UNION ELECTRIC COMPANY
1901 GRATIOT STREET
ST. LOUIS, MISSOURI

JOHN K. BRYAN
VICE PRESIDENT

MAILING ADDRESS:
P. O. BOX 149
ST. LOUIS, MISSOURI 63166

August 14, 1981

Mr. Harold R. Denton
Director of Nuclear Reactor Regulation
U. S. Nuclear Regulatory Commission
Washington, D.C. 20555

ULNRC-480

Dear Mr. Denton:

DOCKET NUMBERS 50-483 AND 50-486
CALLAWAY PLANT, UNITS 1 & 2
FINAL SAFETY ANALYSIS REPORT

Attached is the seismic update information requested by Mr. Rothman of your office by telephone. This information will be formally incorporated into the Callaway Plant's FSAR in the next revision. This information is hereby incorporated into the Callaway application.

Very truly yours,

John K. Bryan

John K. Bryan

BFH/mdj
Enclosure

B001
S
5/5
LIMITED
DISTRIBUTION

STATE OF MISSOURI)
) S S
CITY OF ST. LOUIS)

John K. Bryan, of lawful age, being first duly sworn upon oath says that he is Vice President-Nuclear and an officer of Union Electric Company; that he has read the foregoing document and knows the content thereof; that he has executed the same for and on behalf of said company with full power and authority to do so; and that the facts therein stated are true and correct to the best of his knowledge, information and belief.

By John K. Bryan
John K. Bryan
Vice President
Nuclear

SUBSCRIBED and sworn to before me this 14th day of August, 1981

Barbara J. Pfaff
BARBARA J. PFAFF
NOTARY PUBLIC, STATE OF MISSOURI
MY COMMISSION EXPIRES APRIL 22, 1985
ST. LOUIS COUNTY

cc: Glenn L. Koester
Vice President
Operations
Kansas Gas & Electric
P.O. Box 208
Wichita, Kansas 67201

John E. Arthur
Chief Engineer
Rochester Gas & Electric Company
89 East Avenue
Rochester, New York 14649

A. V. Dienhart
Vice President
Plant Engineering and Construction
Northern States Power
414 Nicollet Mall
Minneapolis, Minnesota 55401

Donald T. McPhee
Vice President
Kansas City Power and Light Company
1330 Baltimore Avenue
Kansas City, Missouri 64141

Gerald Charnoff, Esq.
Shaw, Pittman, Potts & Trowbridge
1800 M. Street, N.W.
Washington, D.C. 20036

Nicholas A. Petrick
Executive Director
SNUPPS
5 Choke Cherry Road
Rockville, Maryland 20850

W. Hansen
Callaway Resident Office
U.S. Nuclear Regulatory Commission
RR#1
Steedman, Missouri 65077

2.5.2 VIBRATORY GROUND MOTION

The vibratory ground motions at the site in central Missouri, for which aseismic design criteria have been established, are based upon the postulated recurrence of the maximum historic earthquakes occurring in several defined seismotectonic regions. The earthquakes affecting the site and governing aseismic design are identified as:

a. A Modified Mercalli Intensity (MMI) XI-XII event (Table 2.5-6) occurring anywhere within the New Madrid Seismotectonic Region located in extreme southeastern Missouri and portions of the adjacent states. The closest approach of the boundary of this source region is 175 miles southeast of the site.

b. An MMI VII event occurring anywhere within the Chester-Dupo or the Ste. Genevieve Seismotectonic regions located in eastern Missouri. The closest approach of these regions lies 70 miles to the east-southeast of the site.

c. An MMI V event occurring within the Missouri Random Region near the site.

The design event superseding all other considerations is taken as a recurrence of the New Madrid event 175 miles from the site. In order to provide an appropriate degree of conservatism, the Safe Shutdown Earthquake (SSE) is defined as a horizontal ground acceleration at foundation level of 0.20g. This is equivalent to an intensity approaching MMI VIII (Modified Mercalli Intensity - see Table 2.5-6) at foundation level. The operating Basis Earthquake (OBE) is a recurrence of the New Madrid earthquake at its historic epicenter. Consistent with the conservatism developed for the Safe Shutdown Earthquake, the maximum horizontal acceleration for the OBE will be 0.12g. These levels are used to anchor the appropriate design response spectra.

2.5.2.1 Seismicity

A list of historical earthquakes with epicenters located within a distance of about 200 miles from the site is presented in Table 2.5-7. This list presents all reported earthquakes within 50 miles of the site, and significant shocks having MMI V or greater within 200 miles of the site. The epicenters of these shocks are plotted on Figure 2.5-49. Table 2.5-8 lists the historic earthquakes that are considered significant to the site. Since the beginning of the nineteenth century only four earthquakes have been reported

within 60 miles of the site. None of these events exceeded MMI V in intensity; the nearest one to the site was at a distance of 40 miles. Eighteen earthquakes of MMI V or greater have been reported within 100 miles of the site, and 60 shocks of MMI VI or greater have been reported within 200 miles. Few earthquakes were of sufficient intensity to cause damage to well built structures.

Although the site has been within the limits of perceptibility of at least 22 shocks within the past 2 centuries, the site intensity has exceeded MMI V only during the historic series of seismic events in the New Madrid area in the years 1811, 1812, and 1895 (Tables 2.5-7 and 2.5-8).

2.5.2.1.1 New Madrid Earthquakes

The upper Mississippi Embayment region has probably been the locus of large earthquakes prior to the destructive events of modern record in 1811 and 1812. According to Fuller (1912), Lyell (1849) reported Indian legends recounting a great earthquake in the Mississippi Valley. This tends to be corroborated by Heinrich (1941), who describes a great ancient Mississippi River shock that was reported to have occurred in [illegible]99 in the same region affected by the 1811-1812 events. The reported epicentral location, however, was in western Tennessee.

The three earthquakes that occurred on December 16, 1811, and January 23 and February 7, 1812 near New Madrid, Missouri are thought to have been the largest ever to occur in the central and eastern United States. These shocks probably generated an intensity as high as MMI XI-XII, were reportedly felt in an area of about 2,000,000 square miles, and changed the surficial topography in an area of about 30,000 to 50,000 square miles. Structural damage from these earthquakes was small due to the sparse population and the related absence of dwellings and other structures. The body wave magnitudes of these events were estimated to be 7.3, 7.2, and 7.5 (Nuttli et al., 1979).

In a report entitled "The New Madrid Earthquake," published by the U.S. Geological Survey in 1912, Fuller apparently gives the most factual and complete account of the historical events that occurred during the years 1811 and 1812. Although criticized by some workers, Fuller made every effort within the scientific standards and state-of-the-art of his period to present facts as best he could. Although he did his field work in 1904, he was able to preserve the basic historical reports that might otherwise have been lost to present day workers.

In the USGS report, he gave many descriptions of the results of the earthquakes in terms of physical features that recorded the intensity of otherwise transitory seismic events. Fuller recognized the fact that ground motion from the New Madrid events was amplified by river alluvium. In describing the damage of the December 16, 1811 shock, he cites Drake's description of the damage near Cincinnati and quotes him as follows:

> "It (the violent earth motion) seems to have been stronger in the valley of the Ohio than in the adjoining uplands. Many families living in the elevated ridges of Kentucky, not more than 20 miles from the river (the Ohio River), slept during the shock; which can not be said, perhaps, of any family in town."

Fuller later describes the amplification of alluvial materials:

> "In the more remote districts the action was less intense, producing only vibrations and tremors. There appears, however, to have been more or less of surface movements, as the shocks were much more distinctly felt by those living in the alluvial flats of the valleys than by those on the rock uplands, notwithstanding that it is only through the rocks that the shocks could be transmitted to the distances observed. The slight vibrations in the latter must, therefore, have been greatly magnified on transmission to the alluvial masses. The intensities in the valley and upland differed sufficiently to be noticeable at the time. Drake, speaking of Cincinnati, says: 'The convulsion was greater along the Mississippi, as well as along the Ohio, than in the uplands. The strata in both valleys are loose. The more tenacious layers of clay and loam spread over the adjoining hills, many of which are composed of horizontal limestone, suffered but little derangement.'"

It is significant to the subsequent evaluation of the intensity of the New Madrid events that in the preparation of the isoseismal maps and attenuation curves presented by various workers herein, most of the data points are from towns and settlements situated within alluvial valleys of rivers and streams, such as Cincinnati, St. Louis, Saline, Ste. Genevieve, Louisville, Natchez, and Pittsburgh.

