Mw 7.0 and SD=300 bars
- o Mw 7.5 and SD=100 bars

Based on constraints provided by the liquefaction data, the working group favored a Mw 7.5 and stress-drop of 100 bars. Figure 20 shows the predicted RVT rock spectra for the three cases assuming a half-space model and a distance of 145 km. The H-Area EBE is a Mw 7.5 at 120 km and stress-drop of 150 bars. The H-Area median spectrum (discussed below) uses a Mw 7.5 at 120 km and stress drop of 100 bars.

Bedrock and Crustal Path Properties

The RVT calculations conducted for H-Area have assumed one of the following three different geometrical attenuation schemes:

- o a simple uniform half-space approximation with 1/R decay
- o an approximation to model the lower decay rate of critically reflected waves as $1/R^{1/2}$
- o an approximation (Ou and Herrmann, 1990) to account for crustal model related direct, reflected, and some multiply reflected arrivals including the Moho bounce

Figure 21 shows median and 84th percentile RVT rock response spectra for Mw 7.5, R=120 km, 150 bar stress drop, and h=15 km, for the three attenuation models (84th percentile derived using EPRI (1993) scaling described below). The three spectra are very consistent, however, selection of other point source depths would result in differences for the Ou and Herrmann (1990) case (Figure 18).

Herrmann (1986) described the crustal model developed from surface wave dispersion from Bowman, SC, to Atlanta, GA. A modified version of this model is used in calculations for H-Area and was also used in the ground motion predictions for K-Reactor (Geomatrix 1991) (Table 7).

Table 7. Modified Herrmann (1986) Crustal Model

H (km)	Vs (km/sec)	density (gm/cc)
5.0	3.74	2.7
9.5	3.76	2.7
14.5	4.01	2.8
inf	4.56	3.3

For development of the rock spectra, anelastic attenuation is accounted for in two ways:(1) the crustal path operator Q that is frequency dependent; and (2) the site-dependent factor Kappa, related to Q by H/(Vs*Qs). where Qs is the average quality factor over a several kilometer range of the near surface rock. The preferred Q model for these investigations is Rhea (1984) (Figure 22) because this model was developed for the southeastern U.S. According to the figure, the Rhea (1984) model will tend to predict greater motions (higher Q, lower damping) at the high frequencies and lower motions (lower Q, greater damping) for lower frequencies as compared to EPRI (1993) "high", "median", and "low" preferred models (Figure 22). The Rhea (1984) model was derived from coda Q analysis of nine earthquakes of magnitudes 1.9–2.8 located and recorded in the South Carolina Coastal Plain. The similar Dwyer model was developed from data recorded in the central Mississippi Valley (Figure 22).

The best (least squares sense) Rhea (1984) model was given by

$$Qc = Qo*(f/f_o)^n$$

$$= 190*f^{0.94}$$

According to Rhea (1984), the 60% confidence interval for Qo ranged from 164-220 and n ranged from 0.79-1.12. The crustal Q operator clearly effects the rock spectra for the Charleston-type earthquake (Figure 23). Assuming a Mw 7.5, 150 bar stress drop, half-space structure, and point source depth of 15 km, the Rhea (1984) Q model shows a dramatic effect on response spectral accelerations (RSA) when compared to the EPRI median Q model. The Rhea (1984) Q model producing greater rock spectra for f> 10 Hz and about 50% lower motions for f<5 Hz.

The ranges of the rock site attenuation operator Kappa are estimated to be 0.01-0.004 sec. with a median of 0.006 sec. (EPRI 1993). RVT calculations for the K-Reactor ground motion predictions used a value of 0.006 sec for Kappa (Geomatrix 1991).

For SRS ground motion predictions, bedrock properties underlying most of the SRS facilities are assumed uniform with a Vs. of approximately 11,500 fps (3.4 km/sec). At H-Area and RTF, the soil column is located above this high-speed rock. K-Reactor is situated above a Triassic rift basin (Dunbarton basin) filled with 3 km of sedimentary rock having a Vs. estimated to be 8,000 fps (2.4 km/sec). This basin is surrounded by crystalline rock. For a first approximation to the ground motion effects of the basin, a one-dimensional plane-layer model is used to approximate the effect of contrasting velocities. Figure 24 shows free-surface (top of soil) RSA for K-Reactor with and without the contrasting velocities of the Triassic Basin. The source is defined as an Mw 7.5, 150 bar stress-drop earthquake at 120 km. Only modest (<10%) increases are observed for the response with the basin and at frequencies f<20 Hz. Figure 25 is similar to Figure 24 except H-Area shallow soil properties were used with the GEI deep soil column. Similar resonances are seen with the basin response exceeding the crystalline. These calculations suggest that spectra developed for K-Reactor, that include the influence of the Triassic basin, will lead to slightly greater ground motion predictions than other similar soil sites that are underlain by strictly crystalline rock.

Soil Properties

Soil properties that can effect ground motion prediction at SRS facilities can be categorized as follows:

o soil column thickness

o shallow dynamic properties including strain dependent soil modulus and damping

o shallow (<250') shear wave velocity structure

o deep (>250') shear wave velocity structure

Soil column thickness is constrained at facility locations by drilling into bedrock. In the vicinity of the H-Area Tank Farms, soil column thickness (h=997') is controlled by borehole HPC-1-1989, which is located approximately 200' from the Tank Farm. Because of the proximity of this hole to H-Area, uncertainty of H-Area soil column thickness is dependent only on the local relief on the basement surface; and any difference in soil thickness results in minor shifts in resonant peaks of predicted site response.

The range of shallow soil Seismic Cone Penetration Test (SCPT) Vs. speeds at H-Area are illustrated in Figures 11 and 12. The variability of individual measurements suggests a standard deviation of about 150–400 ft/sec. Mean Vs. soil profiles for H-Area, RTF, and K-Reactor are compared in Figure 26. Deep soil (>200') shear-wave speeds are constrained by the Pen Branch Fault confirmatory drilling (CFD) site. Figure 27 shows P- and S-wave velocities measured at the CFD site using a suspension logging device developed by the Oyo Corporation (Agbabian Assoc. 1992). Facility site shear-wave velocity variability is well constrained from the many SCPT measurements; however, the CFD velocity model was used for deeper soil velocities.

Dynamic soil properties at H-Area were measured by Law Engineering and are described in the JCO. Figure 13 shows resonant column measurements of soil damping dependence on strain for H-Area in comparison to similarly determined properties for K-Reactor as measured by GEI. Figure 14 similarly shows shear modulus dependence on strain for K-Reactor and H-Area. We note that the Law strain-dependent properties are not depth dependent and suggest greater stiffness compared to measured values for the K-Reactor site. Soil damping, having greater significance to soil response, is greater at H-Area relative to K Area.

Sensitivity of site response to dynamic soil properties for the Charleston-type earthquake are shown in Figure 28. The figure shows the effect of slightly (<15%) decreasing spectral amplitude associated with the H-Area model that incorporates the site-specific H-Area strain-dependent soil properties over the upper 171' (GEI properties for the balance of the soil section) vs the effect of incorporating the H-Area properties in the shallower Tobacco Road. Figures 29 and 30 show the effect of the assumption of deep soil velocity on site response. Clearly the entire soil column velocity profile has a first order effect on site response, with the CFD velocity profile associated with greater motions at the site fundamental period and at high frequency (>20 Hz). The degree to which soil response is non-linear with respect to the input rock spectrum is illustrated in Figure 31. Successive responses to doubling and tripling the rock outcrop motion are shown. Note that the soil response is linear at this range in amplitude for frequencies f<1 Hz.

Summary of Conservatisms in the Distant Event Evaluation Basis Earthquake Spectrum for H-Area

Source Properties

o conservative values of magnitude (Mw 7.5) and distance (120 km) were used

o conservative point source assumption using maximum rock PGA at r = 110 km

o conservative stress-drop of 150 bars (upper range of values considered median)

The magnitude and moment source parameters are above or in upper range of values considered median for the maximum credible event size; source distance is considerably closer than the 1886 epicenter.

Structure/Q

The Rhea (1984) Q model and Herrmann (1986) crustal structure are region specific and there are no apparent conservatisms in these values. For the purposes of this investigation, the Rhea (1984) Q model is considered a best estimate model. However, differences between the Rhea (1984) and EPRI (1993) median eastern U.S. Q model's suggest further investigation (see Issues section).

Kappa/Bedrock

The Kappa value (0.006 sec.) is median from ranges explored by EPRI (1993); no site-specific data are available to provide constraints. Bedrock Vp is constrained by basement refraction velocities; basement shear-wave speeds were assumed using a Poisson solid (Geomatrix 1991). Geometry of the Triassic basin is somewhat constrained by CONOCO data (Domoracki 1994). A one-dimensional model approximation of the ground motion effects of the basin suggest that its presence in the K-Reactor ground motion model does not significantly alter the conservatism of the spectra with respect to its application at RTF or H-Area.

Soil model

Comparison of ground motion models using measured shallow and hypothetical deep soil K-Reactor velocities to the H-Area soil velocities, indicates that the H-Area motions are greater than K-Reactor. Comparisons of dynamic properties indicate that K-Reactor is a much stiffer site with less damping than the H-Area site. Predicted motions for K-Reactor and H-Area, using site-specific properties at H-Area including the use of the faster deep soil profile (CFD), indicates higher motions at H-Area as compared to K-Reactor using the same input bedrock motion for both facilities.

In summary, the EBE distant earthquake spectrum used conservative source parameters (more conservative than median), a very conservative source distance and PGA scaling (maximum PGA at 110 km), region specific elastic and anelastic properties, median value of Kappa, and site-specific soil properties. The source parameters used to develop the distant event K-Reactor spectrum are more conservative than those of a median spectra, as is shown in the following section. Taking into account the differences in the shallow soil properties of H and K Area, and applying a faster deep soil profile, indicates that the distant event EBE spectrum provides slightly greater margin at H-Area than does a median site-specific H-Area spectrum.

H-Area Site-Specific Deterministic Ground Motion Sensitivity Studies

Adequacy of the distant EBE spectrum are evaluated in this section based on the following three approaches:

o Comparison of the EBE spectra to estimates of the 50th and 84th percentile deterministic ground motion using H-Area site-specific properties.

o Comparison of the EBE spectra to LLNL and EPRI uniform hazard spectra.

o Comparison to published EUS spectra.

Distant event spectra are developed in this section for H-Area in a manner similar to the development of the distant EBE spectrum, that is by using the RVT model to develop site rock outcrop spectra and then employing site response analysis to model the soil behavior for H-Area.

WSRC compared the LLNL and EPRI uniform hazard spectra to the distant EBE and H-Area median spectra. The uniform hazard spectrum (UHS) have been decomposed by event magnitudes to illustrate relative contribution to hazard by earthquake magnitude (DOE-STD-1024). Although it is in general difficult to make comparisons between probabilistic and deterministic spectra, the decomposition allows a more direct comparison of the UHS to a deterministically derived spectra.

Deterministic ground motions for a repeat of the 1886 Charleston earthquake require selection of the following key parameters:

o maximum credible source size (moment/magnitude and stress drop)

o focal depth

o distance from site center

o path and site properties

o selection of an appropriate standard error for ground motion variability to derive an 84th percentile ground motion estimate

As discussed above, K-Reactor spectra developed by Geomatrix were "median or average level" of ground motions using conservative source assumptions. For development of 84th percentile motions, a standard error of 0.5 (natural log) was suggested in the study based on standard error values used for past EUS hazard studies. The Geomatrix distant event response spectrum was based on the following:

o A source size of a Mw 7.5 event with stress drop of 150 bars.

o A spectral shape using a source distance of 120 km.

o Ground motion prediction using expected site and path properties.

o Amplitudes scaled by using maximum motions from a source located at 110 km (the distance producing a local maxima on the PGA attenuation curve).

For comparison to the H-Area distant EBE, the following approach is used:

1. Develop H-Area median rock spectra using expected or median source and path properties.

2. Develop 84th percentile rock spectra that accounts for variability and uncertainty in modeling, stress drop, crustal structure, Kappa, and Q.

3. Propagate median and 84th percentile rock spectra to surface using H-Area site-specific soil properties and CFD deep soil velocity profile.

Median Charleston Source Parameters

The Charleston-type earthquake source is characterized as a Mw 7.5 earthquake with stress drop of 100-150 bars. Median stress drop for EUS earthquakes has been reported to be 100 bars by Sommerville et al. (1987), and a 100 bars was suggested for the 1886 Charleston earthquake (Geomatrix 1991). For added conservatism, Geomatrix used a value of 150 bars. EPRI (1993) reported a median EUS earthquake stress-drop of 120 bars with a log-normal sigma of 0.70. For the purposes of the ground motion sensitivity studies, a stress-drop of 100 bars will be considered as a median value.

For a repeat of the 1886 earthquake, a source distance of 120 km is used for the H-Area as this is the distance from the SRS center to the edge of the MMI X isoseismal. A point source depth of 15 km is assumed for the RVT spectral shape. The rock spectral shape was scaled to a weighted average of 0.55g taking into account the range of source depth on computed motions at a distance of 120 km.

Note that in a prior revision of this report, median Charleston source parameters assumed a Mw 7.5 at a distance of 145 km and stress drop of 150 bars. Oversight groups have recommended a Mw 7.5 at a distance of 120 km and stress drop of 100 bars. These positions trade-off a degree of conservatism in median distance vs median stress drop. The predicted motions from these two cases differ by about 10%.

Path Properties

Median path properties are assumed to be described by the Rhea (1984) Q model and the Herrmann (1986) crustal velocity model. Kappa is assumed to be 0.006 seconds, the median used by EPRI (1993) and Geomatrix (1991).

Standard Error

An advanced treatment of statistical variability in EUS ground motion prediction was recently completed by EPRI (1993) (see also Toro et al. 1994). Large numbers of RVT rock motion simulations (>800,000) were made by randomizing stress drop, source depth, Q, and Kappa for mid-continent U.S. earthquakes of magnitude 4.5-8.0 with source distances of 1-500 km. Ground motion variability was partitioned into components of randomness and uncertainty based on the predicted motions, and the degree of misfit found by RVT modeling of EUS strong motion records. These components are dependent on magnitude, distance, and frequency. Randomness accounts for parametric variability including source depth, stress drop, Q model, Kappa, and modeling variability. Uncertainty is derived from the goodness of fit of models to observed spectra.

Variability associated with modeling uncertainty is seen to be independent of distance, as is stress drop and Kappa (Figure 32). Variability increases for decreasing distance because of uncertainty in source depth, and increases at about 100 km because of the uncertainty of the moho depth.

The EPRI (1993) variability and uncertainty regressions are conservative because the parameterization represents large ranges in earthquake source and structure as a consequence of representing the mid-continent U.S. Consequently, a similar analysis using SRS regionally constrained data (e.g., structure and Q models appropriate for Atlantic Coastal Plain and Piedmont) could significantly reduce the standard error.

H-Area Median and 84th Percentile Motions

Rock spectra for K-Reactor were not available from the Geomatrix (1991) work, consequently, an approximation to the distant event rock spectrum was derived (Figure 33). The smoothed K-Reactor soil spectrum developed by Geomatrix is included for comparison. This figure illustrates the smoothed surface and RVT rock motions using Geomatrix (1991) source parameters (i.e., Mw 7.5, stress drop 150 bars, and distance of 120 km). The rock spectrum shown in Figure 33 is estimated to be a good approximation to the rock spectrum developed by Geomatrix (1991), and will hereafter be referred to as the H-Area distant EBE rock spectrum. The H-Area distant EBE rock spectrum was scaled to have the same high-frequency PGA as the value reported by Geomatrix, that is 0.082g (see Figure 18). This EBE rock spectrum will be used in making comparisons to the rock UHS below.

Median and 84th percentile RVT rock spectra for H-Area are shown in Figure 34. The spectra represent a Mw 7.5 earthquake at a distance of 120 km with a median stress drop of 100 bars. The 84th percentile motions shown in Figure 33 are derived by using the EPRI frequency dependent standard error (Toro et al. 1994).

WSRC derived a H-Area surface spectra from the median and 84th percentile rock spectra by convolving the rock motions through the H-Area soil properties (Figure 35). Figure 36 shows the median and 84th percentile spectra and comparison to the EBE rock spectrum. Comparison of the H-Area EBE rock spectrum (Figure 34) and the H-Area median and 84th percentile RSA indicates that the H-Area EBE rock spectrum falls between the 50th and 84th deterministic spectra.

Electric Power Research Institute and Lawrence Livermore National Laboratory Hazard Spectra

Recently, the EPRI and LLNL probabilistic hazard results have been deaggregated by magnitude for both soil and rock outcrop (J. Kimball, 1994 personal communication). In addition, LLNL incorporates a SRS specific soil profile (Chen et al. 1992) that differs from the EPRI and prior LLNL generic soil profiles. The deaggregation is useful to the H-Area investigation because, the distant EBE soil and rock spectra may be compared to the rock or soil site UHS for specific magnitude ranges. Probabilities of exceedance could then be estimated for selected ranges of earthquake magnitudes for specific frequency bands.

Soil and rock LLNL UHS are compared at the $1x10^{-4}$ annual probability of exceedance (Figure 37). The EPRI-Vogtle hazard model uses a generic soil profile, and consequently cannot account for site-specific resonances. The EPRI (1986) and LLNL (1986) soil UHS use a generic deep-soil profile, and averaging techniques have resulted in smoothed or averaged values at the soil resonance fundamental period. This is evident from new site-specific LLNL results for SRS.

Table 8 summarizes the EPRI soil and rock hazard results for an annual probability of exceedance of $1x10^{-4}$. Values are shown for mb>5, mb>6, and M-bar and D-bar. The M-bar and D-bar values are average magnitude and distances determined from the hazard study that contributes to the probability of exceedance. Similarly, Table 9 shows the LLNL soil and rock hazard. Salient features from the EPRI tables are as follows:

o M-bar and D-bar, for any of the three frequencies, are consistent for the rock and soil cases. M-bar differs by less than 0.1 units and D-bar differs by less than 1%.

o The average magnitude and distances are about the same for frequencies of 2.5 and 1.0 Hz (mb 6.4 at 80-100 km).

o PGA is controlled by about mb 5.9 at approximately 35 km.

o Soil PGA is approximately 25% greater t[illegible]-Area site-specific data suggest that PGAs for rock and soil [illegible]bout the same.

o Soil accelerations at 2.5 Hz increase by ab[illegible]ver rock for M>5 which is consistent with the H-Area transfe[illegible] Soil and rock accelerations are the same for M>6, this is [illegible]t with the H-Area transfer function.

o Soil accelerations at 1.0 Hz are a factor of [illegible]er than rock for M>5. This exceeds the H-Area transfer functi[illegible]ut 50%. Soil/rock acceleration ratio is about 3.2 for M>6.

Some features of Table 9 are as follows:

o D-bar, for the three frequencies, are inconsis[illegible]ween rock and soil. M-bar differs by about 0.6 and D-bar diffe[illegible]out 100%.

o The average magnitudes range from 5.5 to 6.[illegible]equencies of 2.5 and 1.0 Hz, and distances range from 39 to 92 k[illegible]

o PGA for rock is controlled by an mb 5.9 at a[illegible] km.

o PGA values differ by about 10% between roc[illegible]oil.

o Soil accelerations at 2.5 Hz increase by about [illegible]ver rock for M>5 which is consistent with the H-Area transfer fu[illegible].

o Soil accelerations at 1.0 Hz are a factor of 2.2 [illegible]er than rock for M>5, which is near the H-Area factor of 2.4 for [illegible]requency. For M>6 soil/rock acceleration ratio is about 2.3.

Table 8. EPRI Hazard Results @ 1 x 10^{-4} for Rock and Soil (Peak spectral values of acceleration are given for M >5, 6, and M-bar and D-bar. M-bar and D-bar values are estimated for all magnitudes M6>5.)

	Rock				Soil			
Ground Motion Frequency	**Spectral Acceleration**		**M-bar**	**D-bar**	**Spectral Acceleration**		**M-bar**	**D-bar**
	M>5	**M>6**	**(m_b)**	**(km)**	**M>5**	**M>6**	**(m_b)**	**(km)**
Peak Accel.	0.19g	0.11g	5.9	34	0.15g	0.09g	5.8	34
2.5 Hertz	0.23g	0.13g	6.3	85	0.14g	0.13g	6.3	84
1.0 Hertz	0.22g	0.19g	6.4	98	0.06g	0.06g	6.4	97

Jack Benjamin and Associates computed deaggregated results using EPRI methodology.

Table 9. LLNL Hazard Results @ 1 x 10^{-4} for Rock and Soil

	Rock				Soil			
Ground Motion Frequency	**Spectral Acceleration**		**M-bar**	**D-bar**	**Spectral Acceleration**		**M-bar**	**D-bar**
	M>5	**M>6**	**(m_b)**	**(km)**	**M>5**	**M>6**	**(m_b)**	**(km)**
Peak Accel.	0.32g				0.36g	0.22g	5.9	21
2.5 Hertz	0.90g	0.73g	5.5	92	0.56g	0.39g	6.1	39
1.0 Hertz	0.42g	0.34g	5.7	71	0.195g	0.15g	5.9	45

These tables show that the LLNL and EPRI deep soil site responses are different at high frequencies. The EPRI soil/rock ratios are greater than 1 for PGA < 0.2g and the LLNL soil/rock ratios are less than 1 for all PGAs. Differences in the EPRI and LLNL rock seismic hazard results are even greater. The LLNL mean rock hazard exceedance is an order of magnitude larger than EPRI mean rock at 0.20g PGA.

The LLNL soil/rock ratio's are more consistent with site transfer functions (Chen et al. 1992) than EPRI because the EPRI study used the generic site correction. LLNL PGAs are more than double EPRI; results at 2.5 Hz are 400% greater, and at 1Hz, are 325% greater. One possible source of this difference is the inclusion of SRS basement sources in the LLNL study. Seismicity experts in that study developed seismic area sources for the SRS Dunbarton Basin area and assigned relatively high activity rates to these zones (J. Kimball personal communication). Faults associated with the basin were discovered in the course of site seismic reflection studies (Chapman and DiStefano 1989). More detailed investigations of these basement faults, including depth and displacement in dateable soil horizons have so far indicated that they are incapable by NRC definition (Stieve et al. 1994, Stephenson and Stieve 1992).

M-bar and D-bar Rock Spectra

As a comparison to the deterministic calculations that were developed by Blume and Geomatrix, we considered here the probabilistic magnitudes and distances (M-bar and D-bar) derived for frequencies believed critical to liquefaction (1–3 Hz) (Costantino, 1994). Figures 38 and 39 show median and 84th percentile RVT rock spectra assuming EPRI and LLNL M-bar, and D-bar for 1.0 and 2.5 Hz respectively. The 84th percentile spectra, from earthquakes with average magnitudes and distances to exceed 1.0 and 2.5 Hz, fall below the EBE rock spectrum for $f < 12$ Hz. However, the 1-2.5 Hz UHS for EPRI and LLNL (Tables 8 & 9) clearly indicate that the EBE rock spectrum is in excess of 10^{-4} annual probability of exceedance.

Rock Spectrum Comparison to UHS

EPRI and LLNL rock UHS (at exceedance of $1x10^{-4}$) were taken from tables provided by DOE (personal communication with J. Kimball, 1994) and are shown in Figures 40 and 41. Also shown in the figures are deterministic median and 84th percentile rock spectra using H-Area specific properties, and the EBE rock spectrum. The UHS were decomposed into contributions for $mb > 5$, 6, and 7. For both EPRI and LLNL, differences in the composite UHS decrease with decreasing frequency as the smaller earthquakes contribute less to the spectra at lower frequencies. The LLNL UHS exhibits far greater range of motions than EPRI with ratios of about 2.5 or greater in the 1-2.5 Hz band. As discussed above, the LLNL exceedances are lower than EPRI (for a specified level of motion), in part, because that study had increased activity associated with basement structures underlying the site.

Figures 40 and 41 illustrate that the hazard contribution from m>7 earthquakes is insignificant above 1-Hz as compared to contributions from m> 5,6 earthquakes. Thus, for the mean rock hazard, the Charleston earthquake is not a significant seismic hazard contributor. The M-bar and D-bar values for both EPRI and LLNL illustrate the same point.

Because large (M > 7) earthquakes do not contribute significantly to the probabilistic seismic hazard, the EPRI and LLNL M-bar and D-bar values are not useful in developing specific criteria to scale or shift the distant earthquake spectra. Consequently, an alternate approach for the distant event spectrum is recommended. Figures 38 and 39 illustrate that rock spectra, derived using UHS M-bar and D-bar values, were not in excess of the EBE rock spectrum for frequencies less than 12 Hz. Thus, the EBE rock spectrum appears to be conservative with respect to predicted rock motions from the average earthquake magnitudes and distances controlling frequencies important to liquefaction.

Rock Spectrum Comparison to Published Attenuation Models

Comparisons of the median and 84th percentile rock spectra were made to two published attenuation models (Figures 42 and 43). The EUS rock spectra developed by Atkinson and Boore (1990) (Figure 42) are compared for source distances of 80–140 km from a Mw 7.5 earthquake. For frequencies less than about 20 Hz, the EBE rock spectra is in good agreement with their 100 km prediction. The 84th percentile spectrum is in good agreement with the 80 km distant earthquake for frequencies less than about 20 Hz. The median spectrum is comparable to the Atkinson and Boore (1990) prediction at 120 km for f < 20 Hz, and more conservative at higher frequencies.