Even the most distant cities where the shocks were felt, (such as Washington, D.C., Boston, Philadelphia, and Charleston, South Carolina), were also situated along rivers or on coastal plain deposits where amplification could be expected due to the properties of the underlying materials. As a

result, the intensities so derived can be judged to be the maximum intensities which could have been noted; in nearby highlands or where ground was more competent, the intensities appear to have been substantially less.

The ground motion felt in the vicinity of the site from the 1811-1812 New Madrid events was the highest of any known to have affected the site and probably induced a site intensity on the order of MMI VI-VII (Nuttli, 1973a).

Nuttli's early work (1973a), as shown on the isoseismal map for the December 16, 1811 event, is shown on Figure 2.5-50. As this map used by Nuttli had no data points for the largely uninhabited region west of the Mississippi River, Dames & Moore undertook an extensive investigation of historical archives in an attempt to obtain new data points. Old maps, newspapers, diaries, letters and other documents were examined to substantiate an estimate of the intensity of the events in the general region of the site. This effort was partially successful in revealing heretofore unpublished information at three locations: St. Louis, St. Charles, and Defiance. In his early evaluation of damage reports after the New Madrid events, Nuttli (1973a) had listed an intensity of MMI VII-VIII at St. Louis. As a result of further analysis, he now considered (Nuttli, 1973b) that these intensities were based upon reports from the old town of St. Louis where it lay on the banks of the Mississippi River (Figures 2.5-51 and 2.5-52); that his previous estimate did not take into account amplification through the underlying alluvial materials; that the intensity in nearby areas underlain by rock would necessarily have been less; and that, consequently, the intensity for St. Louis should now be considered MMI VII. The lowering of the intensity at St. Louis is supported by the knowledge that the village of Herculaneum, 50 miles closer to New Madrid than St. Louis, reported an intensity of only MMI VI, which suggests that the intensity at St. Louis might be lowered further. At St. Charles, about 70 miles from the site, the Kibbee house, the first brick building to be built in St. Charles (about the year 1810), sustained damage indicating an intensity of MMI VII (Olson, 1968, 1973). At Defiance, 56 miles from the site, Daniel Boone's home, which was extant at the time of the 1811-1812 events (Andreas, 1973; Oliver, 1973), sustained damage estimated at an intensity of MMI VII. The St. Charles and Defiance data points lie about 160 miles from New Madrid; the site lies about 200 miles from New Madrid, 40 miles beyond the new data points with their intensities of MMI VII. Based upon these factors, the site must be considered to have been subjected to ground motion of MMI VII or less.

In this research effort, although three definitive data points were discovered, other locations were revealed that

were populated at the time of the 1811-1812 events but yielded no reports upon which intensities could be defined. The absence of reports that would surely have been made had damage been noteworthy is, in a sense, significant, even though such negative data cannot be used in intensity definition. Nevertheless, it is useful to show the size and distribution of the population during the years 1811-1812 because if noteworthy damage had been incurred it probably would have been recorded, reported, or retold. Settlements known to exist in the region that is now Missouri are shown on Figure 2.5-53.

During the War of 1812, the British burned the 1810 U.S. Census records stored in Washington, D.C. The following population figures, however, were found in "View of Louisiana" by Henry Marie Brackenridge, published in 1814 and corroborated in "Darby's Universal Gazetteer," edition of 1827; Bradford's Illustrated Atlas of the United States; "History of the Discovery and Settlement of the Valley of Missouri" by John Monette, M.D., published in 1846; and "The Influence of the Environment on the Settlement of Missouri" by James Fernando Ellis, Ph.D., published in 1929:

St. Charles	3,505
St. Louis	5,667
Ste. Genevieve	4,620
Cape Girardeau	3,888
New Madrid	3,103
Hope Field and St. Francis	183
Arkansas	874
Troops at Military Posts in Territory (est.)	200
Hunting and Trading Parties up the Missouri and Mississippi (est.)	300
Remote Families not found by Sheriff (est.)	300
Total	22,640

Of this total population, 8,011 were slaves. The number of civilized Indians and mixed nationals while not known, could not have been considerable (Brackenridge, 1814).

Cote Sans Dessein, now called Bakersville, was settled on the banks of the Missouri River by about 20 French families (Brackenridge, 1814). Cote Sans Dessein lies only 16 miles from the site, and both the settlement and the site lie about 200 miles northwest of New Madrid. Near Franklin, in the vicinity of Boonville, Missouri (about 55 miles from the site, a colony of Kentuckians numbering about 150 families settled on the Missouri River in Cooper's Bottom in 1810. At the same time, about 150 people settled at Booneslick in the area which later was established as Booneville and (Old) Franklin.

During 1811, other settlers immigrated into the area and erected cabins and forts for protection against Indians (History of [illegible] County, 1884). Booneslick was situated about 55 mil[illegible] west of the site and about 225 miles from New Madrid, about 30 miles further from New Madrid than the site. It is significant that none of these settlements reported damage at the time of the 1811-1812 events.

At the time of the 1811-1812 New Madrid earthquakes, several old lead mines in the region 40 to 65 miles southwest of Ste. Genevieve, were being worked and were located directly between New Madrid and the site (Figure 2.5-53).

At all of these historic locations, sufficient population and structures existed so that had the 1811-1812 series of earthquakes been of sufficient intensity to cause damage, they would have been noted. Reports would have eventually reached the river cities and would have been published. The implications are that the intensity of earth motion to the northwest of New Madrid was probably lower than previously thought. Therefore, based on Nuttli's reduction of the St. Louis intensity to MMI VII and the establishment of MMI VII at Defiance, Nuttli's original isoseismal map is herein revised. Both Nuttli's original map and the revised map are shown on Figure 2.5-50. According to the revised map, the site intensity was about MMI VI-VII.

In work by Stearns and Wilson (1972), the data points for the New Madrid events were interpreted in a different manner. Their isoseismal maps for the December 16, 1811, and February 7, 1812, earthquakes are shown on Figures 2.5-54 and 2.5-55. Their composite for the New Madrid events is shown on Figure 2.5-56.

It is significant that in both Nuttli's and in Stearns and Wilson's interpretations, the attenuation patterns are elongated toward the east and northeast respectively. This pattern is particularly well developed in Stearns and Wilson's interpretation. It is diagnostic that the data points where damage was reported lie along the Ohio River where the most populated towns were located and where amplification through river alluvium would be expected.

2.5.2.1.2 Other Earthquakes Significant to the Site

Other events which were probably felt at the site are included in the list shown in Table 2.5-8 and discussed below.

In 1843, an earthquake with a maximum intensity of MMI VIII occurred in western Tennessee and was felt from Rhode Island to Mississippi and Iowa. The intensity at the site was

probably about MMI II. Memphis, Tennessee, close to the epicenter, suffered the most damage (Coffman and von Hake, 1973). In 1878, an MMI VI shock in southeastern Missouri is estimated by Docekal (1970) to have had an intensity at the site between MMI I and MMI III. The maximum disturbance from this event was in the Mississippi Valley between Memphis, Tennessee, and Cairo, Illinois. Another shock in the Mississippi Valley occurred in 1895 at Charleston, Missouri, where 4 acres of ground sank and formed a lake. This shock, which was felt by people in parts of 23 states and had a maximum intensity at its epicenter of MMI VIII, is estimated to have produced ground motion at the site with an intensity of MMI V-VI (Nuttli, 1974). An isoseismal map for this event prepared by Nuttli (1973c) is shown on Figure 2.5-57. A recent reevaluation of the Charleston, Missouri earthquake indicates that ground motion at the site may have had an intensity of MMI VI (Hopper and Algermissen, 1980, Plate 1). On November 4, 1903, an MMI VII event occurred near Charleston, Missouri, and was felt over an area of about 135,000 square miles. It is estimated from Docekal's work (1970) that the intensity at the site was between MMI II and MMI III. In 1905, an MMI VI event was recorded at Sikeston, Missouri, and was felt over an area of 125,000 square miles. Based on Docekal's data (1970), the intensity at the site was at the bounds of perceptibility. The next shock to be felt at the site occurred in November of 1956 in the Mississippi Valley. At its epicenter in Wayne County, Missouri, the shock was of MMI VI and is estimated to have produced an intensity at the site of between MMI II and MMI III (Docekal, 1970). On March 3, 1963, an earthquake with an epicentral intensity of MMI VI occurred in southeastern Missouri where chimneys and windows were cracked. At the site, it is estimated to have been MMI II to MMI III (Docekal, 1970). On October 1, 1971, an Intensity V shock near Seogwick, Arkansas may have been felt at the site with an intensity of I-III. A similar site effect is estimated to have been felt from the marked tree, Arkansas event of March 25, 1976. The Strawberry, Arkansas earthquake sequence began on February 27, 1979 and continued until March 3, 1979. The largest shock in this sequence had a maximum intensity of MMI VI near Powhatan, Arkansas (NOAA, 1981; Zollweg and Johnston, 1980). The epicentral area corresponds to the physiographic boundary between the Ozark Uplift and the Mississippi Embayment, which appears to be a southwestward extension of the boundary between the Border and West Embayment seismotectonic regions (Section 2.5.2.3.1.2) Intensities of MMI III at Lake Charles and MMI II at Walnut Ridge and Hoxie, indicate rapid attenuation toward both the northwest and northeast (Zollweg and Johnston, 1980, Figure I-4).

From the year 1900 through the present, several shocks have occurred in the upper Mississippi Valley which were probably felt at the site. The first occurred in 1902 near St. Louis, Missouri, with an epicentral intensity of MMI VI. Based on Docekal's work (1970), the site intensity is estimated to have

been between MMI II and MMI III. In 1903, an MMI VI earthquake occurred near Murphysboro, Illinois. This shock was felt over 65,000 square miles and produced a site intensity at the limits of perceptibility (Docekal, 1970). In 1917, an MMI VI earthquake occurred with an epicenter near St. Mary's, Missouri, about 50 miles south of St. Louis. The earthquake, felt over an area of 210,000 square miles, is estimated to have had an intensity of MMI IV at the site (Docekal, 1970). An isoseismal map for this event is shown on Figure 2.5-58. Three MMI V events in 1920, 1939 and 1946, centered at St. Louis, Missouri, Griggs, Illinois, and

Chloride, Missouri, respectively, were felt at the site. The first could have been felt at the site as MMI III to MMI IV, the second and third as MMI I to MMI III (Docekal, 1970). An earthquake centered near Sparta, Illinois, in 1955, had an intensity of MMI VI and was felt in the site area with an intensity of MMI I. In 1978, an earthquake near Webster Groves, Missouri had an intensity of V and was felt over most of the St. Louis area (St. Louis Univ. Geophys. Obs., 1981). The site intensity is conservatively calculated as MMI III (Table 2.5-8).

In 1965, an earthquake occurred near Centerville, Missouri, about 90 miles south-southwest of St. Louis. At the epicenter, the maximum intensity was MMI VI while the site intensity was MMI IV to MMI V (Docekal, 1970). This earthquake was felt over 245,000 square miles. An isoseismal map (Eppley, 1965) for this event is shown on Figure 2.5-59. A 1976 earthquake near Farmington, Missouri had an epicentral intensity of MMI V. A conservative estimate indicates a site intensity of MMI II (Table 2.5-8). In 1977, an earthquake centered near Jackson, Missouri had a maximum intensity of MMI VI. Estimates indicate a site intensity of MMI IV (Table 2.5-8).

Three other earthquakes at distant locations were perceptible in the vicinity of the site during the 19th Century. In 1867, an earthquake with an intensity of MMI VII occurred with its epicenter at Manhattan, Kansas, and was felt as far away as Chicago (Docekal, 1970). It produced an intensity at the site on the order of MMI I to MMI III (Docekal, 1970). The famous 1886 earthquake(s) near Charleston, South Carolina, had a maximum epicentral intensity of MMI X and was felt from Boston, Massachusetts, to New Orleans, Louisiana. The maximum intensity at the site probably was MMI I to MMI II (Bollinger, 1977).

A recent event perceptible at the site occurred on November 9, 1968, in the Wabash Valley. This earthquake had an epicentral intensity of MMI VII and produced an intensity at the site of MMI IV (Heigold, 1968). An isoseismal map for the 1968 event was prepared by Gordon et al. (1970) and is shown on Figure 2.5-60. The 1974 earthquake near Olney, Illinois had an epicentral intensity of MMI VI and produced a site intensity of MMI IV. The epicenter of the September 27, 1981 earthquake in southern Illinois has been relocated to the vicinity of Mt. Vernon and reevaluated as a MMI VII event (Street, 1980). An isoseismal map for this event indicates no felt reports from the site area (Street, 1980, Figure 1). Other Illinois Basin earthquakes with epicentral intensities of MMI V occurred during 1974 and 1978 with conservatively estimated site intensities of III and II, respectively (Table 2.5-8).

2.5.2.2 Geologic Structure and Tectonic Activity

2.5.2.2.1 Regional Tectonic Setting

The Central Stable region surrounding the site is described by Eardley (1962) as a region consisting of a veneer of sediments overlying Precambrian crystalline rocks which have been formed into arches, basins, and other structures primarily as a result of Paleozoic epeirogenic activity. This system of broad arches and basins extends from the eastern Appalachian Mountain Chain to the western Rocky Mountains where it is truncated by the later Laramide Orogeny. To the north, folded Precambrian rocks are exposed at the surface in the Canadian Shield Province. The southern border is defined by the limit of onlapping Cretaceous and Tertiary sediments that characterize the adjacent Coastal Plain Tectonic Province. The Mississippi Embayment to the southeast of the site is delineated by a northeast-trending

reentrant of these Coastal Plain deposits up into the Mississippi River drainage basin.

The tectonic character of the region is the result of a sequence of episodes of relative vertical uplift, subsidence, and tilting of crustal blocks bounded by upthrust faults. The geometry of the blocks appears to be inherited from an older, possibly Grenvillian, structural fabric. The traces of steeply dipping block-bounding faults, associations with faulted monoclines, the strikes of vertical Precambrian intrusives, fracture patterns in Precambrian rocks, fracture patterns in the sedimentary rocks of the region, and traces of minor faults all reflect a consistent geometry (Graves, 1938; Robertson, 1940; Gibbons, 1972).

The geometry and boundaries of the major blocks represent inherited zones of weakness. Some segmentation of blocks by minor faults has occurred, but blocks several tens of miles on a side have generally acted as cohesive tectonic units. Where major, persistent features have acted as boundaries (Ste. Genevieve Fault, Simms Mountain Fault) their role has been passive. These features represent kinematic surfaces which have responded to the episodic uplift of contiguous individual blocks throughout Paleozoic time. The vertical stratigraphic separation and sense of vertical offset along any segment of these features is a reflection of the vertical motions of blocks responding to local uplift, rather than to uniform motion along the entire length of the major faults (Gibbons, 1972).

Folding in the region is either the result of the passive draping of relatively weak sedimentary rocks over the edges of fault blocks, or of the previously mentioned paleotopographic effects. There is no evidence of any folding in the region due to basement-transmitted horizontal principal stresses or to thin-skinned gravity tectonics. A characteristic assemblage of monoclinal folds, curving reverse fault planes, compensatory normal fulats, and minor low angle normal faults illustrate passive response to repeated vertical movements along nearly vertical basement discontinuities (Gibbons, 1972). The tectonics of the region must, therefore, be based upon an understanding of vertical kinematics rather than on lateral or horizontal compressive forces.

The structural features discussed and illustrated in Section 2.5.1 probably reflect basement structures and the features must all be considered deep-seated. Some of these features have probably been caused or influenced by other mechanisms, such as the differential compaction of sedimentary beds emplaced over a Precambrian surface that has substantial topographic relief. However, it is not possible to verify

such origins for individual structural features with the present level of information available regarding the structural geology of central Missouri.

The structural features in the region of the site were probably formed by differential uplift and settlement of crustal blocks in a manner similar to that which resulted in the formation of the Ozark Uplift, the major structural feature in the site area. The relationship between these small features and the Ozark Uplift is imperfectly understood due to the poor exposures and lack of subsurface information. It is nevertheless clear that the forces that formed the Ozark Uplift also were instrumental in the formation of these other minor structures. That these forces acted upon blocks of considerable size has been demonstrated by Gibbons (1972).

The idea of the structural blocks described by Gibbons within the central area of the Ozark Uplift demands comparison to the concept of crustal blocks as proposed by McGinnis (1970). It is conceivable that the uplift and subsidence of crustal blocks is a direct result of vertical forces originating in the mantle. It also might be speculated that the smaller features were formed contemporaneously with the Ozark Uplift and that, consequently, there is a direct relationship. However, this is not necessarily true and it might be reasonable to speculate that minor faulting and folding near the site were formed subsequently by vertical forces working on independent crustal blocks.

The gross geologic structure of the Ozark Uplift is described by the structures on the basement surface as discussed and illustrated in Section 2.5.1.