EPRI (1993) rock spectra differ considerably in shape from the SRS rock predictions (Figure 43), possibly because of the difference in average Q assumed in the models. The EBE rock spectrum is exceeded by the EPRI models at frequencies less than 2-3 Hz for source distances of 120-140 km. The 84th percentile rock spectrum exceeds all EPRI predictions except for the 80 km distant source. This comparison also suggests that the H-Area median spectra are un-conservative as compared to the EPRI (1993) predications for f < 6 Hz.

Conclusions

A review of the technical basis for the H-Area EBE spectra was conducted together with an overview of the history of recent spectra development at SRS. The EBE spectra for H-Area consist of: (1) a 0.19g scaled "local" 5% damped response spectrum and (2) an unscaled spectrum for the "distant" earthquake. The unscaled distant spectrum was based on work completed by Geomatrix (1991) for K-Reactor. Parameter studies related to predicted ground motion were conducted that included variations in earthquake source size and distance, path Q, site base-rock properties, and soil models. Parametric studies were conducted to address the applicability of the EBE distant spectrum to H-Area Tank Farms, establish ground motion sensitivity to the parameters and to establish probability of exceedance of the EBE motions. Based on H-Area data, application of the EBE "distant" earthquake spectrum at H-Area provides motions that are more conservative than median. This judgment is based on assessments of deterministic "distant" event spectra using H-Area specific properties for the 50th and 84th percentile expected motions (Figure 34). These spectra indicate that the EBE "distant" spectrum is in excess of the 50th percentile and less than the 84th percentile of deterministic ground motions (the EBE distant rock spectrum is approximately the 60th percentile of deterministic motion). From a site response perspective, the H-Area spectra indicates somewhat larger motions than spectra derived for K-Reactor, assuming the same input source and crustal path parameters (M_W, r, stress-drop, etc.).

EPRI and LLNL rock and soil UHS were also reviewed for applicability to H-Area. It was determined that the applicability of the LLNL rock and soil UHS were limited until improvements are made in the LLNL seismicity model. The EPRI soil model was also not suitable for a site-specific comparison, however, the rock UHS are useful to compare to deterministic ground motion predictions. Because the M-bar and D-bar values are inconsistent with the deterministically derived controlling earthquake magnitudes and distances, it is problematic to assign a probability of exceedance to the 84th, EBE, or 50th percentile rock spectra for all frequencies. The 84th deterministic rock spectra is "close" to the EPRI $1x10^{-4}$ rock UHS in the 1-2.5 Hz range (Figure 40). That spectra envelopes the EPRI M-bar and D-bar rock spectra at all frequencies. However, the 84th deterministic rock spectrum has a much higher probability of exceedance when compared to LLNL UHS (Figure 41). The contribution to risk of the H-Area EBE rock and 84th percentile distant response spectra will be evaluated in the probabilistic analysis to be completed in a later phase of this investigation.

It is important to note that the EBE spectra together with the 84th percentile deterministic spectrum meet the acceptance criteria as defined by DOE-STD-1024 with the TSEP recommendations for the distant event spectrum. These criteria are considered temporary until specific guidance on the LLNL UHS are developed by the DOE. The TSEP recommendations for applying a deterministic 84th percentile spectrum in lieu of the unscaled distant EBE spectrum effectively compensate for the problematic LLNL UHS but are not consistent criteria for future investigations and facility ground motion prescription.

Additional direction is required from facilities for the performance and hazard goals. The acceptance criteria of DOE-STD-1024 anchors the local median spectral shape to the pseudo-mean of the LLNL and EPRI hazard curves at the 2×10^{-4} annual probability of exceedance. This hazard level falls between that required for PC3 and PC4 facility levels described in DOE-STD-1020 (i.e., corresponding hazard levels of 5×10^{-4} & 1×10^{-4} respectively). This investigation uses a hazard annual probability of exceedance of 2×10^{-4}, corresponding to the highest hazard category of DOE-STD-1024. The distant 84th percentile spectrum is not scaled to any probability derived spectral acceleration, but is near the EPRI 1 x 10-4 UHS at 1-2.5 Hz range. Until the performance/hazard guidelines are issued, engineering evaluation of foundations should use the scaled local and 84th percentile deterministic spectra in their evaluation. Evaluations of structures should use an envelope of the scaled local and 84th percentile deterministic spectra.

Outstanding Issues for Site Spectra

The H-Area investigations have pointed to a number of significant data needs, calculations, and other issues that deserve continued attention and eventual resolution but were beyond the scope of this study. A summary of these issues follows.

Deep soil velocity structure

Although shallow soil Vs variability are well defined for H-Area and other SRS facilities, deep soil velocity structure has an important affect on predicted site response. Because deep down-hole Vs. logging technology is now feasible, these deep measurements should become a standard measurement for SRS site characterization investigations. The measurements should also be incorporated in facility design basis. These additional measurements would provide information on deep Vs. variability. Additional measurements of deep soil Vs. are in progress at the SRS.

Soil Velocity and Dynamic Property Variability

Ground motion predictions should incorporate site Vs variability. Adequate data exists in the shallow soils to fully explore the effects of variability for H-Area and other SRS facilities. An investigation is underway to judge the adequacy and estimate the variance in dynamic properties measured from SRS soil samples. Soil models could be constructed to test the soil response effect of randomness in Vs and non-linear behavior.

Triassic Basin Response

If future assessments are required for K-Reactor or other facilities that may be affected by the Triassic Basin response, then a more detailed model of the basin boundary (3-D) should be investigated, together with a more complete assessment of the basin ground motion (e.g., finite element ground motion prediction model). The acoustic contrast between the basin and crystalline rock may allow the basin to act as an efficient conductor for higher frequency surface waves for appropriately positioned sources. Sufficient data are available to construct a 3-D model of the basin (using reprocessed CONOCO data) in a finite element model to test the effects of the basin on non-vertical ray incidence, incidence at edge of basin, or estimate the effect that the basin may have on surface waves or effect of signals that propagate along basin axis.

Charleston Earthquake Finite Sources

Development of a finite source for the Charleston earthquake will eliminate issues associated with point source models. Trade-off between source magnitude and stress-drop should be explored that reasonably fit the observed 1886 liquefaction.

Savannah River Site UHS

Distinct improvements could be made to the LLNL and EPRI hazard studies by incorporating up-to-date data in the source zone and soil models. Either another revision could be made to the LLNL model or a separate study could be funded by the DOE.

Coastal Plain Q Model

The Coastal Plain crustal Q model has been shown to be an important function in predicting distant earthquake ground motions. The only regional specific model available differs significantly from most of the published EUS models. It would be worth reviewing the data used by

Rhea (1984) and incorporating more recent data to confirm or revise the model.

Ground Motion Standard Error

The assessment of ground motion standard error by EPRI (1993) and Toro et al. (1994) incorporated in this study involves several important assumptions that should be checked. Estimates of the frequency dependent standard errors were band-limited and extrapolations were made at high and low frequency ends of the spectral scaling factors. An evaluation should be made to extend the frequency range of the Toro et al. (1994) standard error coefficients. This evaluation should be done for the southeastern U.S. region containing the SRS which may significantly reduce the standard error.

Distance to Charleston Source

A distance of 120 km is assumed for a repeat of the 1886 Charleston earthquake. The median ground motion estimate nor the standard error accounts for uncertainties in epicentral distance. An evaluation of the probable distance range for the next Charleston-type earthquake could be factored into median and 84th percentile assessments.

Controlling Earthquake Magnitude and Distance

The deterministic magnitude and distance for the EBE local and distant earthquakes are inconsistent with the probabilistic (LLNL and EPRI) average controlling magnitude and distance. These differences should be resolved to fully satisfy DOE-STD-1024 requirements. An assessment of the Bowman event maximum magnitude should also be conducted.

Local Event Spectrum

The local-event spectrum was not a subject of this report, however, an RVT model of median motions should be developed as a check on the Geomatrix (1991) corrected western U.S. empirical spectral shape.

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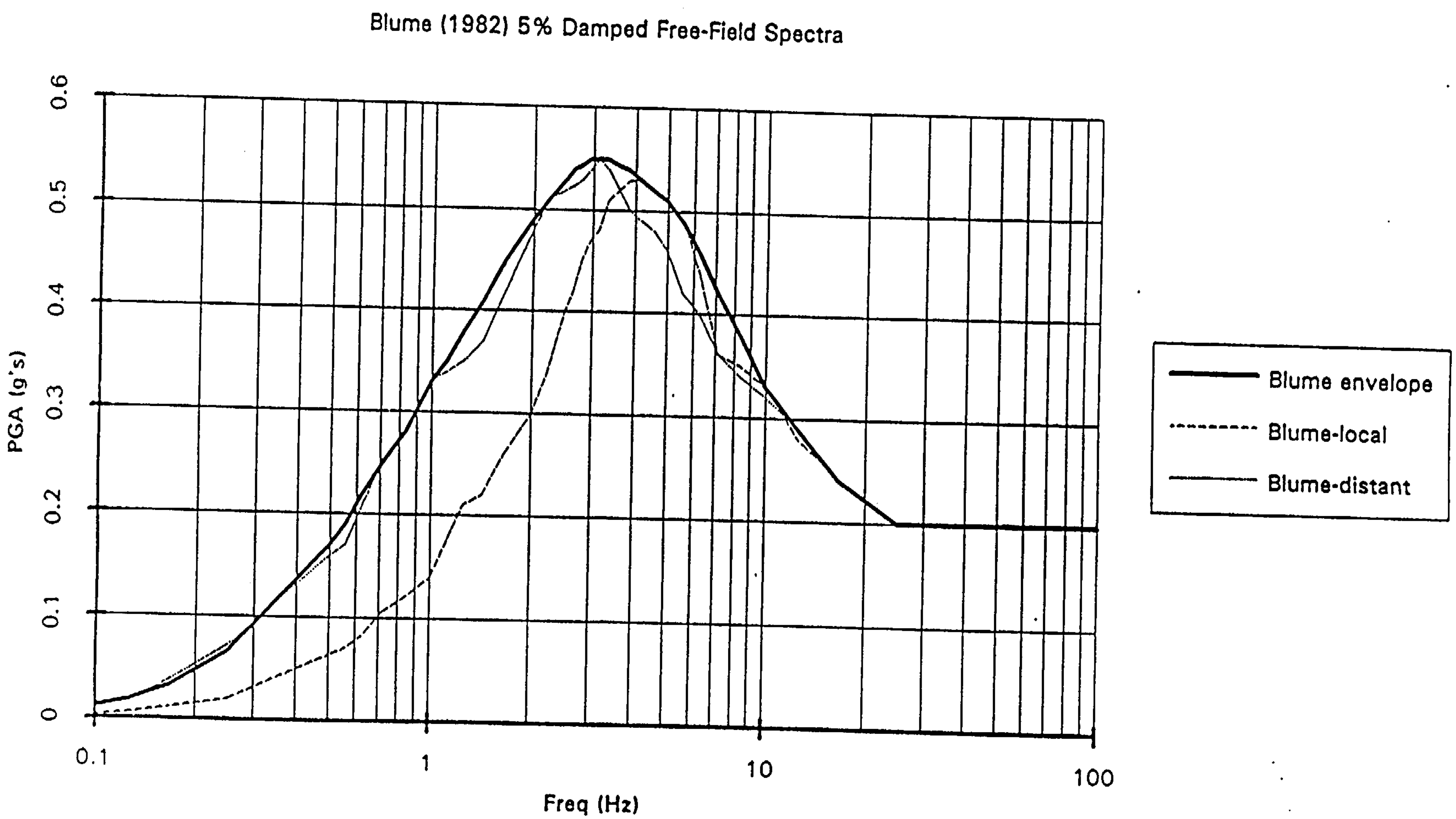

Figure 1. The URS/Blume (1982) recommended 0.2g scaled 5% damped mean response spectra for local and distant earthquakes. Also shown is the Blume recommended envelope spectrum. The envelope spectrum was the basis of facility evaluation from 1982 until recently.

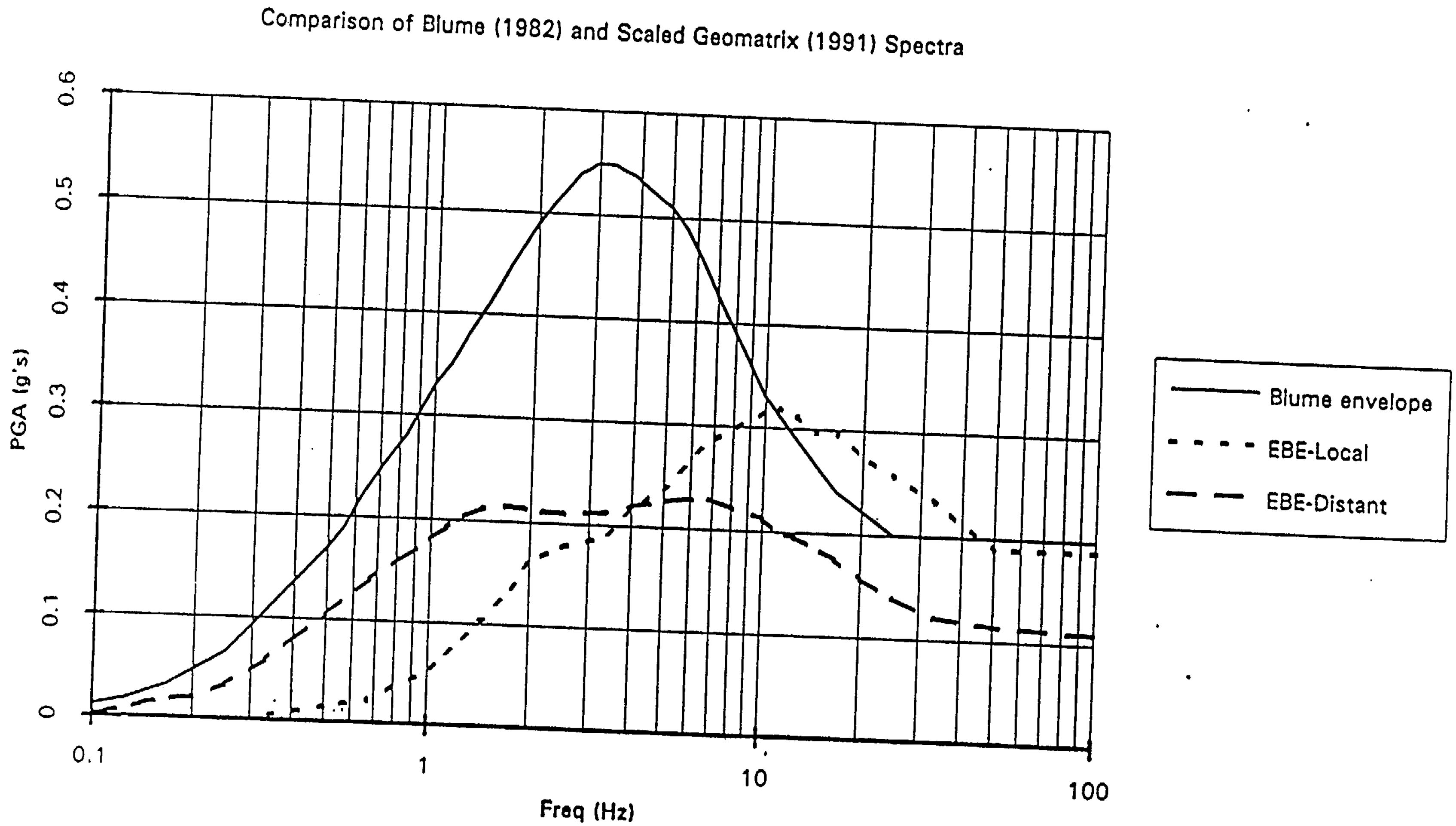

Figure 2. Geomatrix (1991) 5% damped response spectra for the local (scaled to 0.19g) and distant (unscaled) earthquakes used for RTF and ITP/H-AREA (EBE local and distant). The Charleston source is indicated as "distant". The Blume envelope spectrum scaled to the recommended 0.2g is shown for comparison. Note that the Geomatrix distant spectrum has been smoothed.

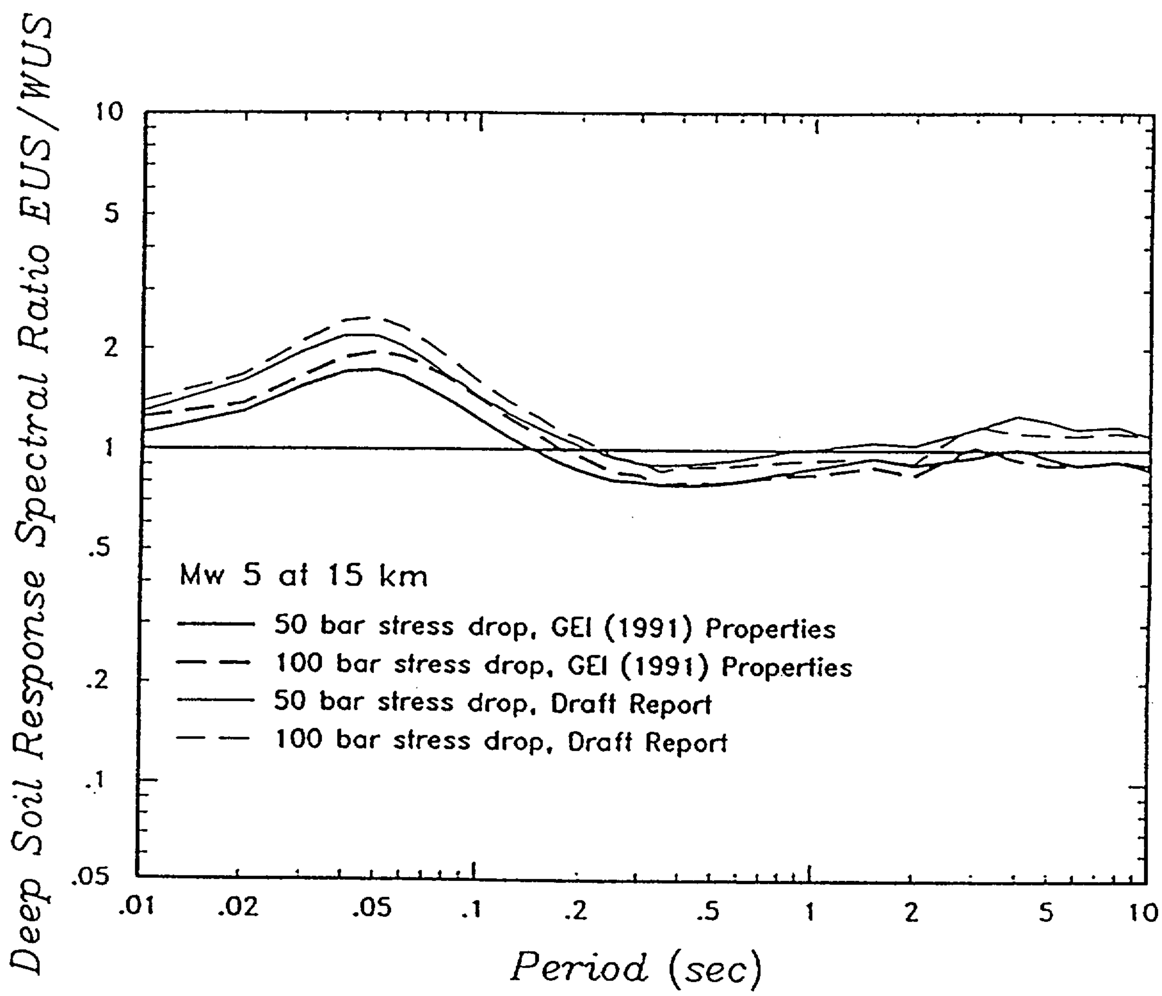

Figure 3. Western U.S./Eastern U.S. deep soil correction developed by Geomatrix (1991) using average properties and RVT simulation.

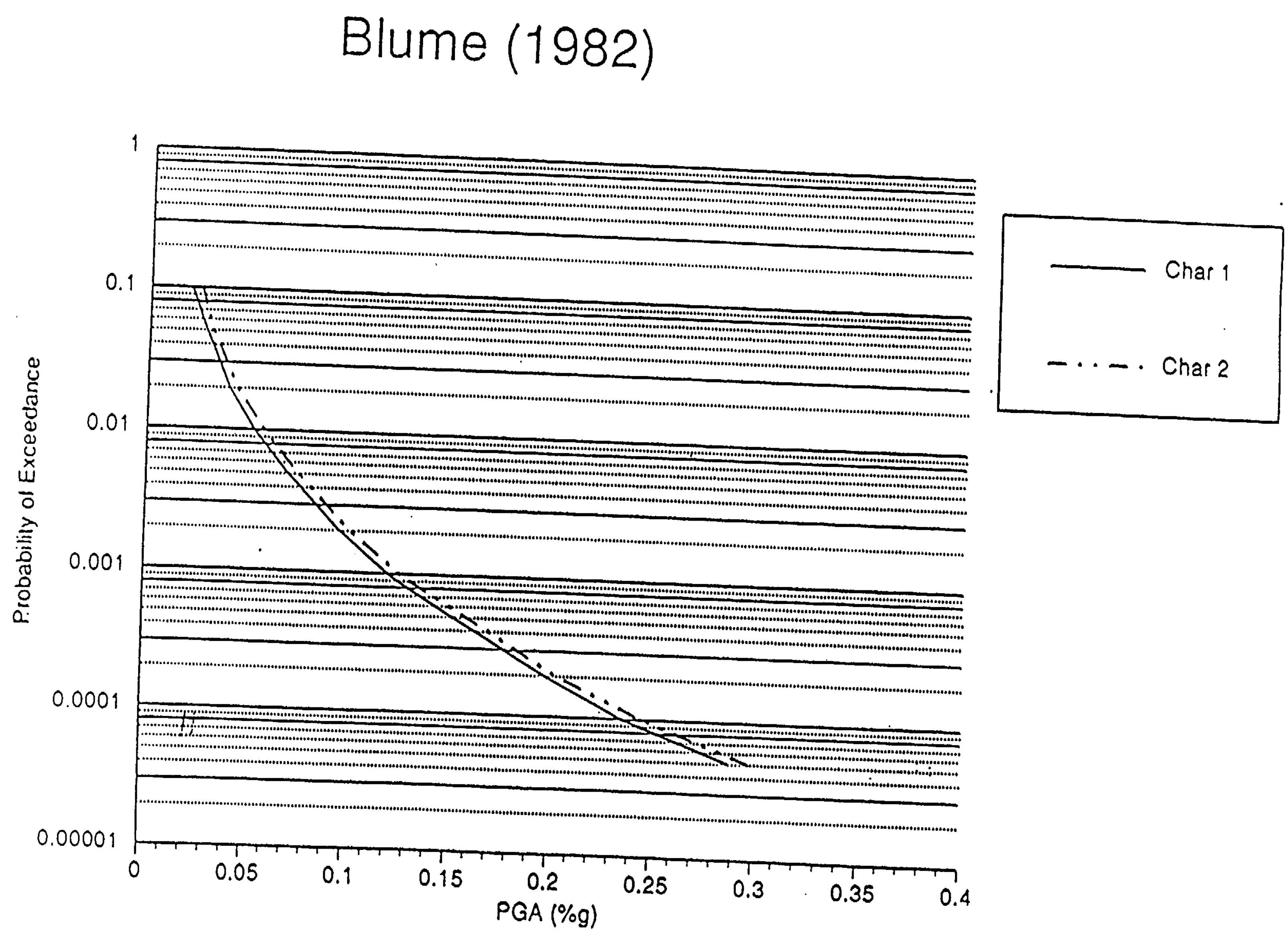

Figure 4. URS/Blume (1982) probabilistic hazard curves for two alternative Charleston source models. Vertical scale is annual probability of exceedance.