2.5.2.2.2 Tectonic Setting of the Site Locale

The site straddles the boundary between the Dissected Till Plains Physiographic Province to the north and the Ozark Province to the south, being situated on a plateau about 5 miles north of and 305 to 325 feet above the flood plain of the Missouri River.

The Ozark Region has been a topographically positive region since at least early middle Cambrian time (Dake and Bridge, 1932). The relief present at that time probably represented the erosional resistance of the thick, silicious extrusive volcanics which comprise the Precambrian core of the St. Francois Mountains. The surface of the Precambrian rocks was deeply incised by streams before the onset of Cambrian sedimentation (at least 500 feet of relief (Dake and Bridge, 1932). The Cambrian and Ordovician sedimentary rocks were

deposited and subjected to differential compaction over the pre-existing topography. Much of the structural geometry of the region is a result of this pronounced paleotopographic effect (Dake and Bridge, 1932; Weller and St. Clair, 1928).

In the area of the site, 25 to 50 feet of glacial and post-glacial soils overlie a 4- to 50-foot thick layer of chert conglomerate with clay matrix. This in turn overlies a series of limestones, dolomites, sandstones, and shales ranging in age from Mississippian to Cambrian. These lie upon the Precambrian basement at a depth of about 2,000 feet below the surface at the site. Within the immediate region of the site, the sediments are nearly horizontal, reflecting the regional dip of about 5 to 10 feet per mile to the northwest. The only known fold structures near the site are the Browns Station (Section 2.5.1.1.5.1.14), Davis Creek (Section 2.5.1.1.5.1.16), Mexico (Section 2.5.1.1.5.1.22), Auxvasse Creek (Section 2.5.1.1.5.1.12), Mineola (Section 2.5.1.1.5.1.23), Big Spring (Section 2.5.1.1.5.1.13) and Kruegers Ford (Section 2.5.1.1.5.1.20) anticlines. There is no evidence to support the presence of the Pershing Bay-Gerald Anticline as discussed in Section 2.5.1.1.5.1.25. The Auxvasse Creek Anticline, which lies about 10 miles north of the site, represents a gentle fold parallel to the Browns Station Anticline. Along its axial trend to the northwest, the Auxvasse Creek Anticline projects into the Davis Creek Anticline. No folds are in evidence to the southwest. These structures are all very gentle. The Auxvasse Creek Anticline has 175 feet of structural relief and the Browns Station Anticline only 100 feet. The indicated time of deformation is from Mississippian to Late or post-Pennsylvanian.

The site lies at a considerable distance northwest of the center of the Ozark Uplift and from most of the major structural features in the surrounding region. Although the same forces that formed the Ozark Uplift during the Paleozoic probably also formed such structures as the Davis Creek and the Browns Station Anticlines, uplift of the former feature was in the range of 5,000 feet, whereas the flexures of the latter features were in the range of only 100 to 200 feet. Clearly, the forces that formed the Ozark Uplift were considerably greater than those that formed the gentle features near the site.

McCracken's (1967) discussion on tectonics of the site region terminates with the following:

> Dips everywhere in Missouri are gentle except in the immediate vicinity of some of the faults. The most prominent structure north of the Ozark dome is the Lincoln fold. This, together with the other larger

> structures such as the Proctor Anticline, Saline County arch, and Browns Station Anticline... trend northwesterly parallel to the principal direction of the Precambrian grain and to the early elongation of the Ozark uplift. It is believed that they originated in block-fault structures in the basement over which the Paleozoic sediments draped to produce the anticlinal and synclinal folds that persist to the surface (Hinds, 1912).

Geologic investigations within 5 miles of the site have revealed no faulting. The closest faults to the site are the Fox Hollow Fault 30 miles west, the Wardsville Fault 30 miles southwest, the Kingdom City Fault 12 miles northwest, and the Cuba Fault about 18 miles to the south. The Fox Hollow and Wardsville faults have displacements of 120 and 100 feet respectively, and are found in Mississippian sediments. The trend of the former is about north and the trend of the latter about northwest; if projected neither would approach the site closer than 30 miles. The Kingdom City Fault has a displacement of 300 feet and is Middle Ordovician or younger in age. The proposed trend of the fault is northeast, which if projected would approach the site no closer than 12 miles. The Cuba Fault is considered to be Pennsylvanian or younger. This fault, which bounds the west side of the Cuba Graben, diminishes northward and cannot be traced more than a few miles northwest of the Gasconade River (McQueen, 1943). At this point, it lies about 18 miles south-southeast of the site. If the Cuba Fault were to be projected along its northernmost strike of North 50° West, it would approach no closer than 10 miles to the site (Fox, 1954).

2.5.2.2.3 Behavior During Prior Earthquakes

It is known that minor to moderate earthquake ground motion has been experienced at the site; however, there is no evidence from lithologic, stratigraphic, structural, or geophysical studies to substantiate such earthquake motion. Also, no evidence from surface mapping has been found that would indicate recent faulting.

2.5.2.3 <u>Correlation of Epicenters with Geologic Structures</u>

The large structural elements within the vast Central Stable Region apparently localize areas of stress relief as marked by characteristic seismicity in certain subregions. While knowledge of the exact seismogenic nature of these subregions is incomplete, the concentrations of seismicity displayed by certain seismogenic zones afford diagnostic observation of what is currently taking place in the crustal rocks. Because such active areas should be recognized, and can for the most part be spatially related to a consistent structural regime,

and since the correlation of indivudal events with specific structures (faults) is lacking, the relationship of earthquakes to geologic structures is better developed on the basis of the historical distribution and gross tectonic regimes, or seismotectonic regions.

2.5.2.3.1 Seismotectonic Regions

Seismotectonic regionalization of the seismically active areas significant to the site has been prepared using the basic approach by Gubin (1967). Data were obtained principally from the literature and supported by personal communication with individuals of the scientific community, a list of whom is contained in the bibliography. Seismotectonic boundaries were delineated by comparison of seismicity, structure, fault plane solutions, and, in the New Madrid Seismotectonic Region, by comparison of gravity, magnetics, ERTS imagery, geomorphology and the resulting distribution or confluence of apparent complementary characteristics.

The term "seismotectonic region" is generally used to describe a tectonic region where seismic activity has occurred in relation to known geologic structures and where earthquake generating forces may still be present. Some large tectonic regions have been the sites of only a few earthquakes, usually relatively small, infrequent and occurring throughout the area without apparent relation to any particular structure. These regions are designated as random regions. There are some stable regions that exhibit extremely low seismicity. In the following sections, individual seismotectonic regions, as shown on Figure 2.5-61, are discussed. The characteristics and seismic activity of these regions are discussed below and summarized in Table 2.5-9.

2.5.2.3.1.1 New Madrid Seismotectonic Region

This region lies about 175 miles southeast of the site. However, earthquake activity in this area historically controls seismic design in a large part of the midcontinent due to its dense seismicity and the large destructive "New Madrid" earthquakes previously discussed.

The primary evidence for the New Madrid Seismotectonic Region is the concentration of high intensity earthquakes that have occurred in the Upper Mississippi Embayment near the town of New Madrid, Missouri and their spatial relation to identified faulting and other structures. Earthquakes that have occurred in historic times near New Madrid with intensities MMI V and greater are shown on Figure 2.5-49. All known perceptible New Madrid events are shown on Figures 2.5-62 and 2.5-63, and are listed in Table 2.5-10.

In the discussions which follow, various data are presented and/or discussed in separate sub-sections so that they can be referred to from time to time in subsequent analyses of the seismotectonic nature of the New Madrid region.

2.5.2.3.1.1.1 Summary Geologic History of the Mississippi Embayment

The historical genesis that led to the present structural conditions in the upper Mississippi Embayment are discussed in Section 2.5.1 and summarized as follows: uplift and erosional beveling of the Pascola Arch prior to Lower Devonian time; subsidence with accompanying deposition of Paleozoic limestones; rejuvenation of the Ozark Uplift to the northwest and the Nashville Dome to the southeast, and the subsidence of the intervening structural trough which became the Mississippi Embayment; advancement of the Cretaceous seas to create the Gulf Coast onlap; and deposition filling of the upper Mississippi Embayment with a series of Cenozoic sands, silts, and clays that included the remarkably uniform and massive Porters Creek Clay of Paleocene age. Surficial geology is shown on Figure 2.5-64. Stratigraphy in the upper Mississippi Embayment is shown in Table 2.5-11. The New Madrid area is the locus of many structural features, some or all of which may contribute to the high seismicity of this area, as discussed below.