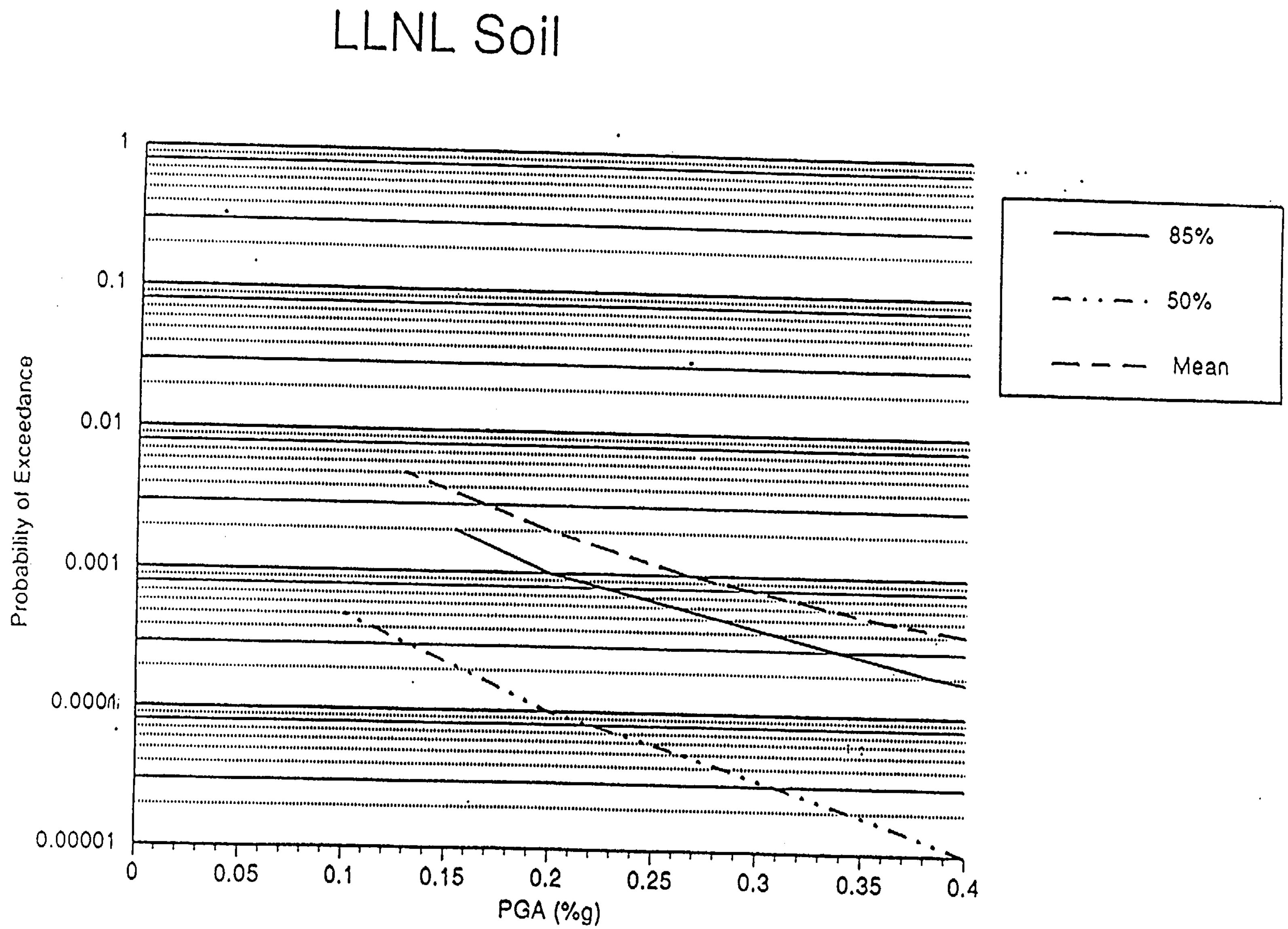

Figure 5. LLNL SRS soil hazard curves. Shown are the statistical 50th, 84th and mean results.

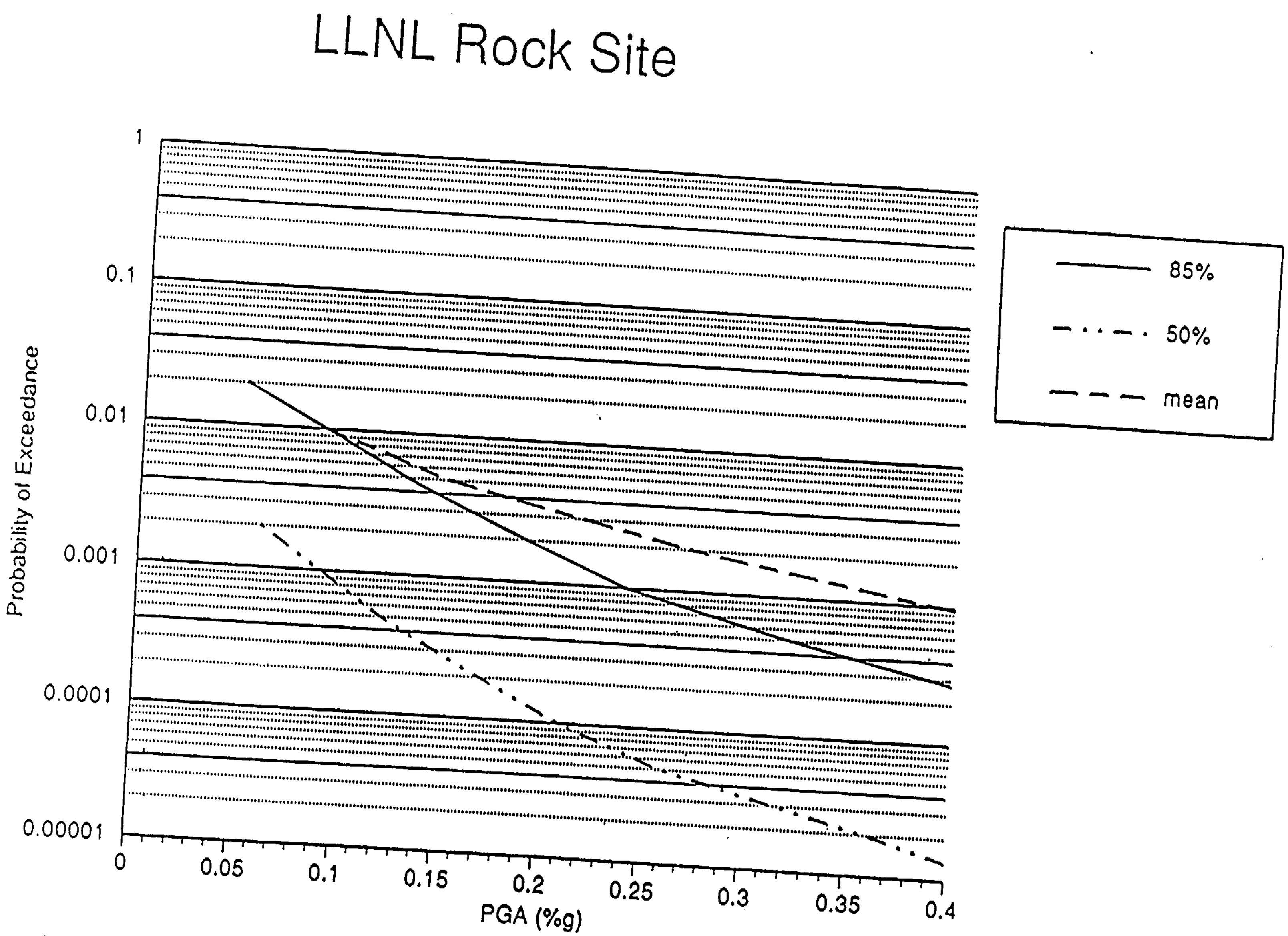

Figure 6. LLNL SRS rock hazard curves. Shown are the statistical 50th, 84th and mean results.

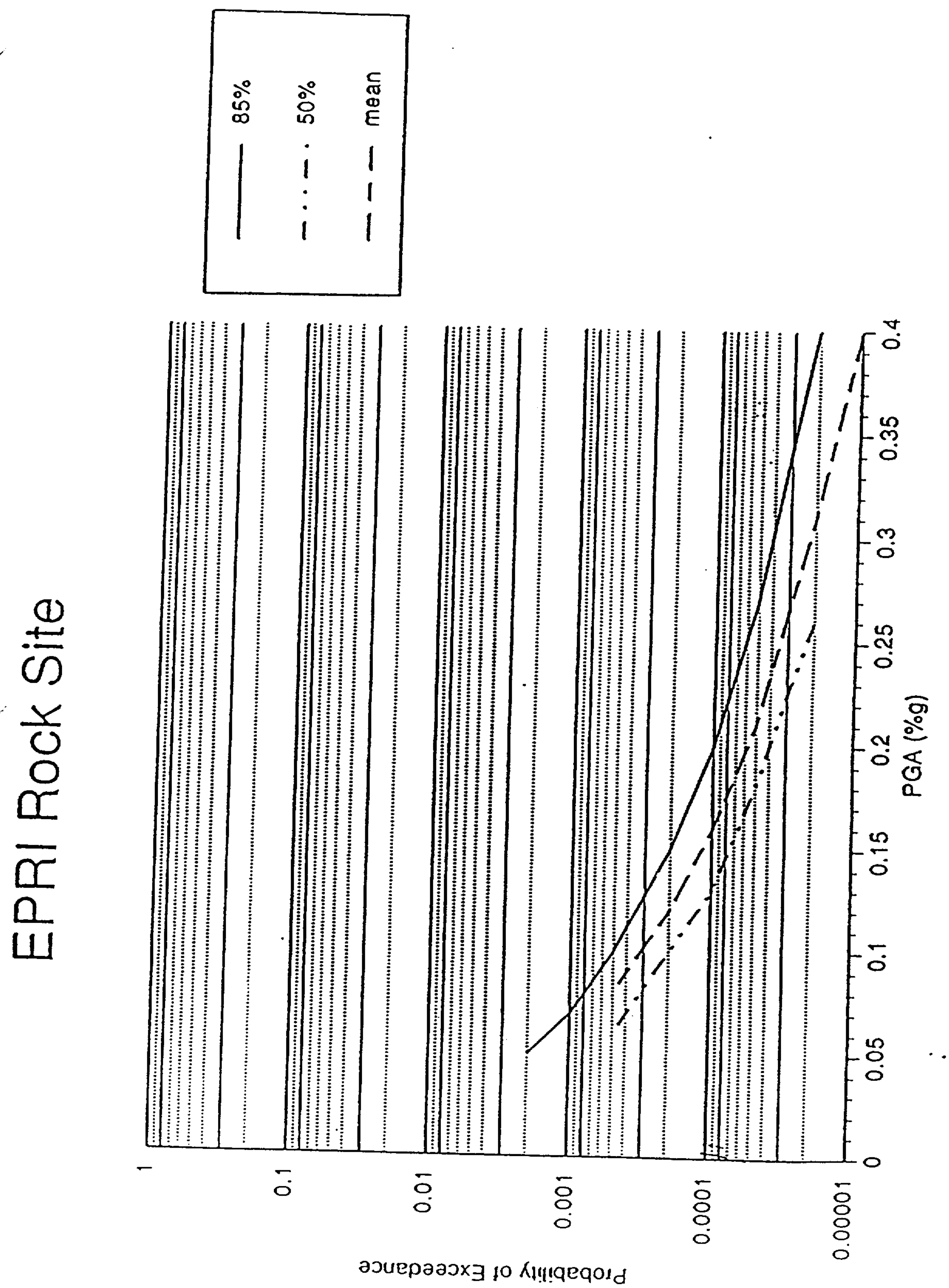

Figure 7. EPRI rock hazard curve for the SRS. Shown are the statistical 50th, 84th and mean results.

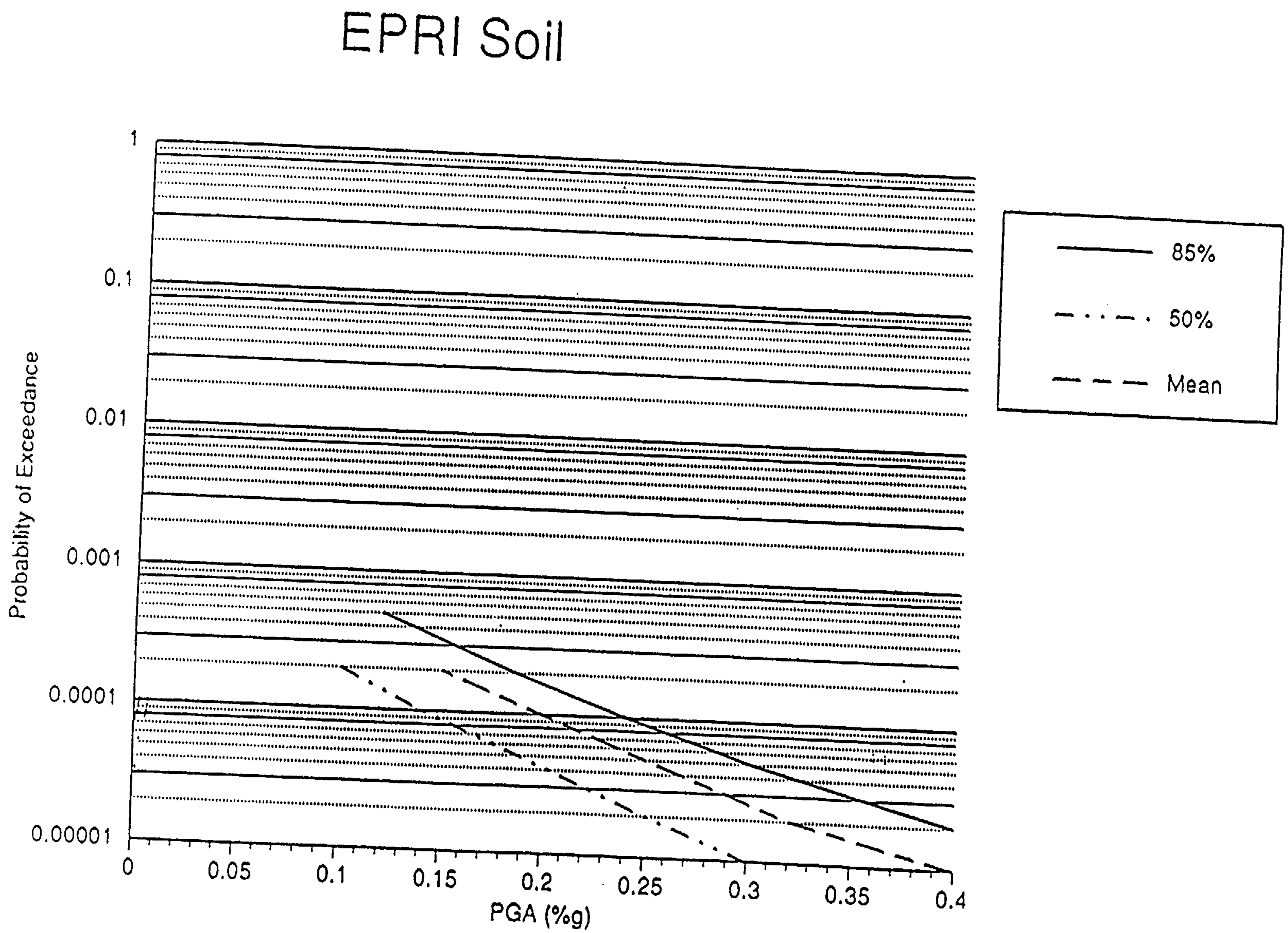

Figure 8. EPRI soil hazard curve for the SRS. Shown are the statistical 50th, 84th and mean results.

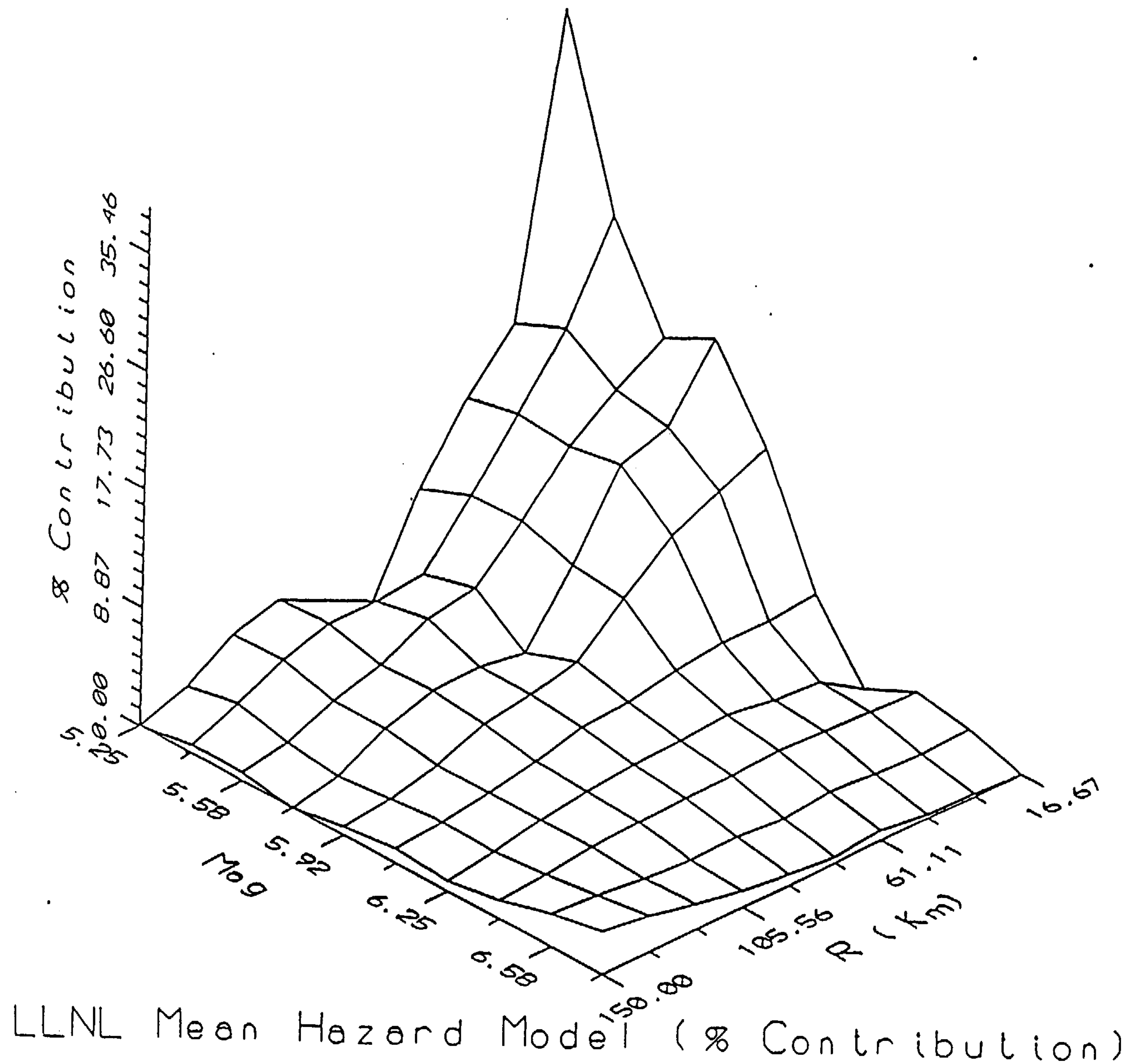

Figure 9. LLNL probabilistic hazard contribution by earthquake size and distance. Shown are percent contributions to mean PGA for an annual probability of exceedance of 2×10^{-4} (Stephenson et al. 1993).

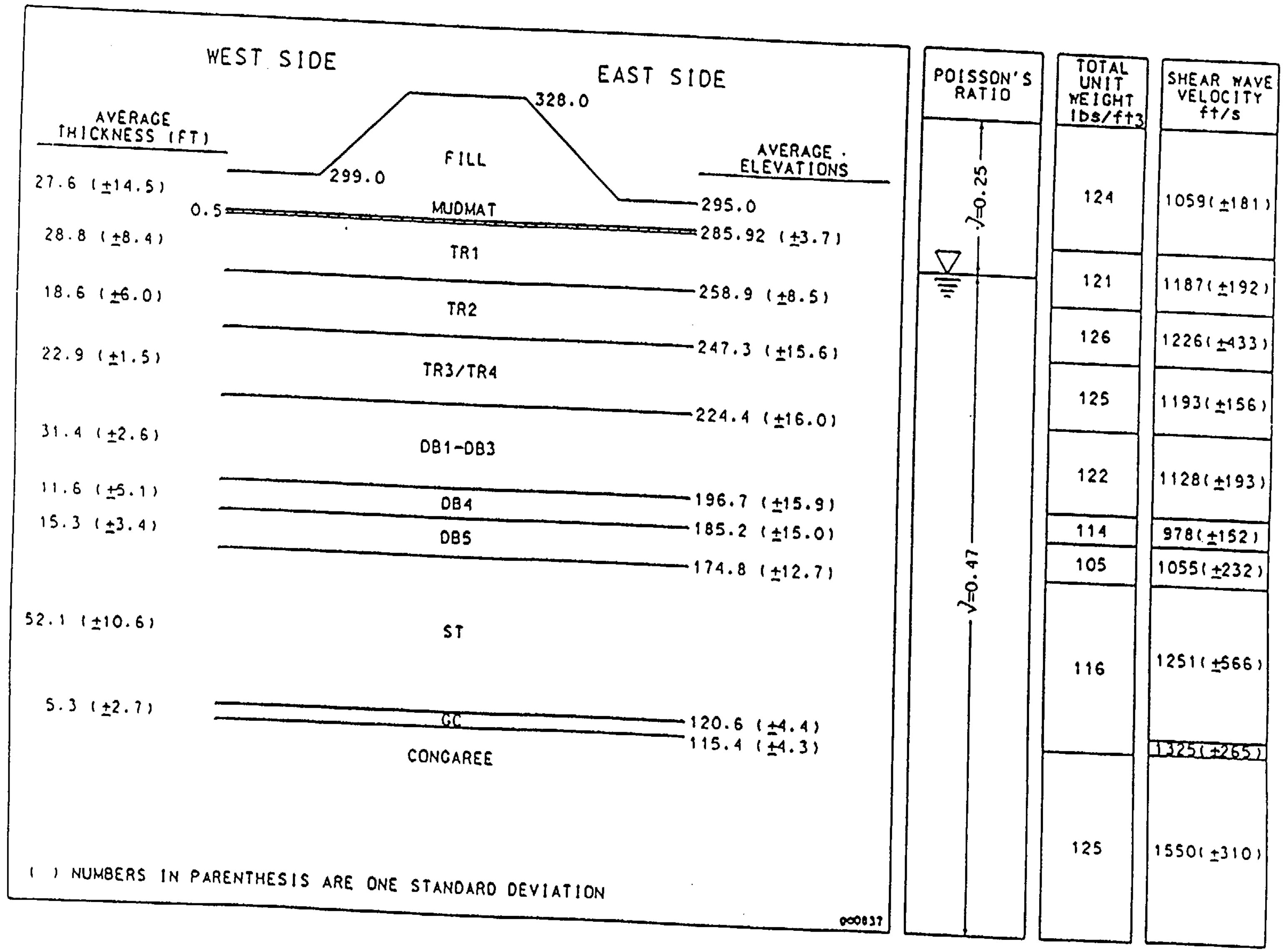

Figure 10. ITP/H-AREA idealized shear-wave velocity, depth/elevations, and formation description.

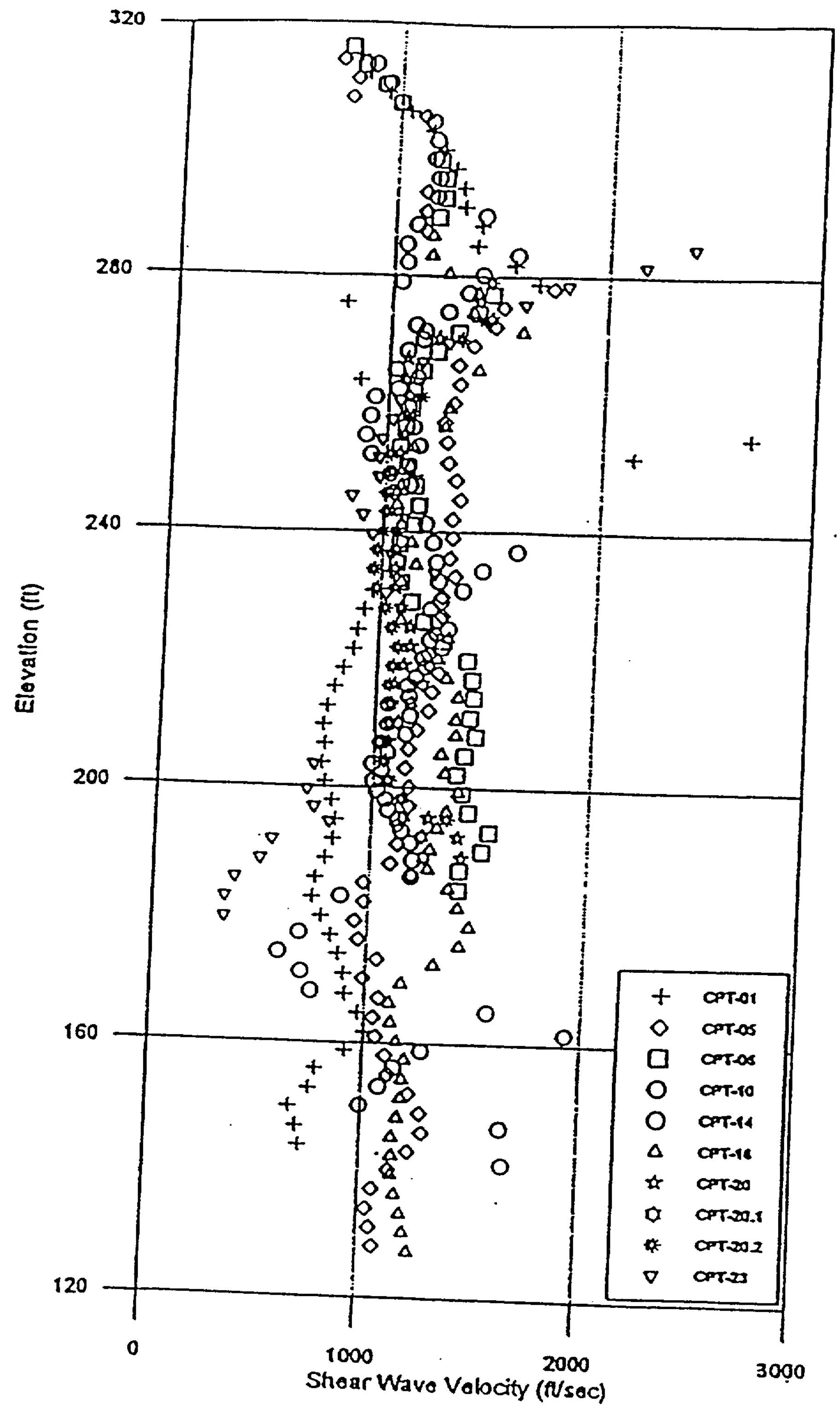

Figure 11. ITP/H-AREA Phase I CPT shear-wave velocity vs. elevation.