2.5.2.3.1.1.2 Tectonic Structures Near New Madrid

Recent and on-going geophysical studies in the upper Mississippi Embayment are characterizing the gross tectonic framework which apparently hosts the high level of seismic activity noted in the area. Figure 2.5-65 presents the structural synthesis of the most recent evaluations, and serves as a basis for bounding the New Madrid Seismotectonic region, as subsequently developed.

The northwest and southeast limits of the "Reelfoot Rift" (Embayment) as shown on Figure 2.5-65, are delineated by Hildenbrand et al. (1977), from available studies. The northwestern boundary is marked by an alignment of intrusives presumed on the basis of well-defined magnetic and gravity highs which lie outside or along the boundary of the rift. The Proposed "rift" zone itself is expressed in the preCambrian basement by a broad zone of subdued magnetic expression (Figure 2.5-67). According to Hildenbrand et al. (1977), this low gradient zone implies 1.1 to 2.4 km of relief between basement inside the zone and basement outside the zone. The southeast margin of the zone also includes magnetic and gravity highs associated with mafic or ultramafic igneous intrusions. To the northeast, the zone of low

gradient terminates against a northwest-trending low that is inferred to represent the buried extension of the northwest-southeast-trending Ste. Genevieve fault zone in western Kentucky (Figure 2.5-66). To the north, the Rough Creek fault zone appears to mark the northern boundary of a large northwest-trending graben in the Precambrian basement. The graben is a major structural feature which appears to have formed initially in late Precambrian to early Paleozoic time (Soderberg and Keller, 1981). O'Leary and Hildenbrand (1978) observe that aeromagnetic data indicate a morphological configuration of the Precambrian basement totally unexpressed by either Paleozoic or postPaleozoic rocks. The authors propose that current embayment seismicity is genetically related to buried regional fault systems which, in turn, are related to trough structure in the basement. The areal distribution of present earthquake activity, the configuration of lineaments, and the morphology and depth of magnetic basement imply such a relationship.

Known faults and folds near New Madrid are shown on Figure 2.5-66. (Note: In the following discussion on faults, the numbers in parentheses refer to map index numbers on Figure 2.5-66.) The faults that lie close to the area of intense seismicity include the Greenville Fault (18), the English Hill Fault (15), the Aquilla Fault (2), the Idalia Fault (20), the three (First, Second, and Third) Mississippi Valley faults (42), the Jackson Fault (21), the Black Fault (4), the Ste. Genevieve Fault System (38), the Fluorspar Fault Complex (Illinois 2), the Rough Creek Lineament (Illinois 3), and the Wabash Valley Fault System (Illinois 5).

The Greenville Fault (18) was inferred by McCracken and McCracken (1965) during preparation of a structure map for Missouri. Although the exact strike of the fault is not discernible due to thick mantle cover, the workers gave a mapped trend direction of about North 45° East. The Greenville Fault lies outside the seismically-active area near New Madrid, well within the elevated crustal blocks that form the St. Francois Massif. It therefore has no relationship to the northeasterly trending faults which have been displaced by recent activity in the area of New Madrid.

The English Hill Fault (15) was mapped by Steward (1942) and by Grohskopf (1955) in the same area as the Idalia Fault (20) (Farrar and McManamy, 1937; Grohskopf, 1955), and Aquilla Fault (2) (Farrar and McManamy, 1937) and another described as the Albright Creek Fault. Grohskopf (1955) inferred the connection between the short segments of the English Hill, Idalia, and Albright Creek Faults to form a continuous fault zone, as marked by Crowleys Ridge, a topographic feature striking northeast with a length of over 30 miles. However, recent seismic surveys and subsequent drilling (Zoback, 1979) have not determined any offset of bedding at depth across the Crowleys Ridge structure, and its definition as a major fault system is

unwarranted at this time. The Aquilla Fault has a very short mapped trace and cross-cuts the main trend with an approximate strike of North 60° West.

About 10 miles southeast of the Idalia and English Hill faults lies another fault having a parallel strike trend. This fault is the westernmost of three major Mississippi Valley Faults (Section 2.5.1.1.5.2.13) and will be termed here the "First Mississippi Valley Fault". It has a strike direction of about North 40° East and an inferred length of about 40 miles. This "First" fault has a bifurcation with a strike direction of roughly North 30° East and a length described as about 20 miles; it closely coincides with a line of epicenters and constitutes a line of seismic contrast. This line, as discussed in Sections 2.5.2.3.1.1.6 and 2.5.2.3.1.1.7, is considered to be the northwestern boundary of the New Madrid Seismotectonic Region as described by this study. The Second Mississippi Valley Fault is located slightly east of the Mississippi River and east of the town of New Madrid. It has a strike direction at its southern end of about North 30° East changing to about North 10° West at its northern end. This "Second" fault has an inferred length of about 95 miles. The "Third" Mississippi Valley Fault lies south and southeast of the first two and displays a crosscutting strike to the irst two Mississippi Valley faults. It has a mapped length of about 80 miles with a South 75°East trend, sub-parallel to the axis of the Pascola Arch near its southeastern extremity.

The Jackson Fault was identified by McQueen (1939) who described a graben with a displacement of 200 feet, but who was unable to identify the strike direction. Gealy (1955) further detailed this fault. It has a strike of about North 75° West and a described lenth of 15 miles (Dake, 1930; James, 1951; Kiilsgaard, 1963), and a mapped strike direction of about North 80° West.

The closest approach to the site of the Ste. Genevieve Fault System (38) is that segment in Illinois known as the Rattlesnake Ferry Fault lying about 70 miles north of the town of New Madrid. The total length of the Ste. Genevieve Fault System is about 100 miles. Although it has an overall trend direction of North 60° West, the system is highly imbricated and displays many strike directions throughout its length.

The well-known Fluorspar Fault Complex lies from 90 to about 160 miles to the east of the Ste. Genevieve fault system. Although the individual faults of this complex have strikes about North 40° East, in aggregate they cover a broad area about 50 miles long and 25 miles wide. Recent investigations indicate that some of the northeast-trending faults displace Paleozoic rocks in the Flourspar District and extend southwestward beneath late Cretaceous sediments of the Mississippi Embayment in south Illinois. The relatively uniform thickness of the Cretaceous sediments and the configuration of their base indicate that essentially all of the displacement on faults in the underlying Paleozoic rock occurred prior to the deposition of the Cretaceous sediments (Kolata, Treworgy and Masters, 1981; IL State Geological Survey, 1973).

The Rough Creek Fault System lies about 95 miles north of New Madrid. It has an overall trend direction of North 75° West and a length of about 180 miles (Section 2.5.1.1.5.2.3).

The Wabash Valley Fault System lies about 110 miles northeast of New Madrid.

The Pascola Arch (Section 2.5.1.1.5.1.24) lies about 30 miles southwest of New Madrid and has an axial trend of about North 45° West. The Moorman Syncline, which lies about 90 miles northeast of New Madrid, generally reflects the change in trend direction between the Fluorspar Fault Complex and the Rough Creek Fault System. Three hinge lines or "Bending Zones" (Stearns, 1973) form folds at the center of the upper Mississippi Embayment and its junctures with the Ozark and Nashville domes (Section 2.5.2.3.1.1.7). Lineations that may reflect tectonic structures are discernible from ERTS imagery, from geomorphological trends in topography, and from geophysics. A magnetic map and a gravity map for the region around New Madrid are shown on Figures 2.5-67 and 2.5-68, respectively. Lineations after O'Leary and Hildenbrand (1978) are shown on Figure 2.5-69.

2.5.2.3.1.1.3 Well Logs Near New Madrid

The logs from drillholes near New Madrid provide the basic data upon which structural contour maps have been prepared by Stearns (1974). The information from these wells is shown in Table 2.5-12 and the locations are shown on Figure 2.5-70. For each well, the following data are presented: name of the property owner, name of the drilling company, completion date, location by section, township and range, surface elevation, total depth and sea level elevation of formation boundary. The authority for formation boundaries is the Missouri Geological Survey, except for those marked by an asterisk. These were picked for this study from sample or electric logs in the Missouri Geological Survey file. The wells are listed alphabetically by county and sequentially by township and range. Abbreviations are standard except for stratigraphic boundary "picks": TPC stands for top of the Porters Creek Clay (of Paleocene age); TPAL stands for base of Cretaceous (relatively soft) sands and clays and top of undifferentiated Paleozoic formations.

2.5.2.3.1.1.4 Fuller's Report

Fuller's USGS report (1912) is useful in delineating areas of maximum disturbance for technical discussion and evaluations of ground motion, as discussed below and in Section 2.5.2.1. Among those features Fuller described were fissures, faults, landslides, the uplift of domes and the depression of "sunk lands," and the phenomenon he termed "extrusion," which resulted in the ejection of water, sand, mud, and gas. The most noticeable features of these phenomena that remain today

are "sand blows" that, through erosion, are beginning to lose their distinctive appearance, and thus do not convey to the modern observer the violence associated with their formation. Fuller quotes a description by an engineer named Bringier who witnessed this unusual event and told how:

> (the water forced its way through the surface deposits) ... blowing up the earth with loud explosions. It rushed out in all quarters, bringing with it an enormous quantity of carbonized wood, reduced mostly into dust, which was ejected to the height of from 10 to 15 feet, and fell in a black shower, mixed with the sand, which its rapid motion had forced along; at the same time the roaring and whistling produced by the impetuosity of the air escaping from its confinement seemed to increase the horrible disorder. In the meantime the surface was sinking and a black liquid was rising to the belly of my horse.

The mechanism that caused this phenomenon is related to the disruption of the ground by faulting or fissuring within an area of loose sand saturated with water. Due to the influence of the energy from strong ground motion, the sands were subjected to liquefaction and were extruded through the fissures at the surface into the air. The area of "sand blows" and other earthquake features is well shown on Fuller's original map, which is reproduced as Figure 2.5-71. The area of "sand blows" together with the other features of ground disturbance mapped by Fuller are significant, for they define the area of violent motion.

2.5.2.3.1.1.5 Fault Plane Solutions Near New Madrid

Using variations in the technique for determining fault plane mechanisms indicated by seismic waves, Street et al. (1974), and Herrmann (1978, 1979) have presented maps showing several fault plane solutions for recent earthquakes in the area of southeastern Missouri, including the area around New Madrid. A composite map of available solutions is shown on Figure 2.5-72 and a list of parameters is shown in Table 2.5-13. The symbols shown represent the usual stereographic plot of the data; however, the white quadrant represents compression and the black quadrant tension. These solutions will be referred to from time to time to evaluate fault trends and relative motion.

2.5.2.3.1.1.6 Distribution of Current Seismic Activity

Numerous seismic recording instruments operate in, or are proposed for, the mid-continent site region, particularly in

the active portion of the highly seismic Mississippi Valley. Permanent stations operated by St. Louis University are SLM (St. Louis), TYS (Tyson), PRM (Pea Ridge Mine), FVM (French Village), CGM (Cape Girardeau), and WLA (Wittsburg Lake). A seismograph was installed at St. Louis in the year 1909, whereas other stations belonging to St. Louis University began operating in 1962 and later. The other permanent stations are ROL (Rolla), operated by the University of Missouri at Rolla since 1962; FAV (Fayetteville), operated by the University of Arkansas since 1952; LWK (Lawrence), operated by the University of Kansas since 1950; MHK (Manhattan), operated by Kansas State University since 1962; and DBQ (Dubuque), operated by Loras College since 1962.

Recent installations and those proposed for the near future are shown on Figure 2.5-73. In view of the large number of seismographs around the plant site, as described above, it is expected that any sizeable seismic event in the site region can be easily detected and monitored.

On the basis of the several years' dense instrumental coverage in the New Madrid region, additional evidence for defining the areal extent of seismogenic structure is presented. Figure 2.5-74 shows all recorded earthquakes in the area beteen July 1974 and December 1980. The density of activity clearly outlines a gross northeast trend of activity along the axis of the embayment, broken by a short northwest trend in the Reelfoot region before continuing again along the preferred structural grain. The northwestern extent of the activity stops abruptly near the First Mississippi Valley Fault zone or the west side of Bending Zone 2 (as subsequently described), becoming suddenly diffuse to the northwest. The suggested solutions for focal mechanisms shown on Figure 2.5-72 for this area are somewhat correlative with the pattern shown on Figure 2.5-74.

It is now thought (Aggarwal, 1977) that the distribution of relatively small earthquakes determined from a dense network of stations over a short period of time may be a reasonably reliable indicator of the major features of the long-term earthquake distribution. Aggarwal (1977) has noted such a correlation in New York State and southern Quebec. Tarr (1977) also has suggested that the currently active (and monitored) zone of seismicity in the Charleston, South Carolina area is closely associated with the rupture surface of the large destructive shocks of 1886. It can be observed on Figures 2.5-74 and 2.5-66 that immediately northwest of the westernmost (First) Mississippi Valley fault the activity is

suddenly subdued to absent. This diminished activity suggests that stresses are being (and probably will be) relieved in the more central portion of the embayment along the seismogenic structures that have generated the major historical earthquakes. The apparent northwestern limit of dense seismicity, also bounded by the west side of the rift zone (Figure 2.5-65), lies more than 175 miles from the site.

2.5.2.3.1.1.7 Analyses and Determination of Boundaries of New Madrid Seismotectonic Region

The spatial distribution of the highly-seismic area generating historical earthquakes around New Madrid should be examined in light of all known geologic structures or features. A multiplicity of coincident interfaces obtained from independent data sources tends to confirm a discrete seismogenic zone, outside which large events are not expected to occur.

Earlier work by Stearns (1973, 1974) indicated that the crust underlying the New Madrid area is a focus of several intersecting tectonic elements. He suggested that recent northeasterly trending faulting, which may be associated with the New Madrid events, coincides with a zone of weakness rooted in the Paleozoic sediments that form the trough of the upper Mississippi Embayment, and that these events are further localized by an intersection with the southeast-trending Pascola Arch. Subsidence of the trough was promoted by an increasing sediment load. He presented the following evidence and drew his conclusions as follows:

a. The Pascola Arch, as discussed in Section 2.5.1.1.5.1.24, was formed in the Early Paleozoic and was beveled by erosion before Lower Devonian time. Contours drawn on top of the Knox Dolomite, as shown on Figure 2.5-75, reveal the configuration of the structure. It has an axial trend of about North 45° West. The axial crest is well delineated and lies only 15 miles southwest of New Madrid.

b. In the geologic section across the Mississippi Embayment, as shown on Figure 2.5-76, the sediments have a hevron shape in the central area of the Embayment and flatten to the northwest in the vicinity of the Ozark Escarpment and to the south-east in the area of the Nashville Dome. Stearns (1973) interpreted the three reversals of curvature as hinge lines, or as he preferred, bending zones.

The bending zones are revealed through interpretation of the contour map on the top of the Paleozoic rocks (Figure 2.5-77). Bending Zone 1 (Figure 2.5-83) is seen as a sharp break in the contours along the western flank of the Nashville Dome. Bending Zone 2 is shown by the bottom of the trough. Bending Zone 3 is shown by the broadening of contours along the trend of the Ozark Escarpment.

c. In a similar treatment of the Cenozoic sediments of Figure 2.5-77, uninterpreted contours on top of the Paleocene Porters Creek Clay are shown on Figure 2.5-78. Bending Zones 1 and 3 lie beyond the limits of the formation; however, Bending Zone 2 is evident as the trough of the syncline.

d. Analysis of the structural contours, as produced from the well data in Table 2.5-12, reveals anomalous areas both in the contours on top of the Paleozoic sediments of Figure 2.5-77 and in those of the Porters Creek Clay of Figure 2.5-78. The anomalous areas are outlined on Figure 2.5-79.

e. Lineations compiled from topographic maps and from ERTS imagery are shown on Figure 2.5-69.

f. Interpretation of the combined information from the above figures is embodied in a revised contour map for the Paleozoic sediments on Figure 2.5-80 and for the Porters Creek Clay on Figure 2.5-81. The Pliocene and younger faults from Figure 2.5-81 are shown alone on Figure 2.5-82.

g. The contours at the base of the Cretaceous sediments become more widely spaced and define a lineament on each side at the embayment. The contours on top of the Porters Creek Clay become more widely spaced and form a second lineament, again on each side of the embayment. These are shown in relationship to the three bending zones on Figure 2.5-83.

h. The east and west boundaries of Bending Zone 2 are coincident with the line where the contours on top of the Porters Creek Clay become more widely spaced;

i. The various features discussed above are superimposed upon a single map, as shown on Figure 2.5-84. On this figure are shown: the structure contours on top of

the Knox Dolomite at an elevation of 3000 feet below sea level and defining the Pascola Arch at sea level; the western end limits of the northeast-trending faults as shown for the Paleozoic and Pliocene and younger faults (Figures 2.5-81, 2.5-82, and 2.5-83); the east and west side of Bending Zone 2; epicenters of earthquakes over MMI VII; and the area of sand blows.