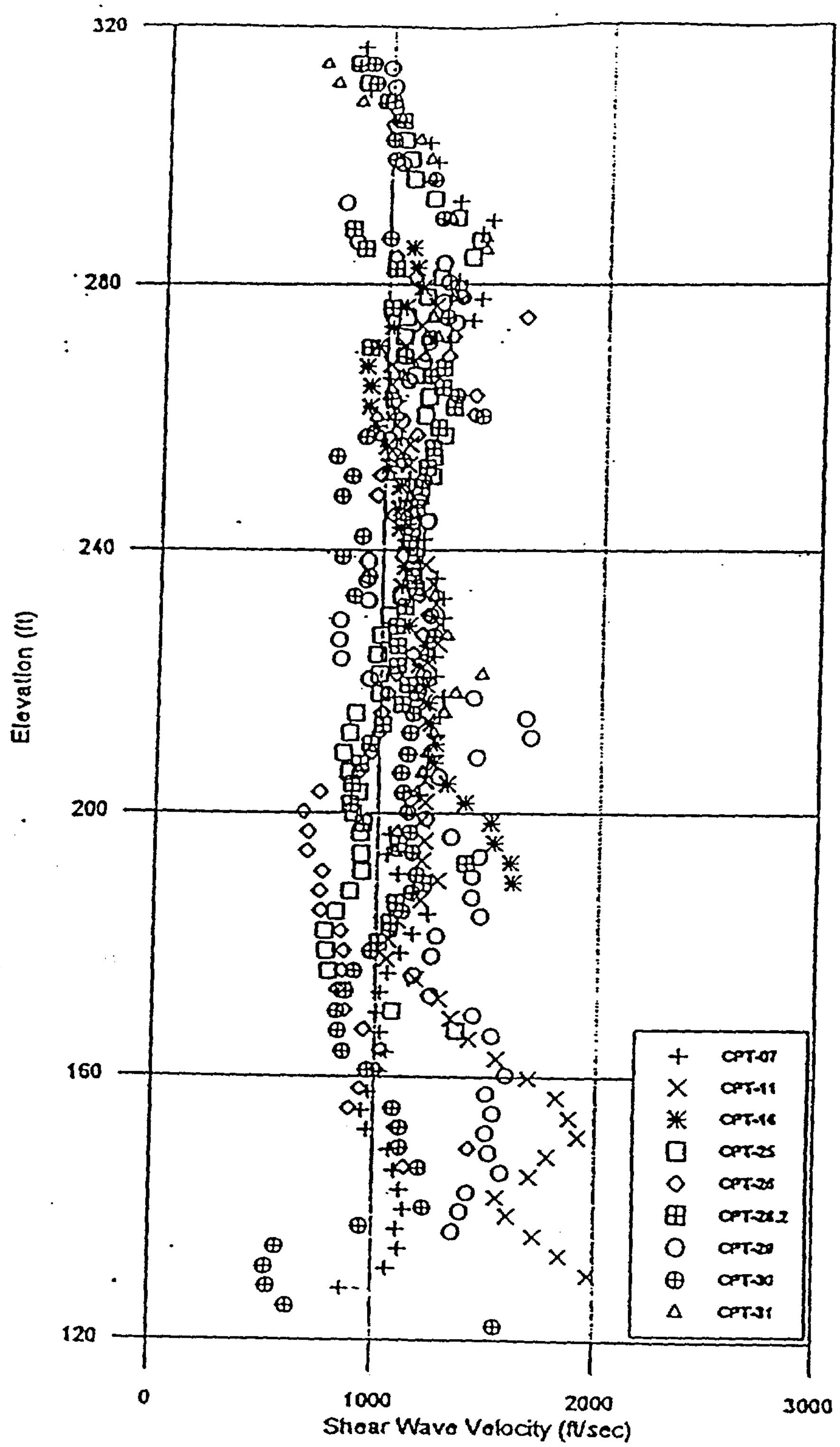

Figure 12. ITP/H-AREA Phase II CPT shear-wave velocity vs. elevation.

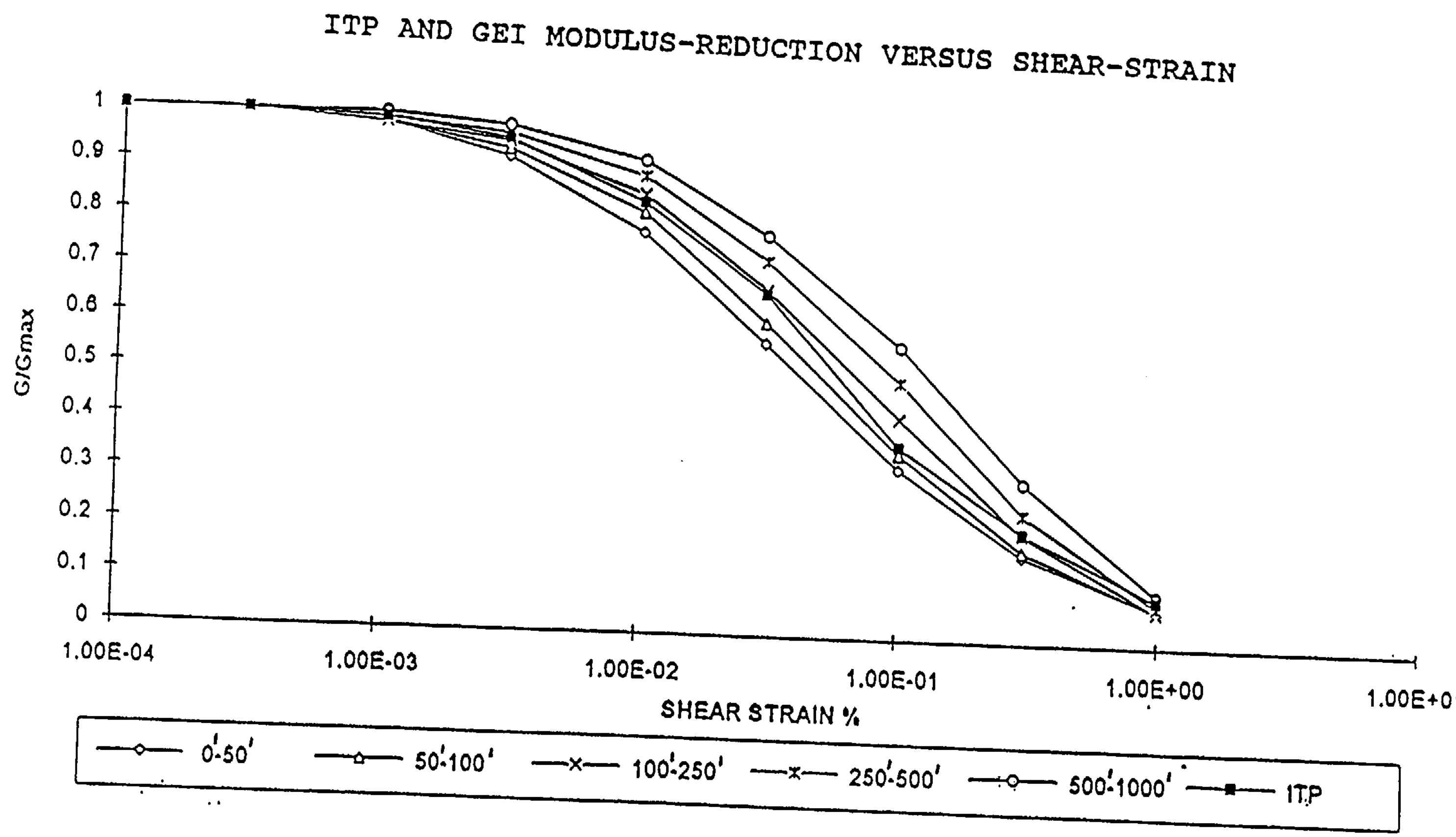

Figure 13. Modulus curve measured for ITP/H-AREA (solid) in the upper 170' of non-fill soils. Also shown are GEI derived relationships for K-Reactor that illustrate the depth dependency.

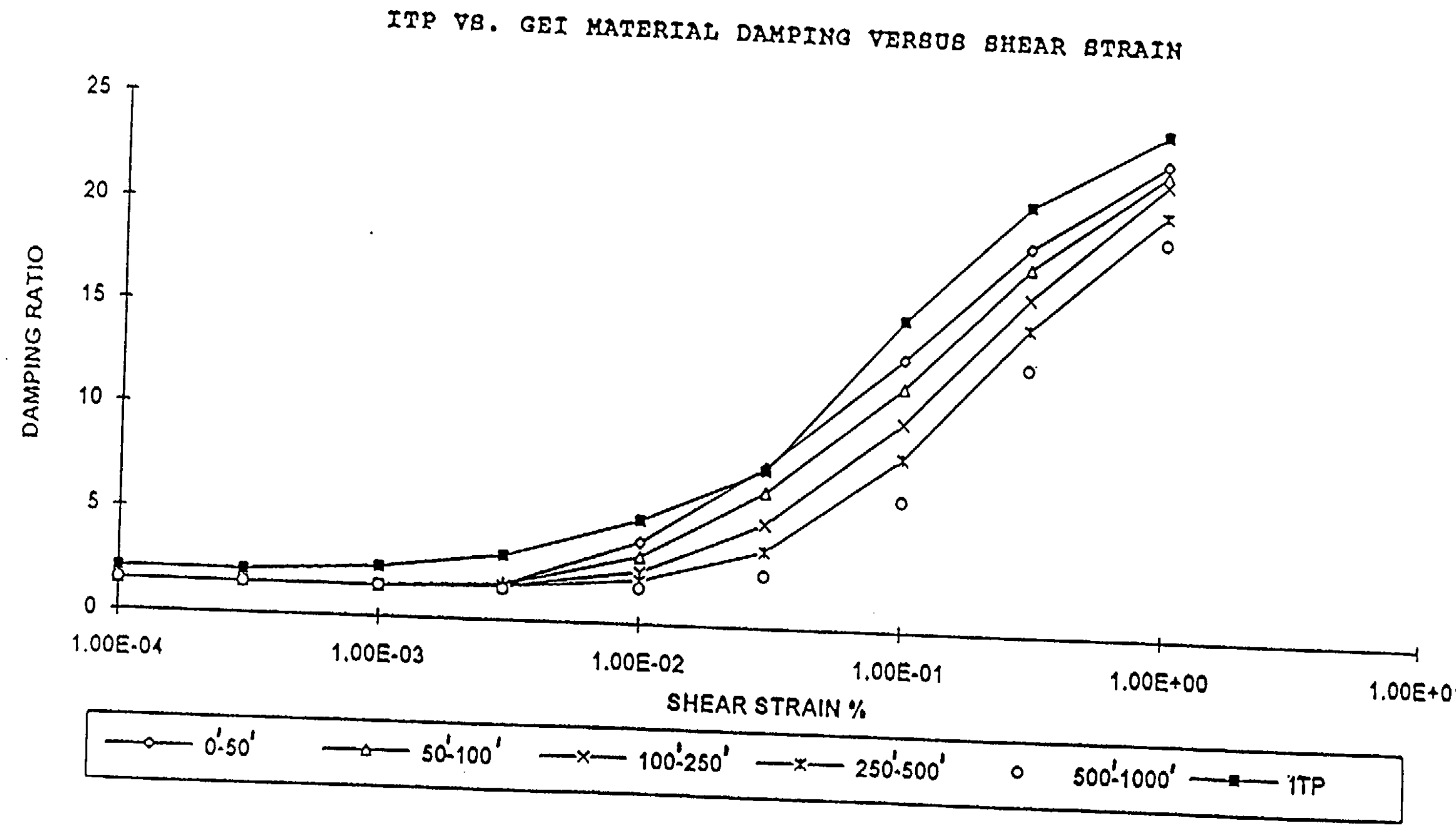

Figure 14. Damping curve measured for ITP/H-AREA (solid) in the upper 170' of non-fill soils. Also shown are GEI derived relationships for K-Reactor that illustrate the depth dependence.

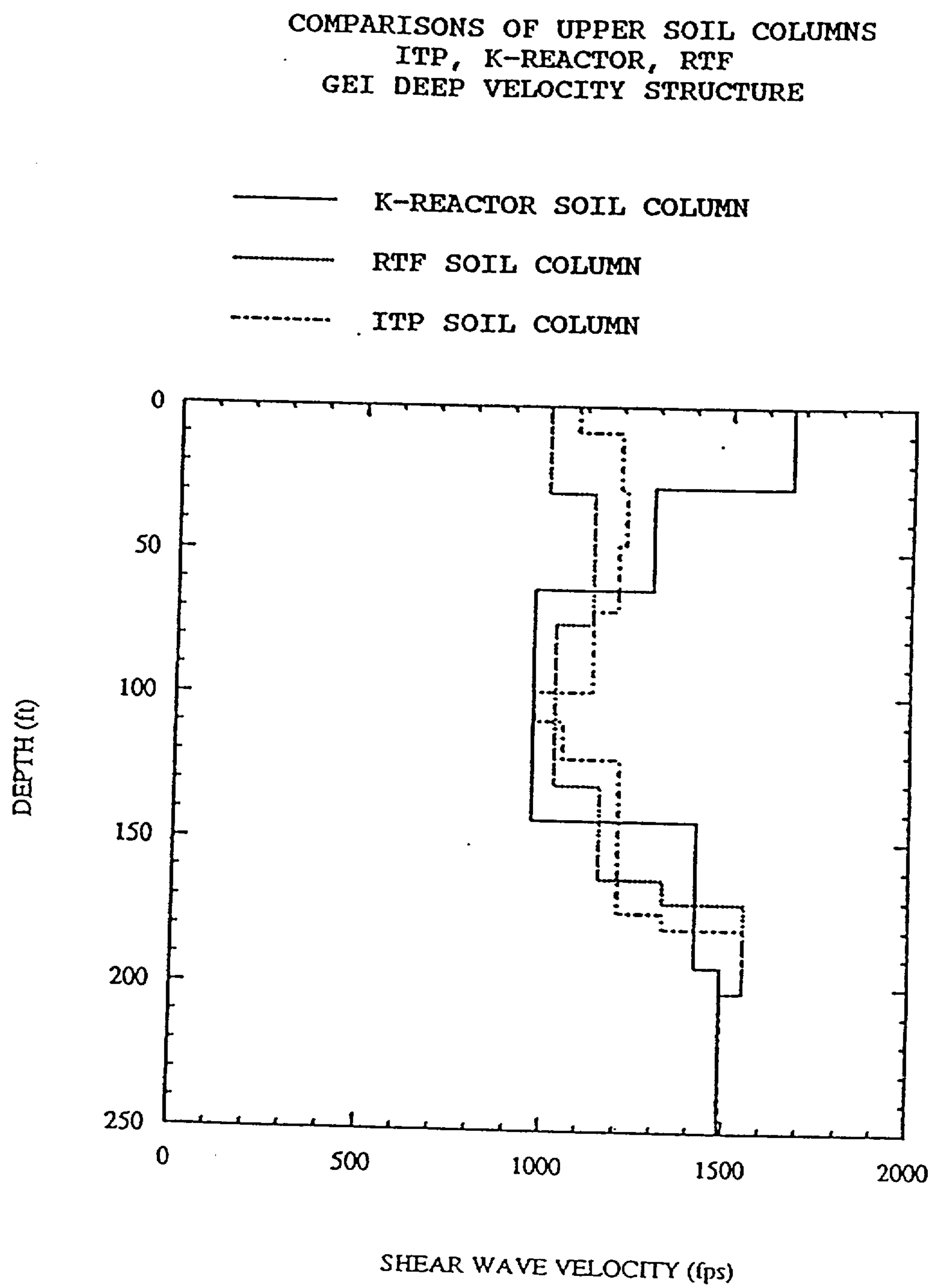

Figure 15. Statistical averages of shallow (0–250 ft) shear-wave velocity for the ITP/H-AREA, K-Reactor, and RTF.

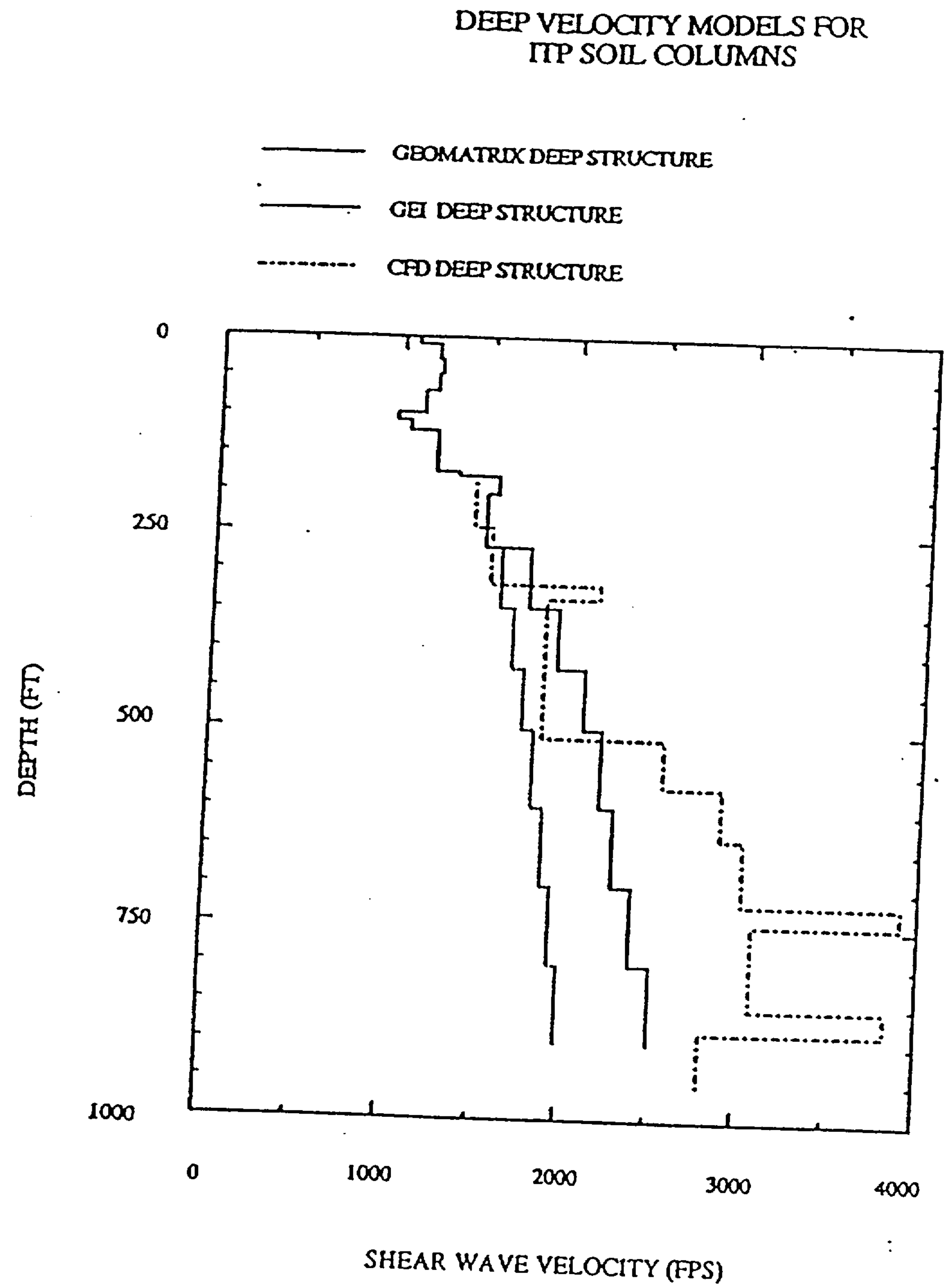

Figure 16. Shear-wave velocity vs. depth comparison. Deep soil velocity profiles used at ITP/H-AREA (using measured values from the Pen Branch Confirmatory Drilling Program) with assumed profiles used at K-Reactor (Geomatrix, GEI).

Savannah Riv Site Area Seismic Map

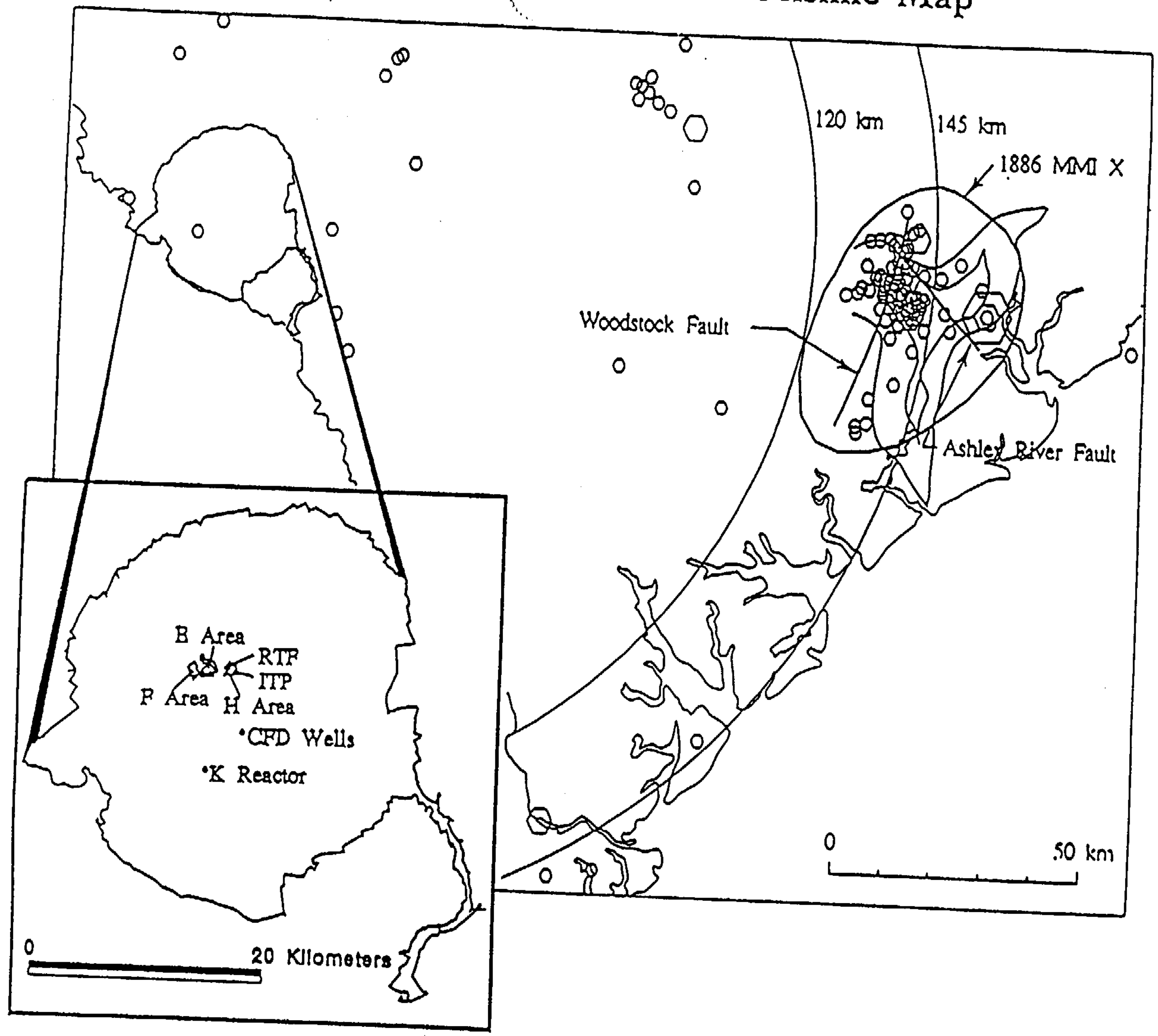

Figure 17. Charleston earthquake distances from SRS. Radii shown are measured from site center. Dark irregular lines are the isoseismals for the Charleston earthquake taken from Dutton (1890).

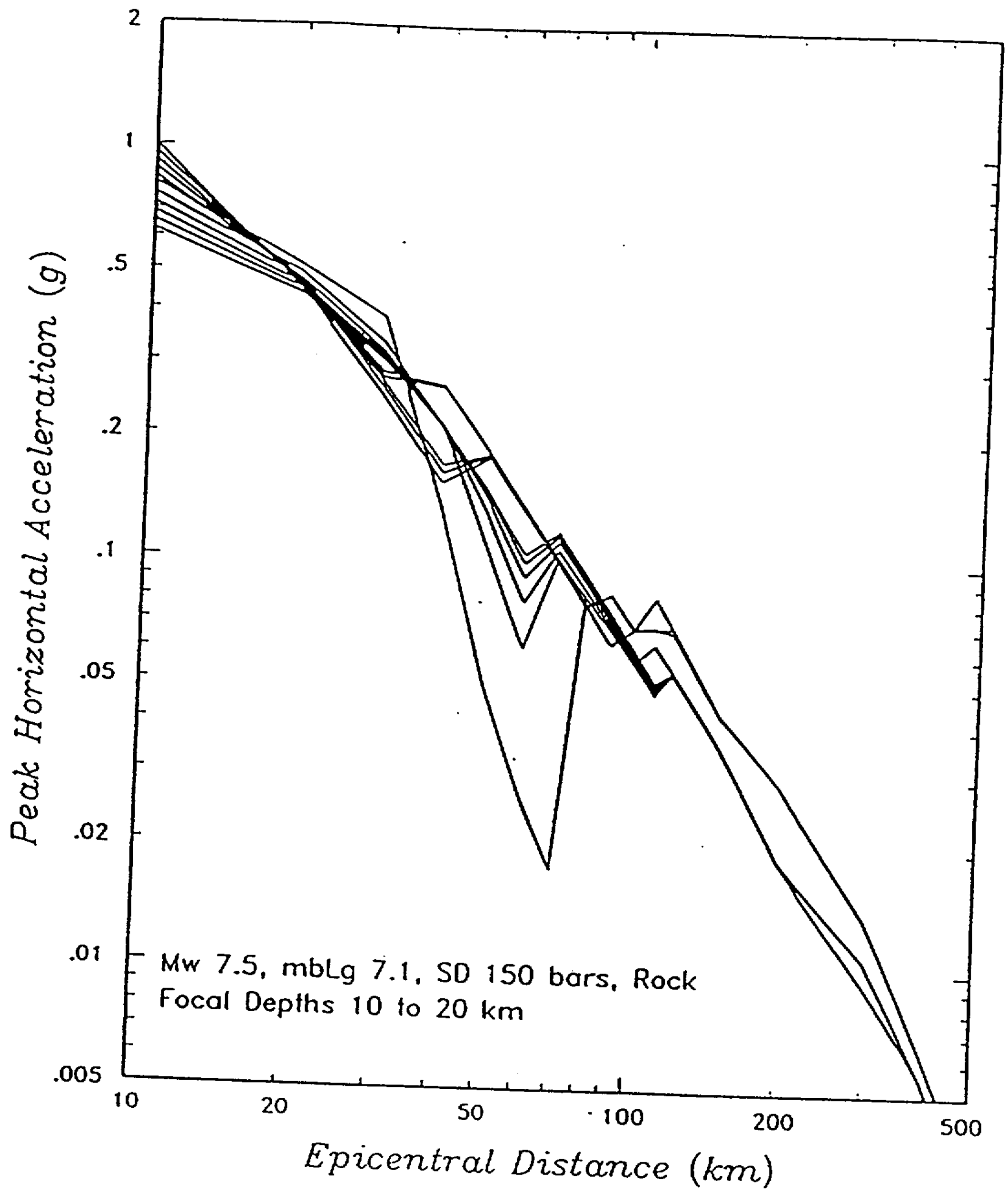

Figure 18. Geomatrix figure showing effect of focal depth on PGA estimate for Mw 7.5 Charleston earthquake. Results are shown for point source depths of 10–20 km.

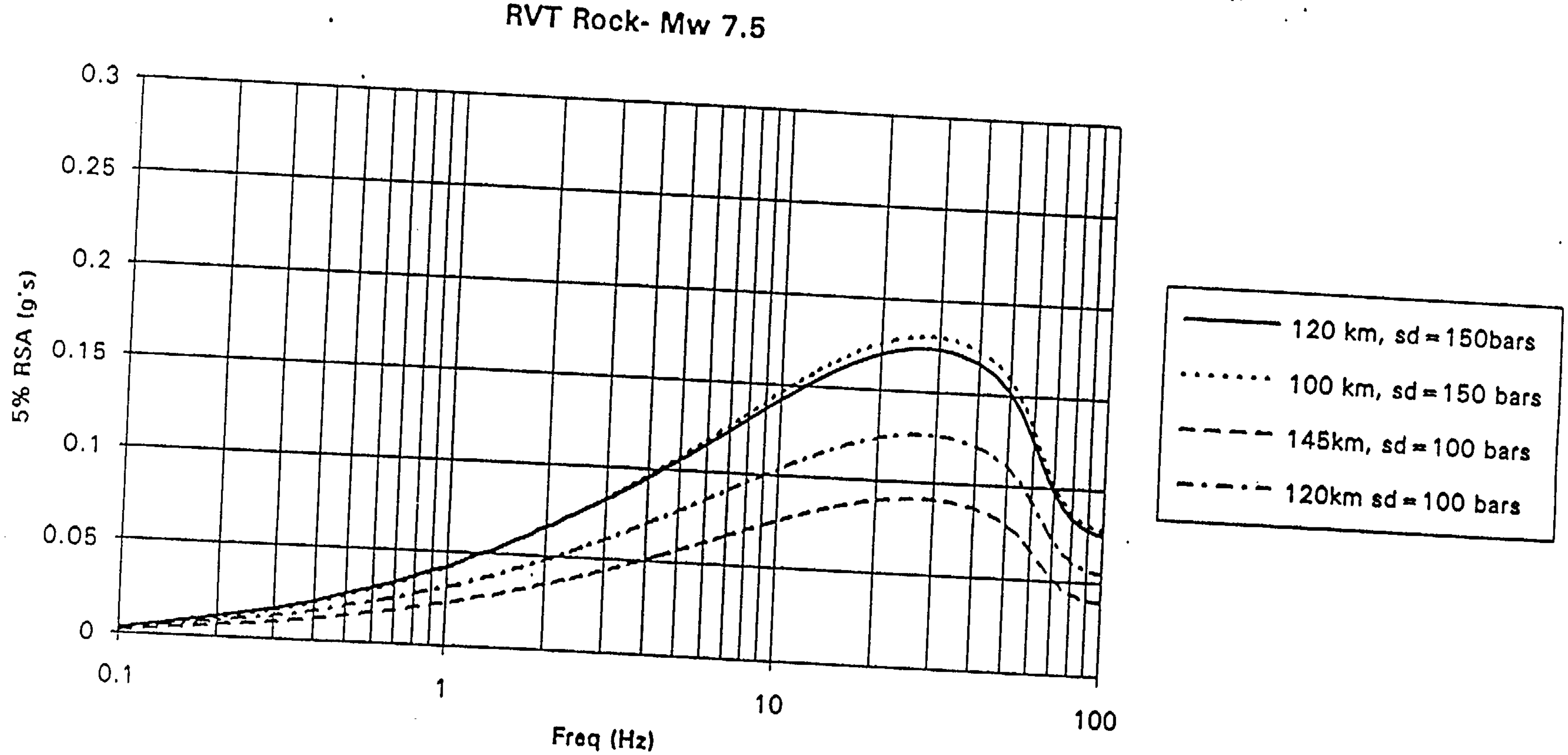

Figure 19. Sensitivity of SRS 5% damped rock spectra to Charleston source distance and stress-drop. Mw 7.5 source size with distances of 100-145 km and stress-drops of 100-150 bars.

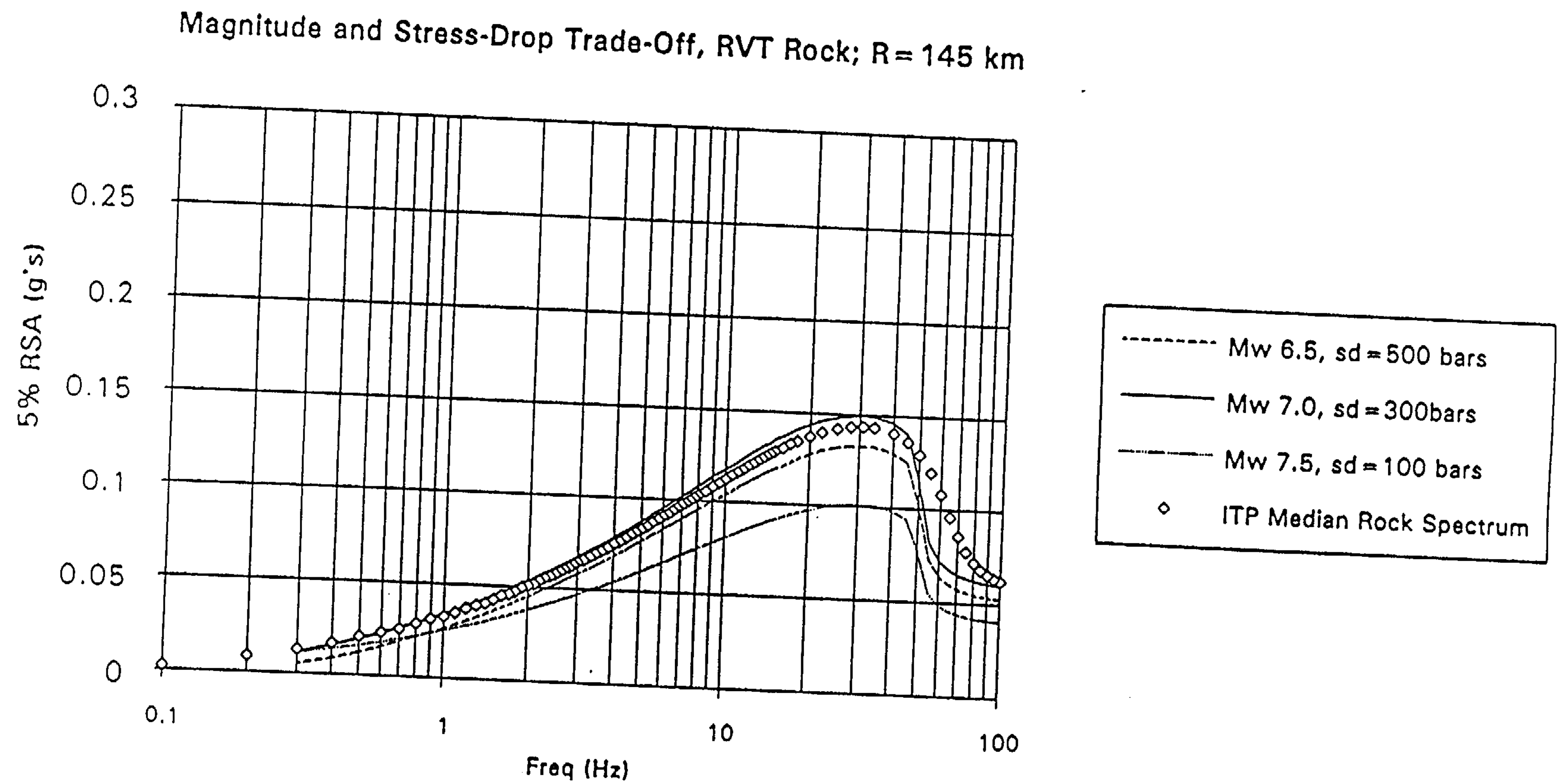

Figure 20. Comparison of rock 5% damped spectra for Mw and stress-drop tradeoff. Distance is 145 km; half-space assumed.

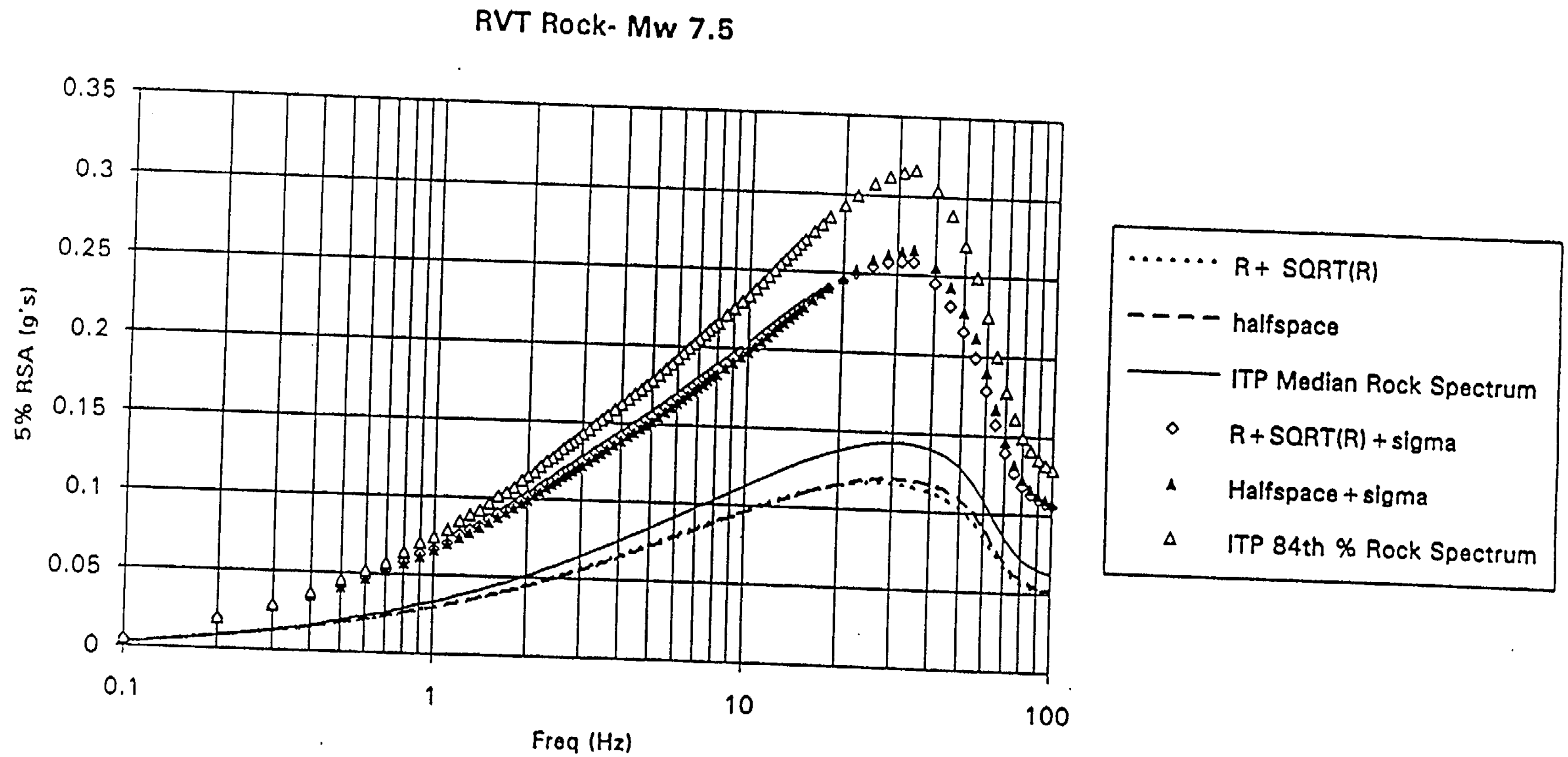

Figure 21. Comparison of median and 84th rock spectra for three attenuation models. Source is Mw 7.5, 150 bar at 120 km distant.

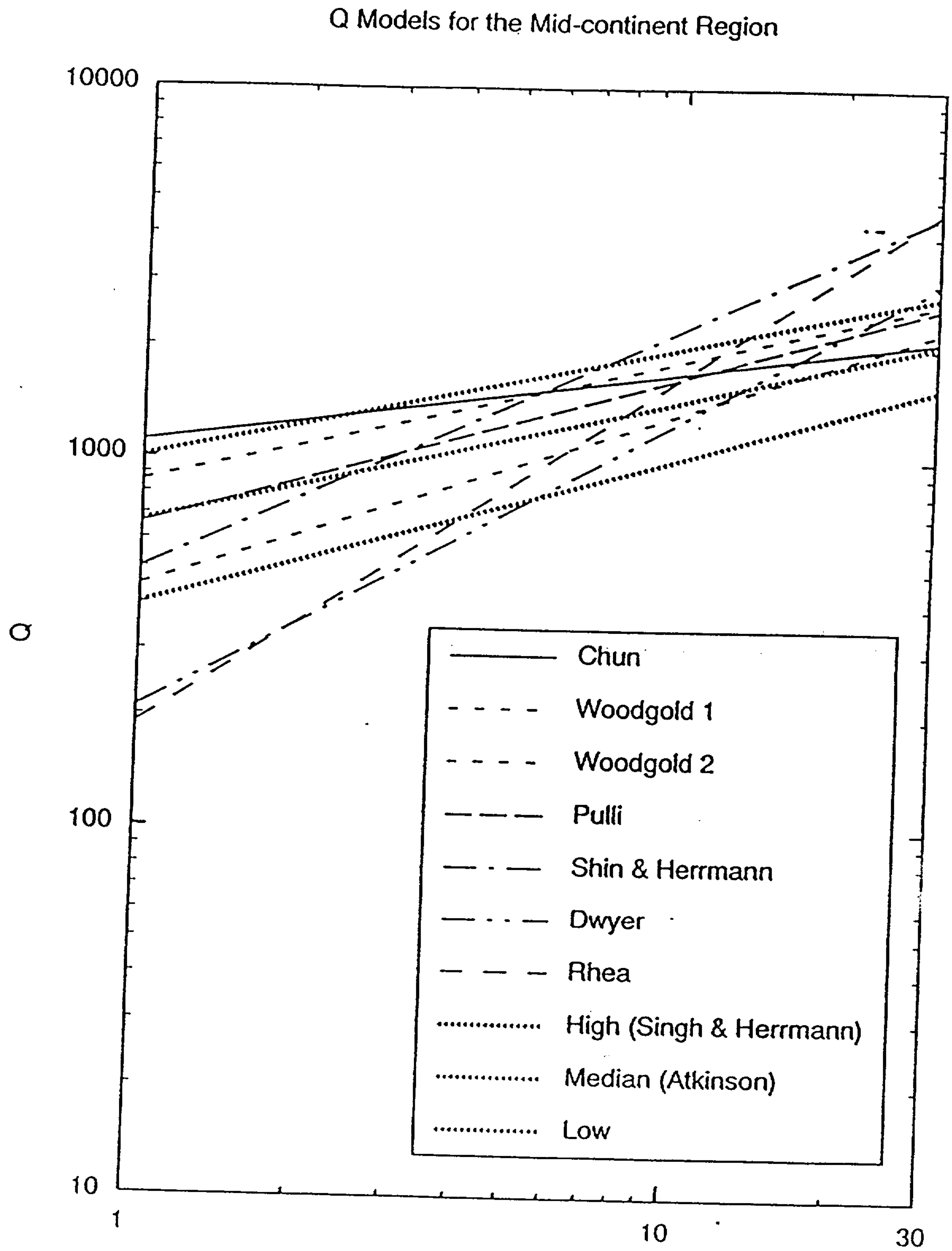

Figure 22. Comparison of Q models for mid-continent region that includes Rhea (1984). Figure was taken from EPRI (1993).

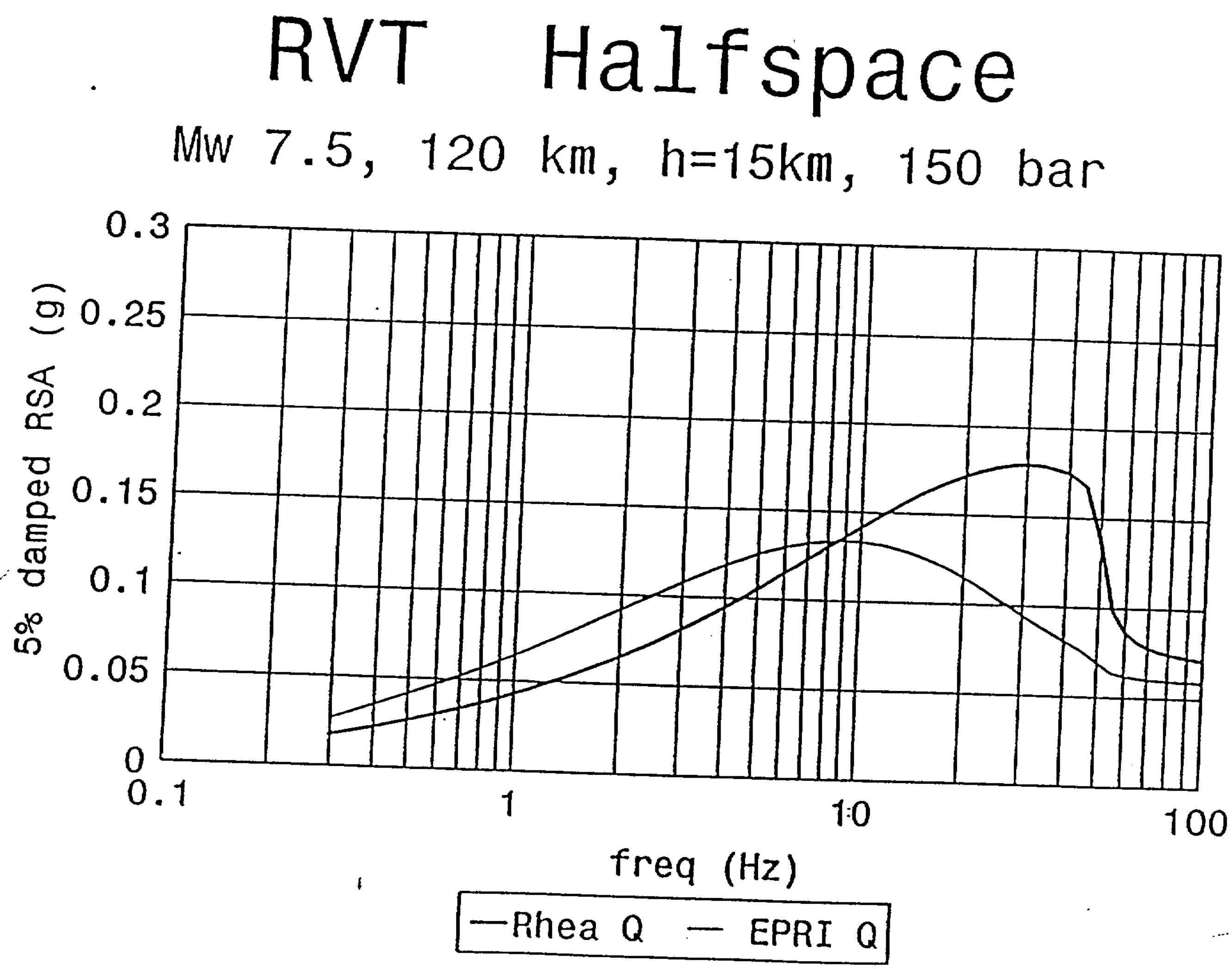

Figure 23. Comparison of rock response spectra for a Charleston-type earthquake (Mw 7.5, 150 bar stress-drop, 120 km distant) assuming Rhea (1984) and EPRI (1993) median Q.

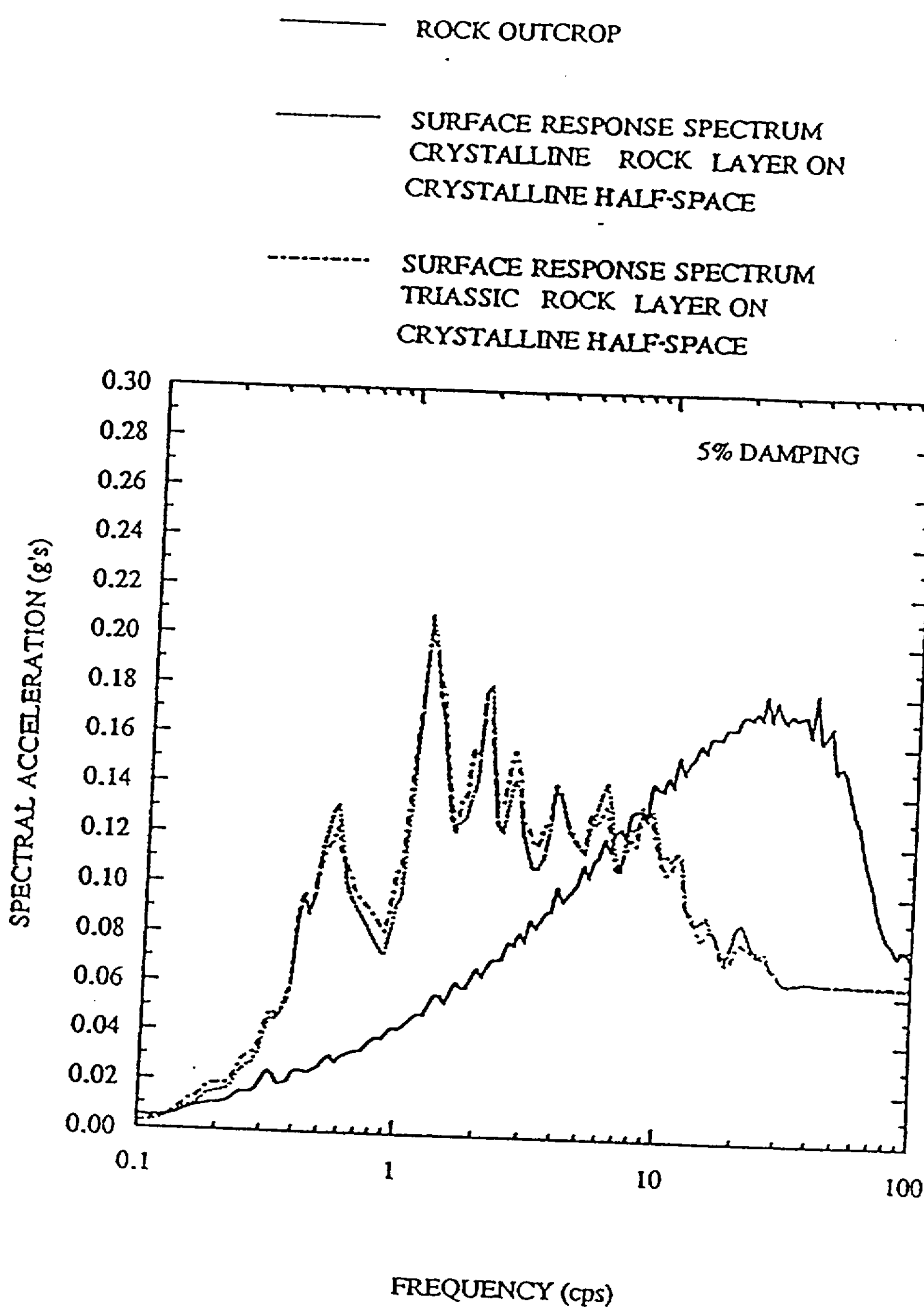

Figure 24. Calculated K- Reactor 5% damped spectra with and without the effects of the Triassic basin. Rock spectra used as input shown.