The area of strong ground motion is well delineated by the areal extent of the sand blows (Section 2.5.2.3.1.1) as shown on Figure 2.5-85. Work by Stearns and Zurawski (1974) showed that the extent of the sand blows was not limited by the availability of the water or sand required for liquefaction to occur. Subsurface geologic and hydrologic conditions to the northeast, southeast and southwest are similar to those in the sand blow area and would not have imposed a limiting factor. To the northwest the sand blow area abuts against Crowleys Ridge where conditions are not suitable for liquefaction; however, the geologic terrane northwest of Crowleys Ridge is not significantly different from that of the sand blow area east of Crowleys Ridge. Had strong enough ground motion occurred to the northwest of Crowleys Ridge, liquefaction and sand blows would have occurred.

The geologic and hydrologic conditions are shown in plan on Figure 2.5-85 and geologic cross sections, modified after Fisk (1944), are presented on Figure 2.5-86. The drill holes shown on Figure 2.5-85 indicate the depth to the water table, depth of clay and silt cohesive soils, and the depth of sand.

j. Using the above as a base, Stearns (1973) derived a definition for the Reelfoot Seismotectonic Structure, as shown on Figure 2.5-87. The northern boundary lies at the -3000-foot contour on top of the Knox Dolomite on the northern flank of the Pascola Arch. The same -3000-foot contour, on the south flank of the Pascola Arch, forms the southern boundary. The eastern boundary is formed by the eastern limit of the northeast-trending faults that coincide with the eastern side of Bending Zone 2. The western boundary is the western limit of the northeast trending faults, the southern end of which is projected southward parallel to the area of sand blows until the line intersects the -3000-foot contour on the southern flank of the Pascola Arch.

The work by Stearns in describing his Reelfoot Seismotectonic structures had considerable merit. However, analysis of Stearns' work in light of more recent data indicates that the basic concept can be refined even more.

Further analysis for this report was pursued by superimposing upon Stearns' map of Figure 2.5-84 the following information:

a. All of the faults presented by Stearns for the Paleozoic, Pliocene and younger formations on Figures 2.5-80 and 2.5-82.

b. All the epicenters shown on Figure 2.5-63;

c. The First, Second, and Third Mississippi Valley faults as depicted on Figure 2.5-88;

d. The principal outlines of the significant magnetic and gravity anomalies shown on Figures 2.5-67 and 2.5-68;

e. The lineations from ERTS and topography (O'Leary and Hildenbrand, 1979) shown on Figure 2.5-69;

f. Pertinent fault plane solutions taken from Street, Herrmann and Nuttli (1974) and Herrmann (1978, 1979) as shown on Figure 2.5-72; and

g. An analysis of the relative strain release of the New Madrid area in terms of cumulative energy released by all tectonic earthquakes since the New Madrid events of 1811-1812, as shown on Figure 2.5-89.

The composite plot of these factors is shown on Figure 2.5-90.

Analysis of the composite plot and background data indicates that:

a. Intrusive masses lie along, or just west of, a line of faulting that corresponds to the First Mississippi Valley Fault and the northwestern boundary of the rift zone, both of which have a trend of about North 45° East passing northwest of Charleston, Missouri.

b. Crowleys Ridge and its pronounced lineaments, as discerned from the investigation of topography and ERTS photography, are coincident with the English Hill and Idalia fault trends. This topographic feature has an overall linear trend of North

47° East but probably does not represent major structure at depth (Zoback, 1979; Kolata, 1978; Bristol, 1978).

c. Crowleys Ridge and the First Mississippi Valley Fault are parallel and lie about 10 miles apart. A distinctive line of epicenters lies along the northeasterly trend of the latter. Although Stearns (1973) chose a line of presumed faulting along Crowleys Ridge to define the northwestern boundary of his Reelfoot Seismotectonic Region, this work redefines this region of high intensity motion as the New Madrid Seismotectonic Region and conservatively places the northwestern boundary at the First Mississippi Valley Fault, which is preferentially chosen on the basis that:

   1. The principal seismic activity is bounded to the northwest by the westernmost northeast-trending zones of major structure in the embayment rather than by the Crowleys Ridge, which probably does not represent major faulting.

   2. Faulting southeast of this boundary is recent and active as evidenced by the seismic history and Holocene disruption (Russ, 1979).

   3. Seismic monitoring in the embayment region defines a distinct zone of epicenters (Figure 2.5-74) marking the western limit of stress relief. The westward extension of this zone is contained by the First Mississippi Valley Fault.

   4. The change in the seismicity alignment from the preferred northeast trend to a primarily northwest trend occurs at the intersection of the Reelfoot rift with the axis of the Pascola Arch. Further, this zone of major seismicity occurs between the Bloomfield and Covington plutons (Figure 2.5-65) which are related to the anomalous structural conditions (rifting) of the crust in this locale. This circumstance of major earthquake area and extensive gravity highs and associated magnetic anomalies has been noted by Kane (1977) in or near seven major seismic areas in the eastern United States. This coincidence of structure and seismicity is contained to the northwest by the First Mississippi Valley Fault.

d. The eastern boundary of the New Madrid Seismotectonic Region is delineated by the coincidence of the change in the density of epicenters toward the southeast with the fault that is identified as the Second Mississippi Valley fault in the discussion of Section 2.5.2.3.1.1 and as shown on Figures 2.5-10, 2.5-88, and 2.5-90. To the south, the trend of the second Mississippi Valley Fault projects into a series of lineations that coincide with a line beginning at the south end of the North 40^{O} East faults described above, and extending in a curving line until it merges with the line of faults that Stearns (1973) describes as the East Limit of the northeastern trending faults. As the southern end of the New Madrid Seismotectonic Region is beyond the scope of this study, Stearns' southwestern seismotectonic boundary serves as a reasonable boundary and is so accepted for the purpose of this report.

The northern extent of the New Madrid seismic zone is herein terminated (pinches out) at the Fluorspar Fault Complex and the western Kentucky Faulted belt. Investigations in the extreme southern tip of Illinois (Kolata et al., 1977 ,1981) have disclosed no recent tectonic movement in the faults of this area, most of which have been displaced in post-Paleozoic to pre-late Cretaceous time. Closely spaced drilling at two localities in Pulaski County disclosed that faults in the immediate area are probably due to landslides or solution cavity collapse (Kolata et al., 1977).

Bending Zone 2 has been defined by Stearns (1973, 1974) as the synclinal axis of the Mississippi Embayment (Section 2.5.2.6.1.1.6). The structural significance of Stearns' Bending Zone 2 is that it coincides with a series of unique and anomalous tectonic features including: a zone of northeast-southwest trending faulting; the area of sand blows, the zone of concentrated epicenters for violent seismic events; and a location at the trough of the Mississippi Embayment. The location of Bending Zone 2 is spatially coincident with the combined New Madrid-Reelfoot Seismotectonic regions such that they occupy the full width of Bending Zone 2. This may be clarified by noting on Figure 2.5-91 that the line indicating the First Mississippi Valley Fault is also approximately coincident with the west side of Bending Zone 2. Stearns considers that Bending Zone 2 provides evidence of the presence of an underlying zone of tectonic weakness and instability. Whether or not the Bending Zone by itself constitutes a mechanism for the generation of strong motion events is not of great importance; rather it is more important to note that it is coincident with a focus of multiple

anomalous conditions. Thus it cannot be demonstrated whether the Bending Zone is a contributary agent to the strong motion events at this focus or, rather, a result of the forces that cause the seismicity. In any case, the coincident presence of Bending Zone 2 with other anomalous features appears significant even though the ultimate mechanism for strong motion events has not yet been recognized.

In summary, as shown on Figure 2.5-91, the New Madrid Seismotectonic Region is bounded on the northwest by the First Mississippi Valley Fault, the west side of Bending Zone 2, and the rift boundary. On the east, it is bounded by the eastern (Second) Mississippi Valley Fault. To the north, it is bounded by the change in strain release along the northwest trend coincident with the -3000-foot contours on the northern flank of the Pascola Arch. This bounded region is characterized by strong motion earthquakes with intensities of MMI IX and greater superimposed upon a background of repetitive lower-intensity events.

Historical and current seismicity data, together with this analysis, indicate that strong motion events greater than MMI VII are limited to the New Madrid Seismotectonic Region as defined herein and will approach the site no closer than about 175 miles.