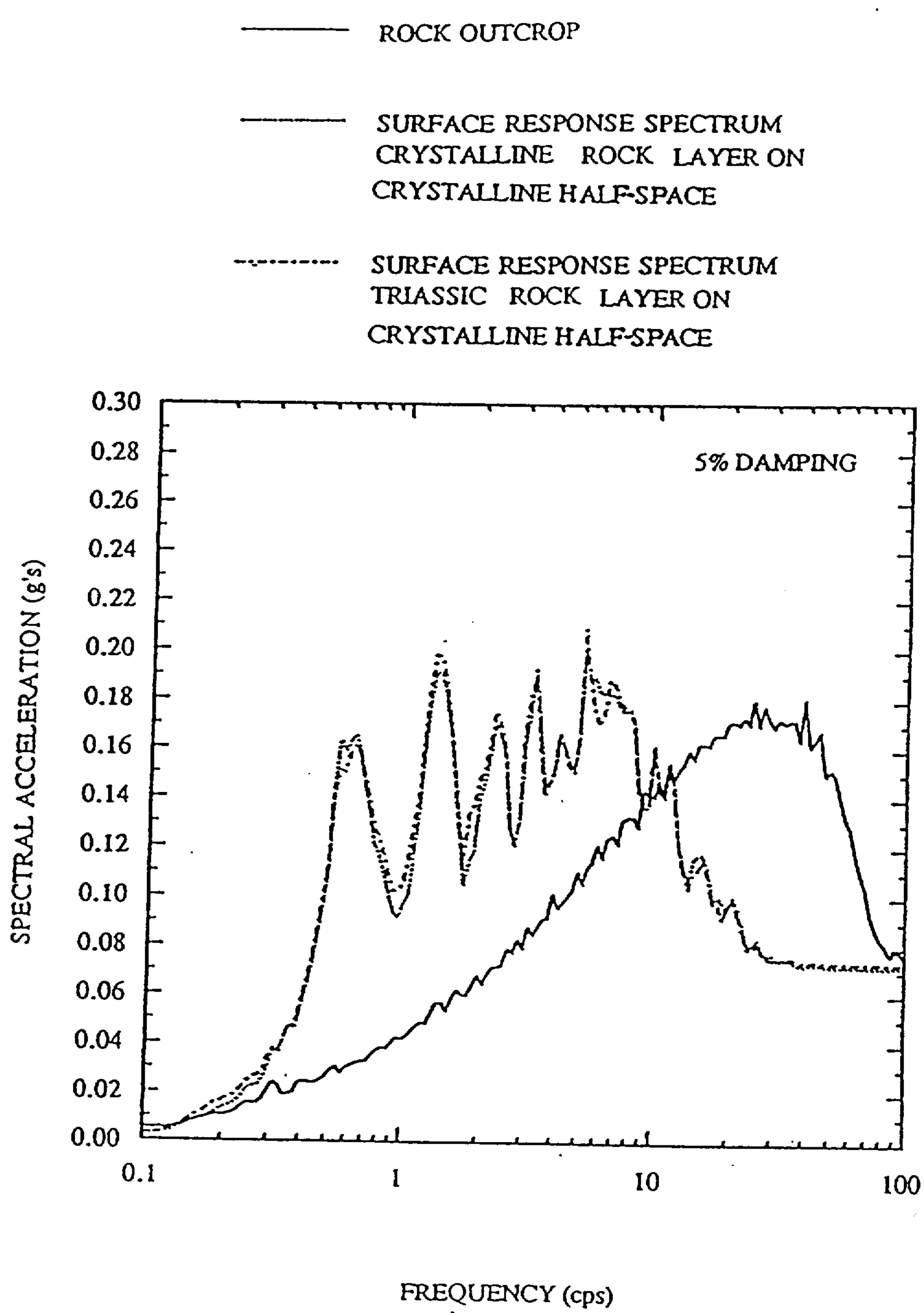

Figure 25. Calculated ITP/H-AREA 5% damped spectra with and without the effects of the Triassic basin. Rock spectra used as input shown.

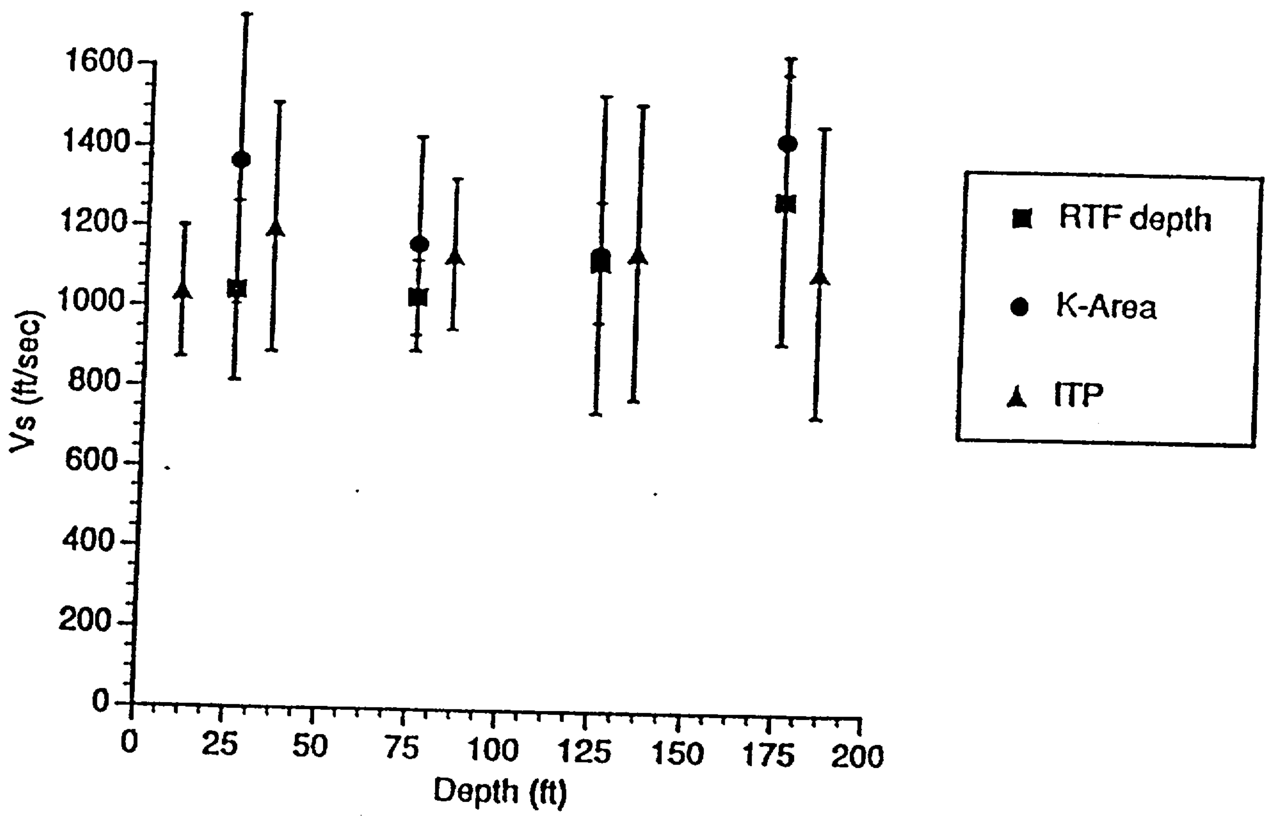

Figure 26. Comparison of mean shear-wave velocity soil profile for ITP/H-AREA, K-Reactor and RTF. Also shown are +- 1-sigma values.

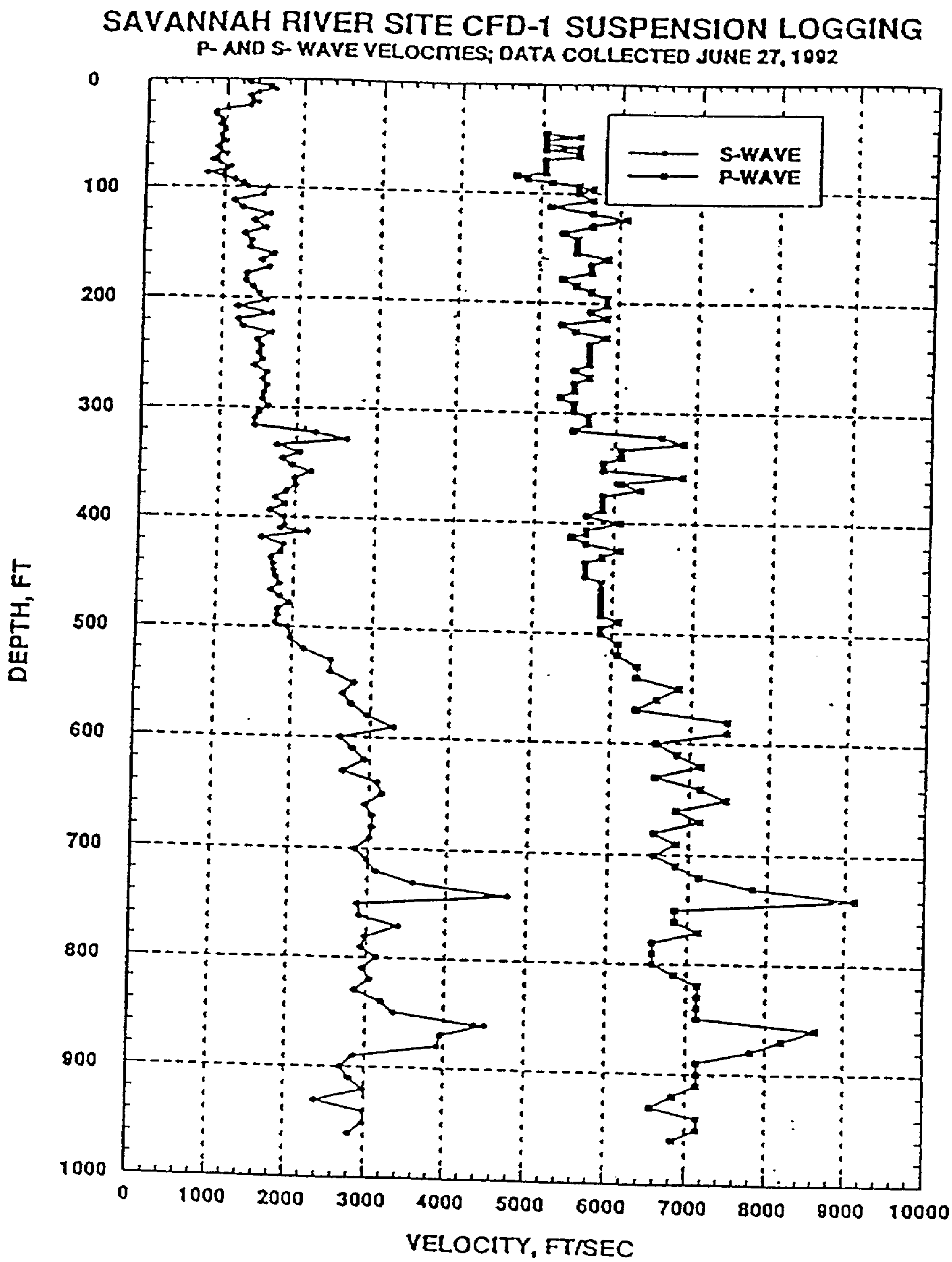

Figure 27. Oyo suspension P- and S-wave velocity logger results vs. depth. Measurements taken at the Pen Branch confirmatory drilling site (Agbabian 1992).

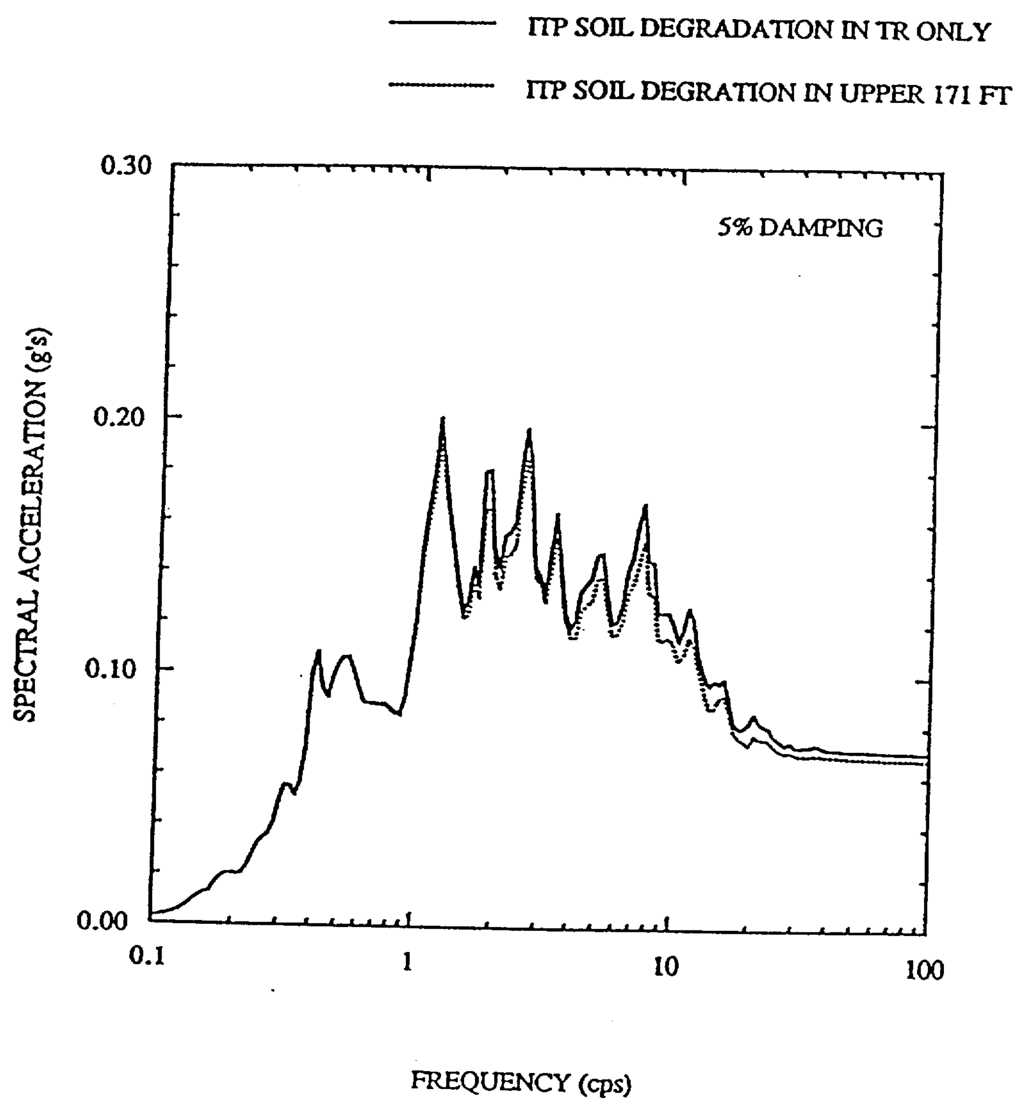

Figure 28. ITP/H-AREA 5% damped response spectra comparison of degradation models for the Tobacco Road or upper 170' of non-fill soils.

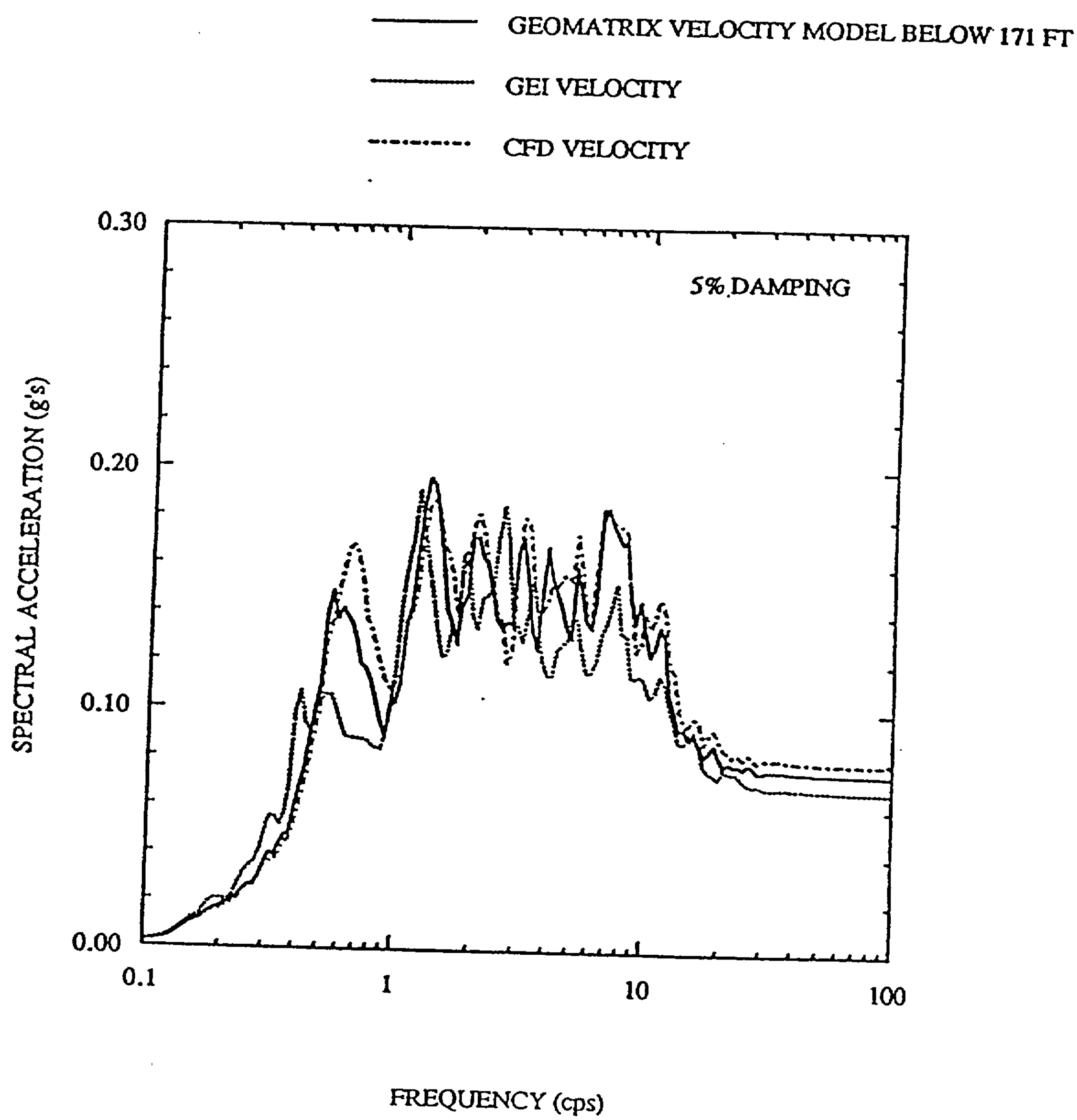

Figure 29. ITP/H-AREA response comparison with three different soil velocity profiles with identical bedrock input.

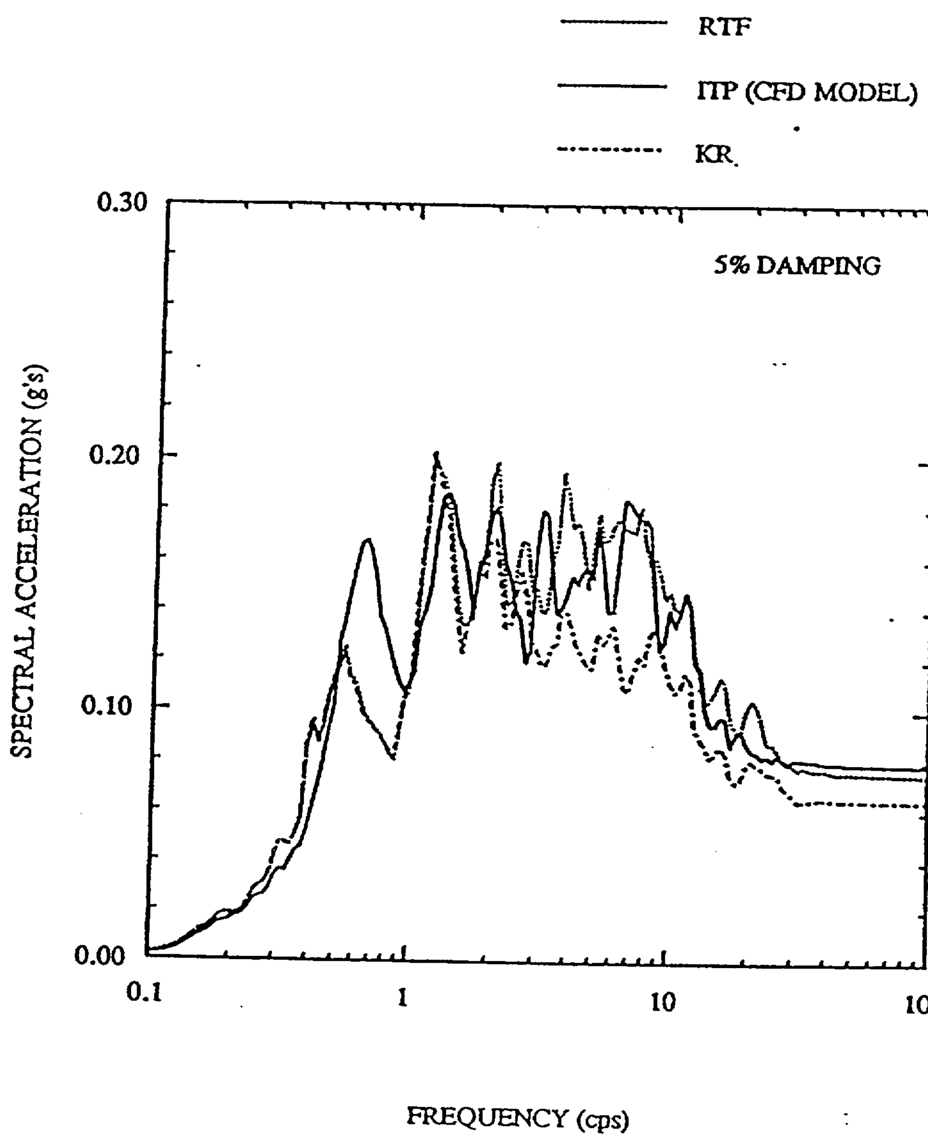

Figure 30. ITP/H-AREA response compared to K-Reactor and RTF using identical bedrock input.

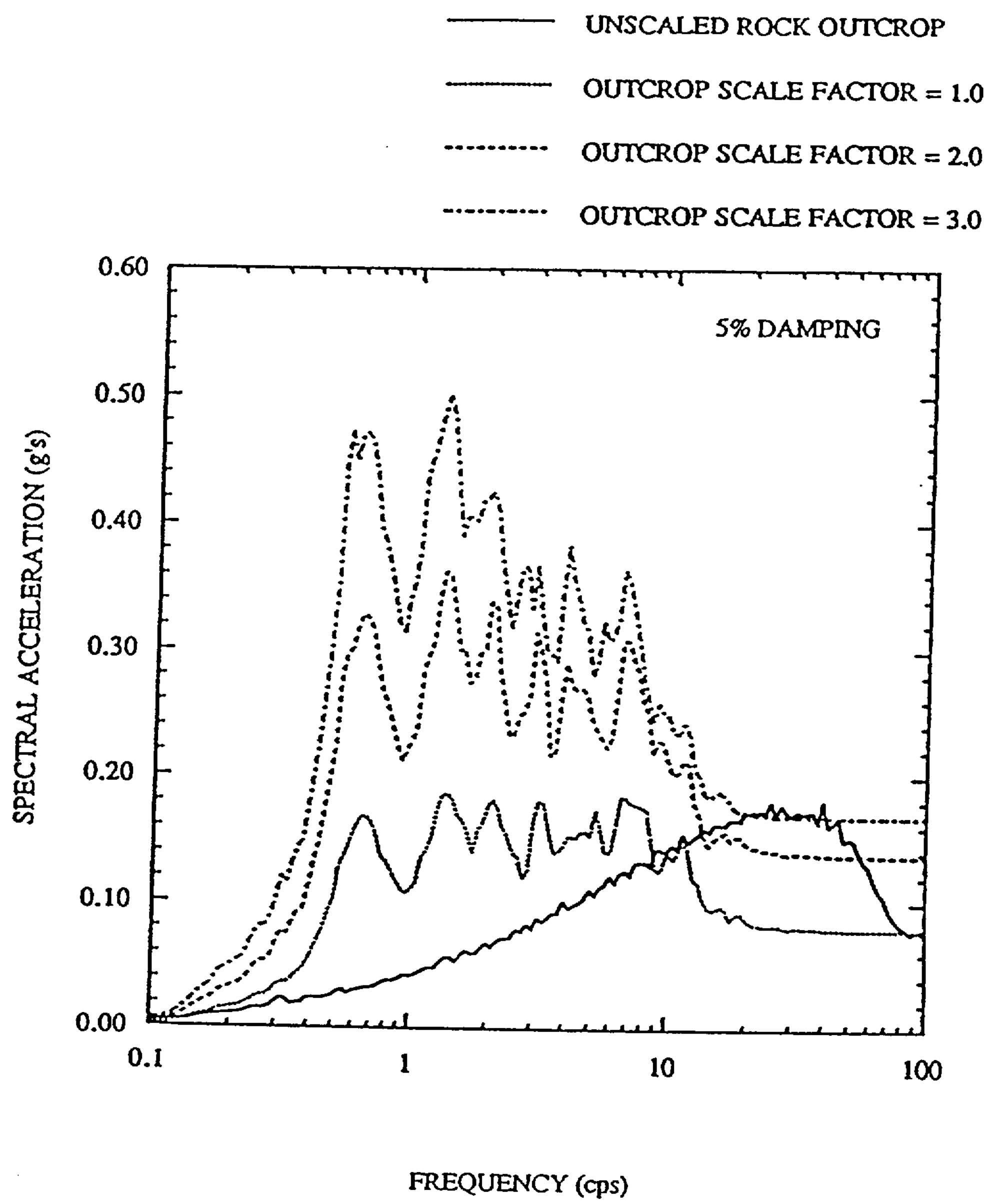

Figure 31. ITP/H-AREA comparison of scaled rock input effect on surface motion. Input motion is shown as solid and response with rock scale factor of 1.0, 2.0, and 3.0. Also shown is the unsealed rock input.

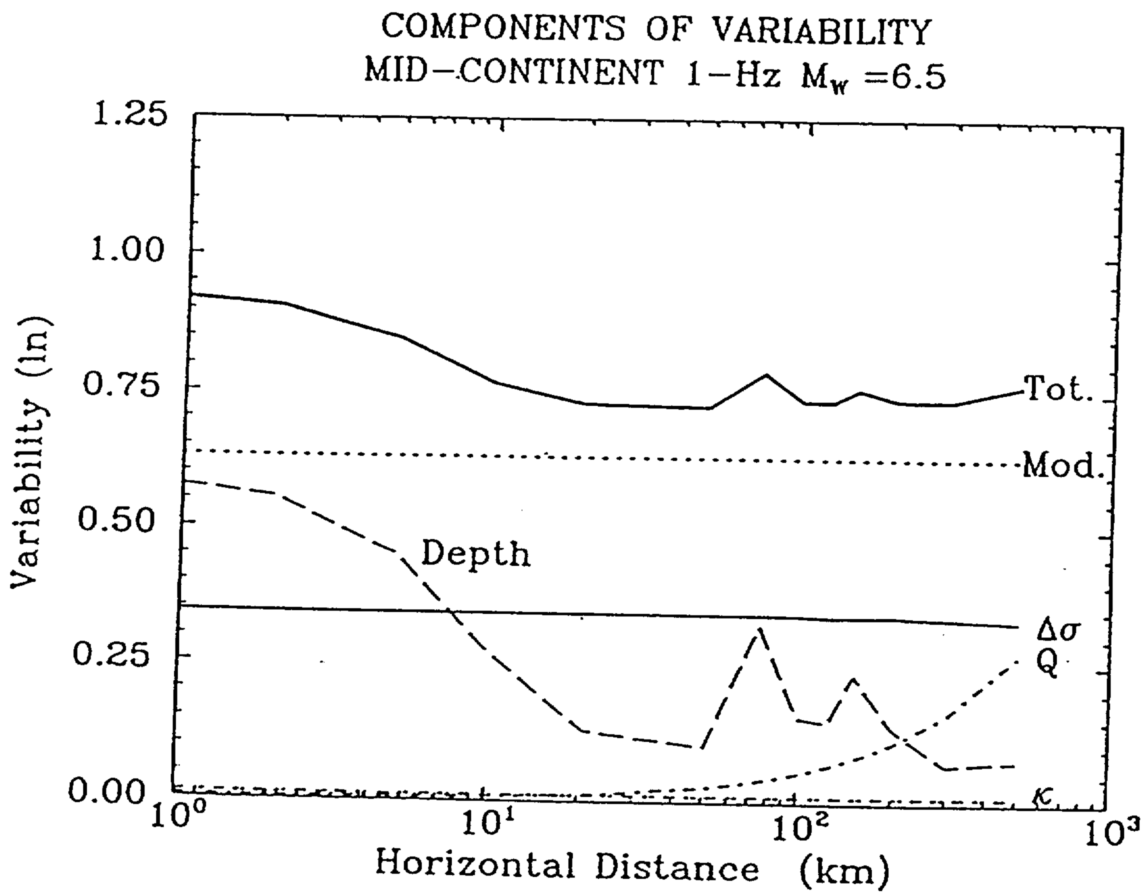

Figure 32. Composition of variability of estimated rock motions vs. epicentral distance for Mw 6.5 at 1-Hz (EPRI, 1993). Variability composed of modeling, hypocentral depth, stress-drop, kappa, and Q.

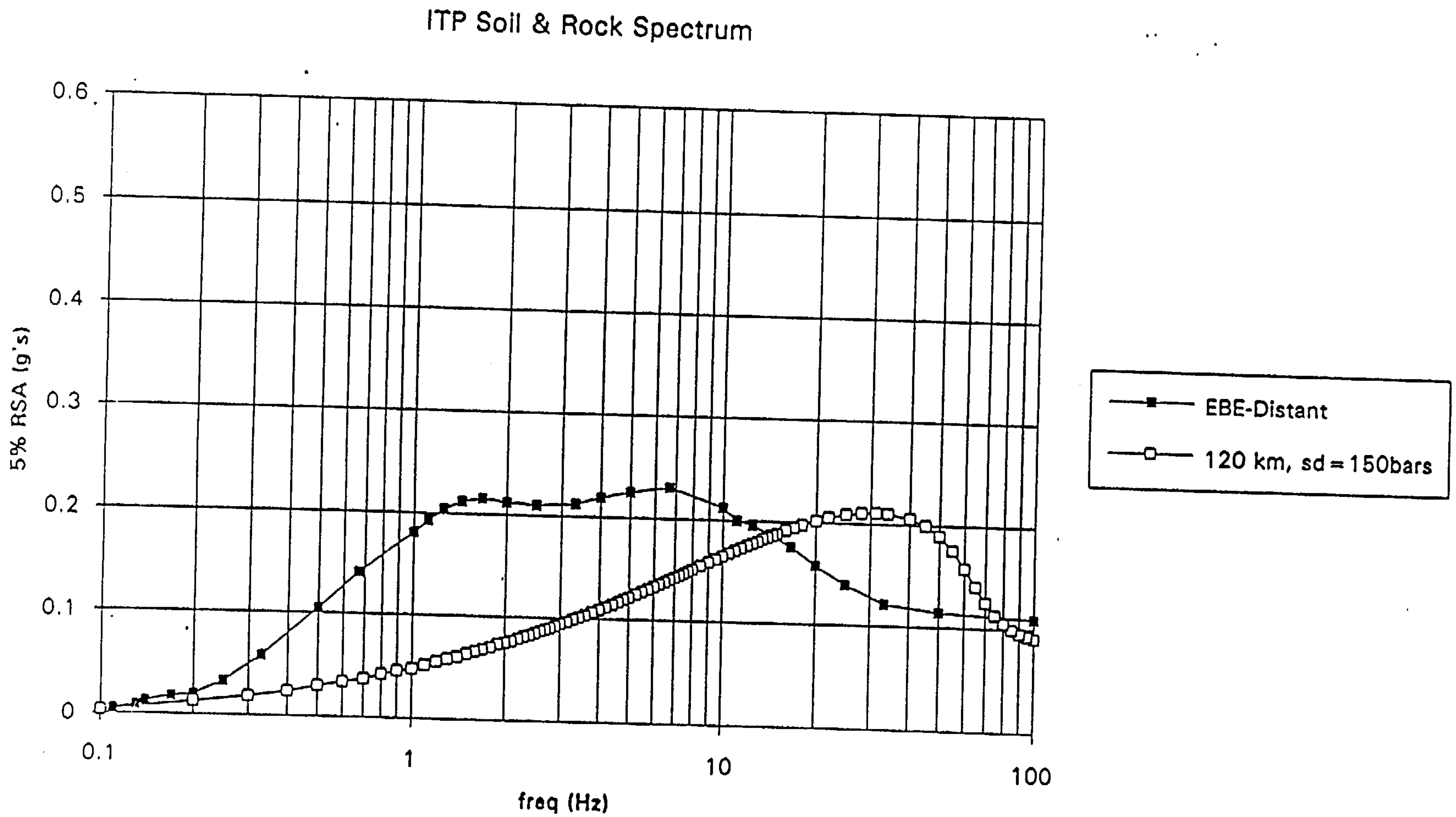

Figure 33. Comparison of rock spectra for Mw 7.5, stress drop 150 bar and 120 km distance, and the distant EBE soil spectrum for the ITP/H-AREA. This rock spectrum closely approximates the Geomatrix (1991) bedrock spectrum and is labeled the EBE rock spectrum.

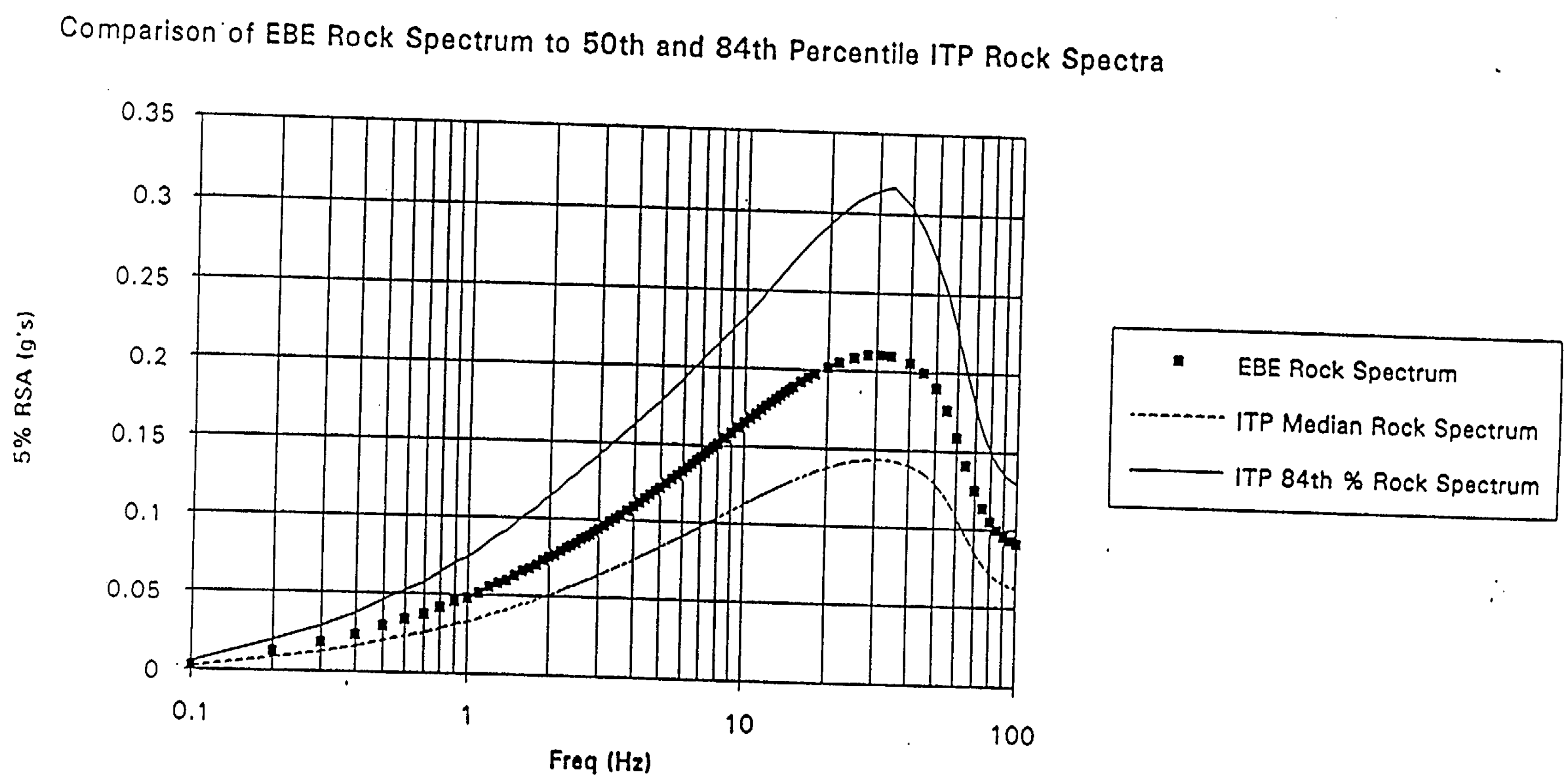

Figure 34. ITP/H-AREA median and 84th percentile rock spectra (Mw 7.5, 100 bar stress drop and 120 km distance). Also shown are the EBE rock system.

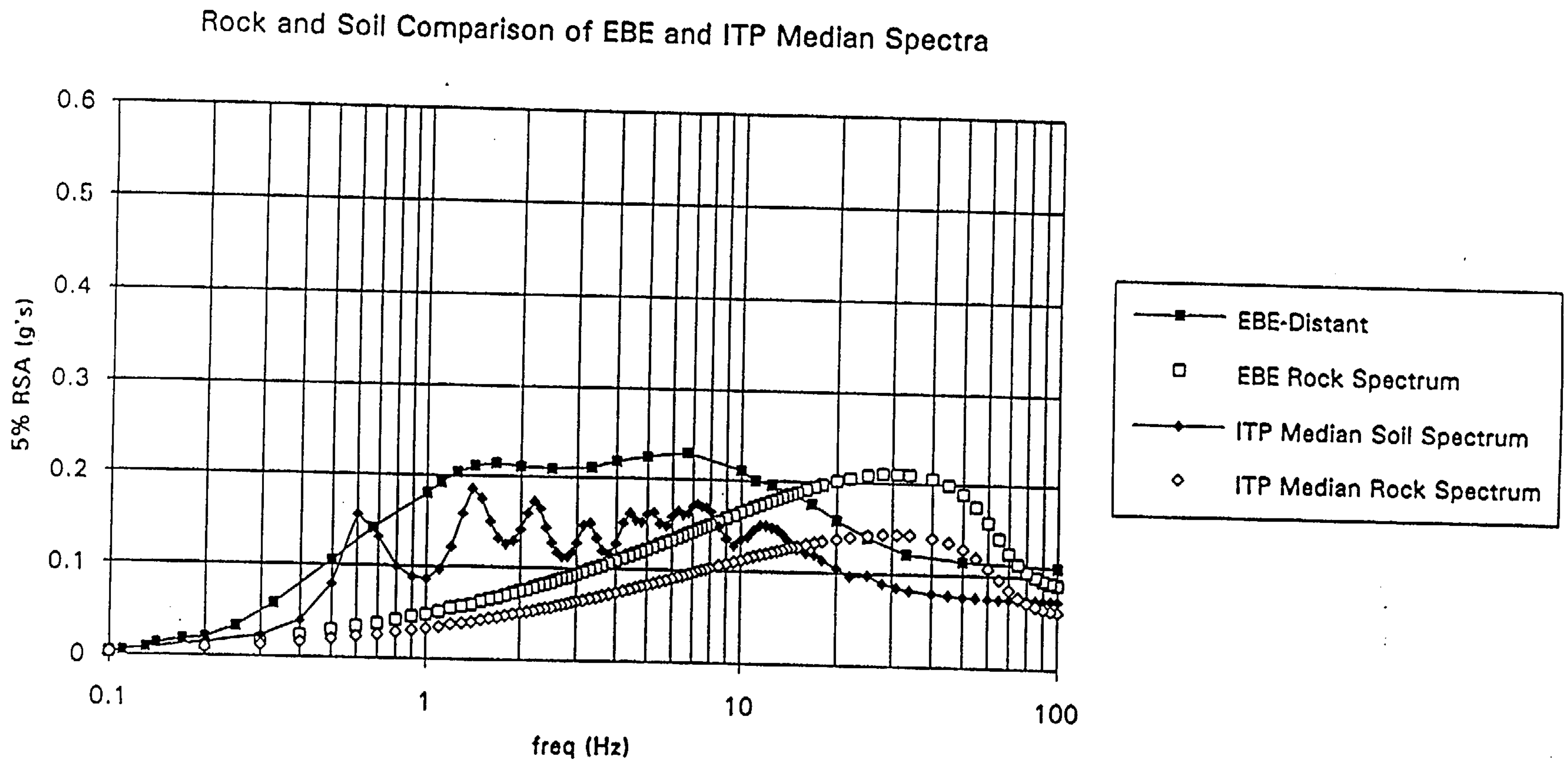

Figure 35. ITP/H-AREA surface spectra derived from median rock spectra. Shown with EBE distant soil spectra and corresponding rock spectra.

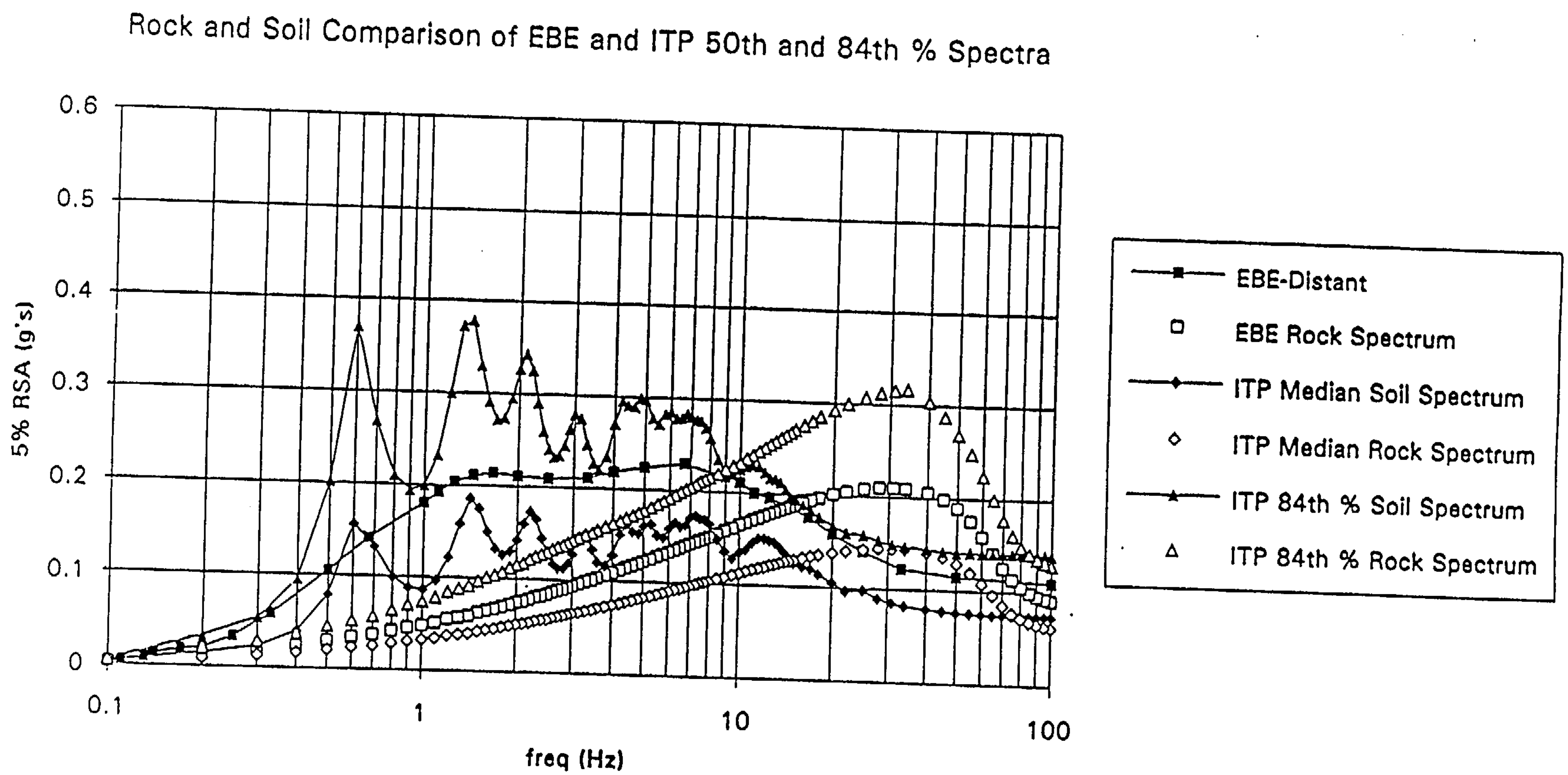

Figure 36. EBE and ITP/H-AREA surface spectra derived from median and 84th percentile rock spectra.

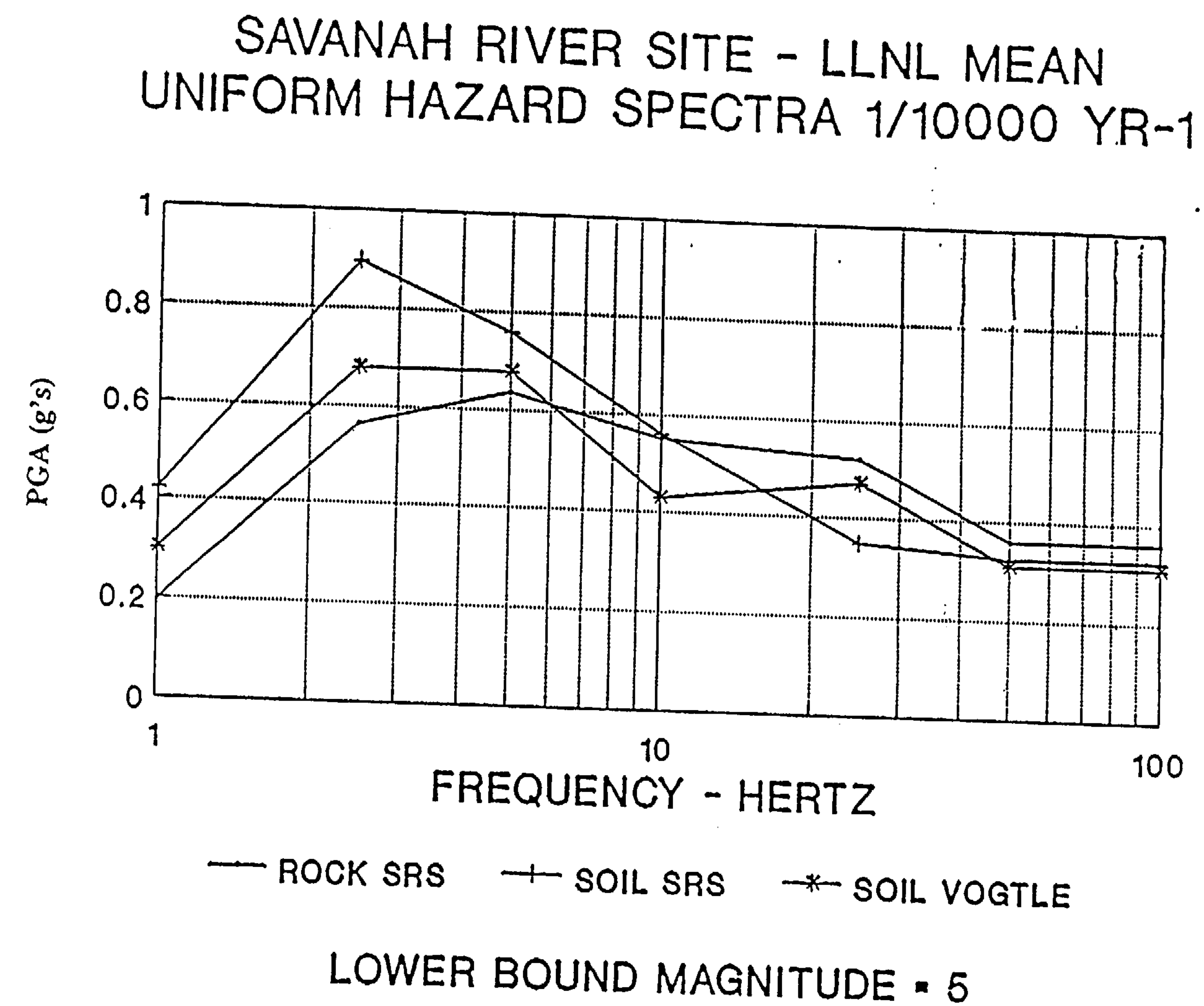

Figure 37. Comparison of LLNL UHS for rock and soil at SRS, and generic soil at Plant Vogtle.

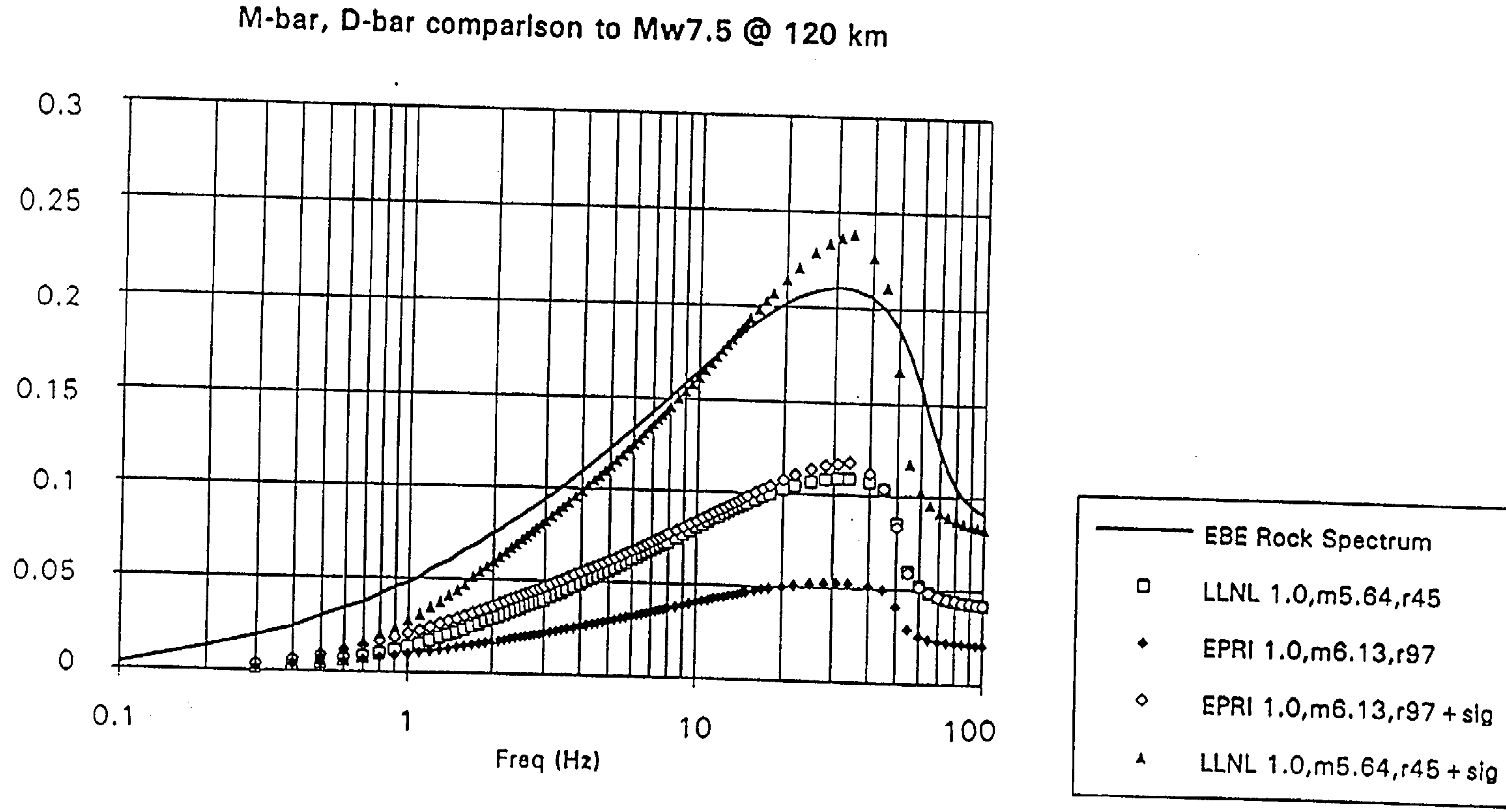

Figure 38. Computed rock median and 84th spectra using 1.0 Hz m-bar and d-bar estimates from EPRI and LLNL. Magnitudes in legend are moment magnitudes (Tables 8 and 9 use body-wave magnitudes).

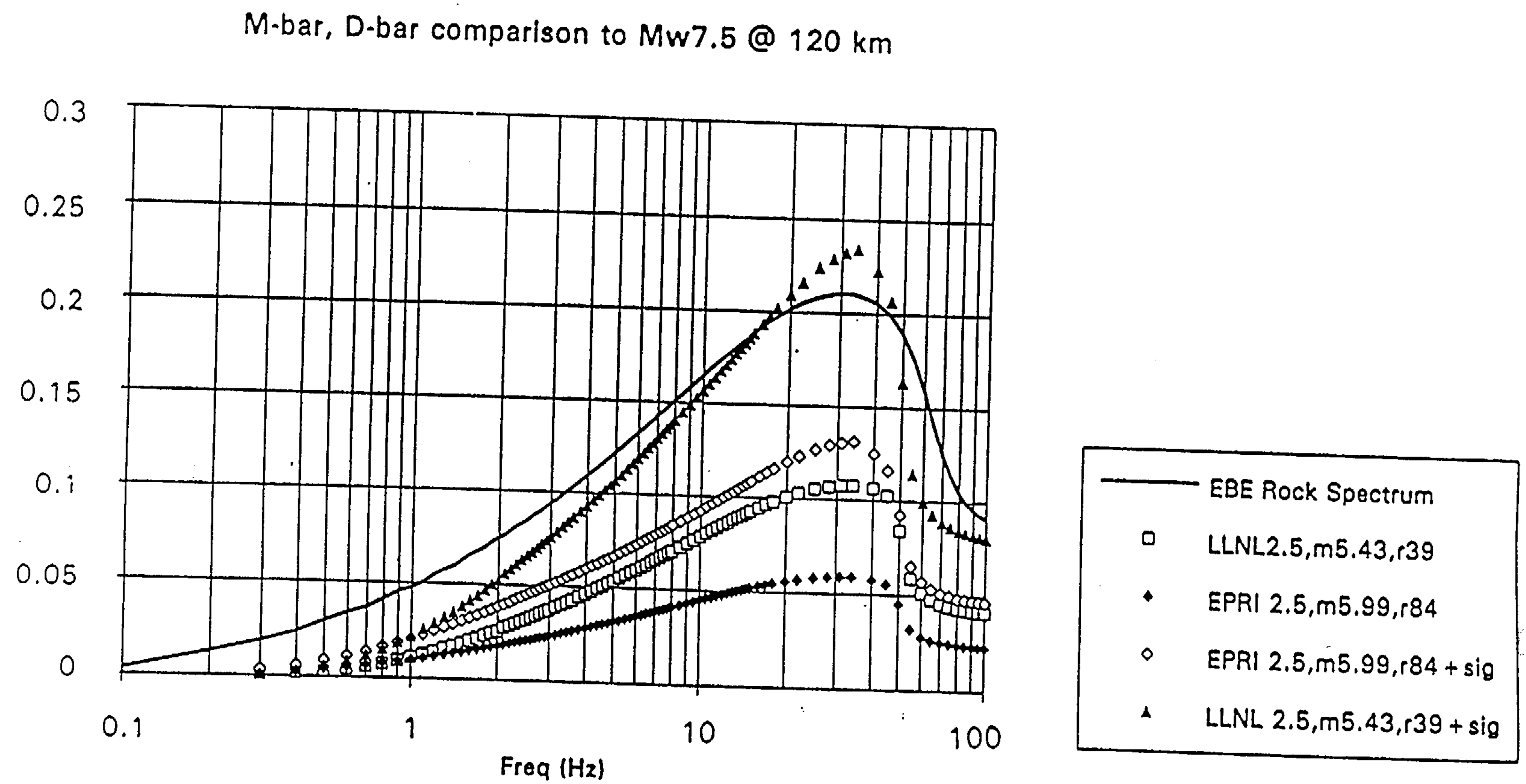

Figure 39. Computed rock median and 84th spectra using 2.5 Hz m-bar and d-bar estimates from EPRI and LLNL. Magnitudes in legend are moment magnitudes (Tables 8 and 9 use body-wave magnitudes).

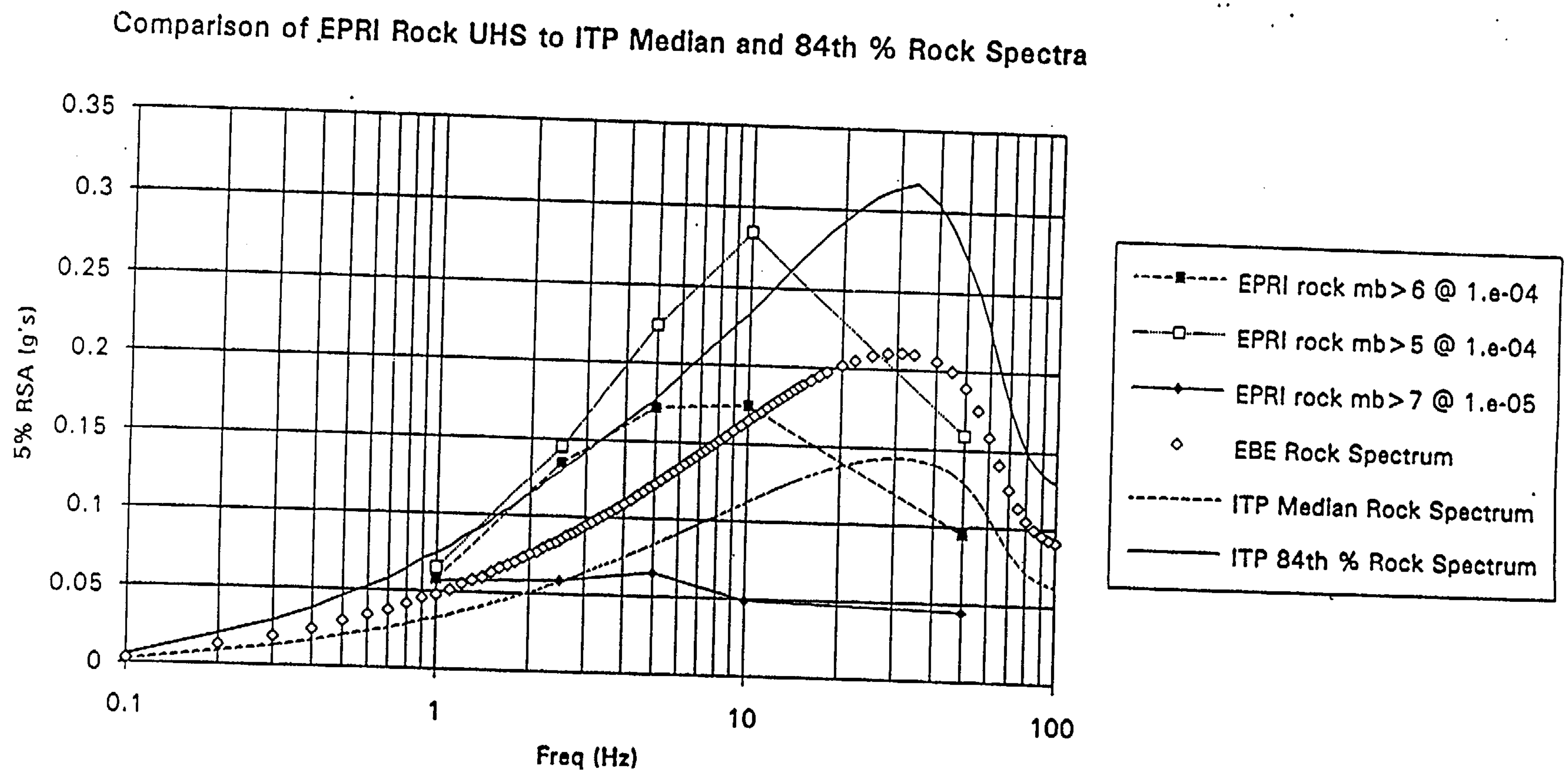

Figure 40. Comparison of EPRI mean rock UHS @ 1×10^{-4} (for magnitudes mb > 5,6) to ITP/H-AREA median and 84th percentile deterministic rock spectra. Also shown the EBE rock spectrum. UHS at 1×10^{-5} annual probability of exceedance for mb > 7.

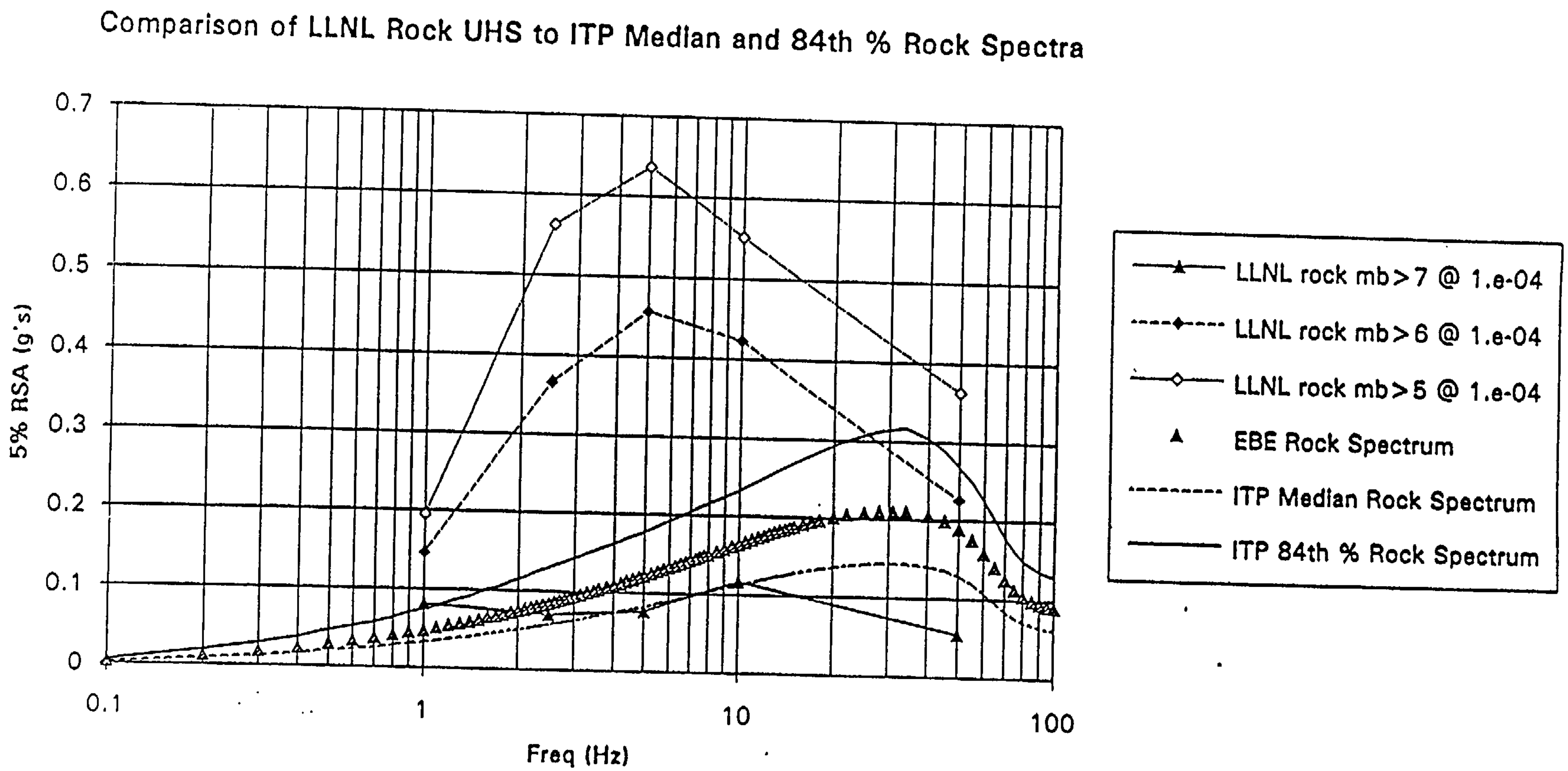

Figure 41. Comparison of LLNL mean rock UHS @ 1×10^{-4} to ITP/H-AREA rock median and 84th percentile deterministic spectra. Also shown is the EBE rock spectrum.

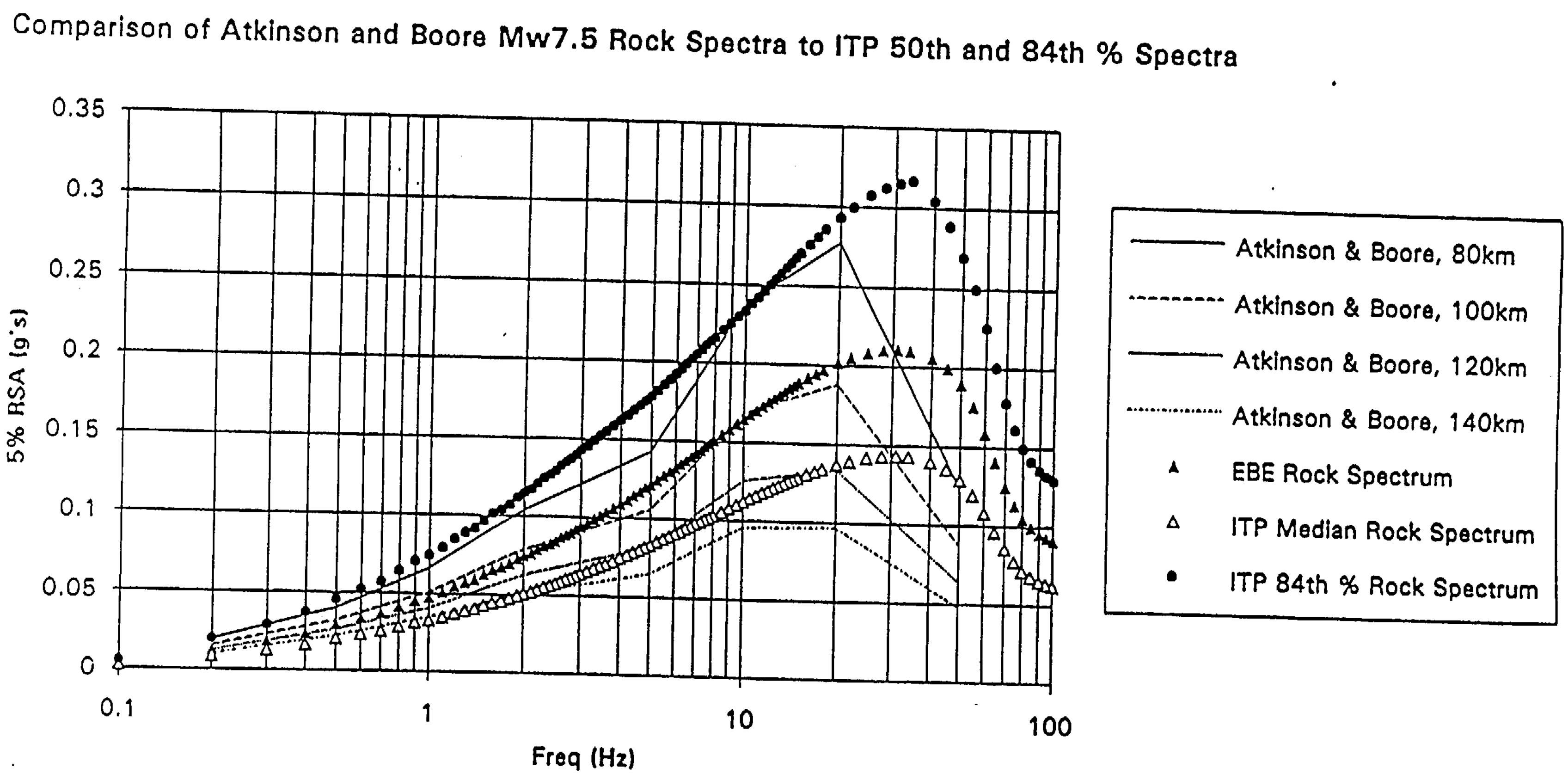

Figure 42. Comparison of ITP/H-AREA rock spectra to Atkinson and Boore (1990) 5% rock spectra prediction for Mw 7.5 at distances ranging from 80 to 140 km.

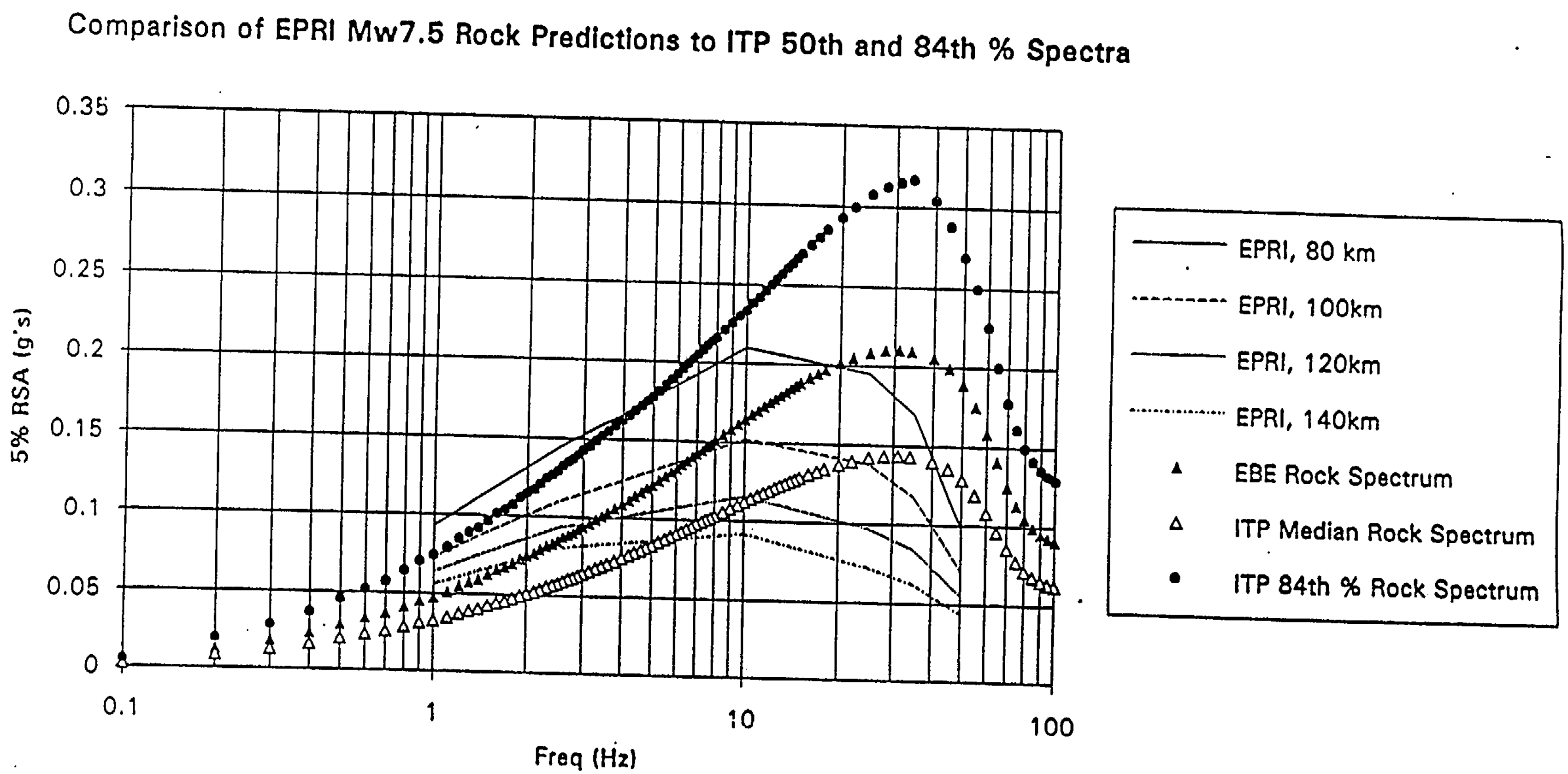

Figure 43. Comparison of ITP/H-AREA rock spectra to EPRI (1993) 5% rock spectra prediction for Mw 7.5 at distances ranging from 80 to 140 km.