2.5.2.3.1.2 Other Seismotectonic Regions

Although there is much evidence available to delineate the New Madrid Seismotectonic Region, other areas of the surrounding region have not been so intensively studied; the boundaries of seismotectonic regions, therefore, are not completely established. Nevertheless, certain gross trends can be discerned, and it is useful to delineate them in the light of present knowledge even though they are subject to refinement as more data become available.

2.5.2.3.1.2.1 Reelfoot Seismotectonic Region

Some seismicity is related to the region east of the New Madrid Seismotectonic Region as herein defined. However, it is characterized by fewer and lower-intensity events that separate it from the New Madrid Region. The New Madrid Seismotectonic Region is characterized by strong ground motion of about MMI IX or higher, whereas the region to the east is characterized by events MMI VI or less, with no earthquake to the east having generated ground motion greater than MMI VII. The contrast in seismicity lies along the line of the eastern (Second) Mississippi Valley Fault (approximately along the Mississippi River) and constitutes the boundary of the lower intensity events.

According to O'Leary and Hildenbrand (1979), geomorphologically, the northern part of the Mississippi Embayment is divided into two distinct terrains. The authors observe:

> "The half of the embayment east of the Mississippi River has normal basinal features: tributaries that drain down the dipslope toward the axis of the basin; a crenulated, eroded contact of basin sediments on Paleozoic "basement" rocks; development of a shallow cuesta on the most resistant unit. The western half on the other hand, has tributaries to the Mississippi that flow S20W, parallel to the axis of the basin; the contact with the Paleozoic border rocks is a very subdued fall line; the uppermost sediments are less than a million years old and surround inliers of older rock; earthquake epicenters are thickly concentrated near the river and less so to the west. These features all suggest that the west half of the embayment is presently undergoing a tectonic development independent of the east half."

A preliminary analysis indicates that the eastern border of this region of lower intensity lies approximately coincident with Stearns' (1972) eastern limit of faulting, as shown on Figure 2.5-82. The northern boundary abuts the Fluorspar Fault Complex and the Western Kentucky Faulted Belt, which are regions of complex structural conditions lying south of the east-west trending Rough Creek Fault System (Section 2.5.1.1.5.2.3).

This area of lower seismic activity is herein described as the Reelfoot Seismotectonic Region. It consists of a triangular area bounded on the west by the New Madrid Seismotectonic Region, on the east by the East Embayment Block (discussed in Section 2.5.2.3.1.2.2), and to the north by the Fluorspar Fault Complex and Kentucky Faulted Belt (Section 2.5.2.3.1.2.4).

2.5.2.3.1.2.2 East Embayment Seismotectonic Region

The East Embayment Seismotectonic Region is generally coincident with the eastern portion of the Mississippi Embayment. This area has had no known fault movement since Cretaceous time and only a very minor history of local seismic events (Stearns and Wilson, 1972). The eastern boundary of this region is the Nashville Dome and coincides with the edge of the Mississippi Embaymen and with the escarpment of the Nashville Dome (Cumberland Plateau), all of which constitutes Stearns and Wilson's (1972) Bending Zone 1. This boundary apparently represents a physiographic and old tectonic border and it does not appear to be related to significant modern seismic activity (Stearns and Wilson, 1972).

The northern boundary is a continuation of the edge of the Mississippi Embayment as it curves westward and abuts against the Western Kentucky Faulted Belt and further west against the southern edge of the Fluorspar Fault Complex. There is little contrast in seismicity across the northern boundary, although incidence of seismicity is somewhat higher to the north. The western boundary with the Reelfoot Seismotectonic Region lies along Stearns' (1972) eastern limit of northeast trending faults.

2.5.2.3.1.2.3 Nashville Dome

The Nashville Dome is largely unfaulted and represents a major tectonic uplift initiated in the Paleozoic. It is now a structurally stable area and essentially aseismic (Stearns and Wilson, 1972). The eastern boundary of this region with the East Embayment Block lies along Stearns' Bending Zone 1, which coincides with the escarpment of the Nashville Dome.

The northern boundary between the Nashville Dome and the Western Kentucky Faulted Belt is geologic and represents the margin of the tectonic dome. To the north, there are many mineralized faults and the seismicity is somewhat higher (Stearns and Wilson, 1972). The eastern and southern boundaries of the Nashville Dome are not critical to the purpose of this report.

2.5.2.3.1.2.4 Fluorspar Fault Complex and the Western Kentucky Faulted Belt Seismotectonic Region

The Fluorspar Fault Complex and the Western Kentucky Faulted Belt are two complex systems of faults that lie in southern Illinois and western Kentucky. The faults of the Fluorspar Fault Complex are characterized by a series of faults having a North 40° East trend covering an area 40 miles wide by about 60 miles long. This series of faults extends from beneath the late Cretaceous sediments of the Mississippi Embayment on the south to the east-west trending Rough Creek Fault Zone on the north. The Western Kentucky Faulted Belt is characterized by faults having a trend of about North 60° East, and lying in an area about 80 miles long east to west and about 40 miles north to south. The north boundary of this region is considered as lying along the Rough Creek Fault Zone. The Wabash Valley Seismotectonic Region, as discussed in Section 2.5.2.3.1.2.5, lies to the north. The southern boundary lies along the northern boundaries of the Reelfoot, the East Embayment Seismotectonic regions, and the northern flank of the Nashville Dome. The eastern boundary of the Illinois Basin Random Region and the Ste. Genevieve Seismotectonic Region lies along the projection to the northeast of the Northwestern boundary of the

New Madrid Seismotectonic Region, as discussed in

Section 2.5.2.3.1.1, and corresponds to a line of contrast in seismicity. To the west lies the Illinois Basin Random Region, where seismic activity is low with a few random events that have reached a maximum of MMI VII, the Ste. Genevieve Region, and the Border Region.

The region of the Fluorspar Fault Complex and the Western Kentucky Faulted Belt is a basically stable area with only a few low intensity, randomly-occurring earthquake epicenters (Baxter et al., 1973; Stearns and Wilson, 1972). The pattern of seismicity is diffuse and historic earthquake epicenters appear to show no relationship to known faults (Kolata, Treworgy and Masters, 1981).

2.5.2.3.1.2.5 Wabash Valley Seismotectonic Region

The Wabash Valley Seismotectonic Region consists of the area surrounding the Wabash Valley faults. This system is generally parallel set angle normal faults that bound horst and grabens. The region has moderate seismic activity; the maximum earthquake associated with the region is of MMI VII (Figure 2.5-49). Some authors have proposed that this region represents a northern extension of the New Madrid Fault Zone. However, recent studies (Bristol and Treworgy, 1978) conclude that the Wabash Valley fault system is not contiguous to the faulting to the south (Kentucky fault zone, Shawneetown-Rough Creek fault zone, Fluorspar fault complex, New Madrid fault zone), but, rather, the result of different faulting mechanisms. The authors cite that the amount of displacements along the Wabash system decreases southward and that the faults do not intersect, or cannot be extended to, the Shawneetown fault zone immediately to the south. Also, the lower level of seismicity of the Fluorspar Fault Complex - Western Kentucky Faulted Belt tends to refute such a connection. The boundary of this region to the northwest is with the Illinois Basin Random Region and is based on the absence of northeast-trending faults to the west, the change in degree of seismicity, and the lack of correlation of structures with epicenters to the west. The boundary of this region to the south is discussed in Section 2.5.2.3.1.2.4. The boundary to the east lies beyond the scope of this report.

2.5.2.3.1.2.6 Illinois Basin Random Region

The Illinois Basin Random Region comprises the Illinois Basin tectonic province. This region has low seismic activity but has produced a few events of intensity as high as MMI VII. In general, the earthquakes cannot be related to known structural features and must be considered as having a random occurrence anywhere within the region. Work by McGinnis and Ervin (1974) led them to believe that earthquakes may more often occur between crustal blocks as delineated by steep gradients on gravity maps.

To the west, the Illinois Basin Random Region is separated from the Ste. Genevieve and Chester-Dupo Seismotectonic regions and the Missouri Random Region by the structural change that separates the Illinois Basin from the Ozark Uplift (Section 2.5.1.1.5.1.11) and the Lincoln Fold (Section 2.5.1.1.5.1.21). The bordering Ste. Genevieve and ChesterDupo Seismotectonic regions exhibit greater total seismicity than the Illinois Basin Random Region.

In contrast, the Missouri Random Region has much less total seismicity than the Illinois Basin Random Region and has had no seismic event greater than Intensity MMI V. The boundary between these two regions is marked by a series of structures that closely follow the Mississippi River, including the Cap au Gres Fault (Rubey, 1952; Tikrity, 1968) and the Lincoln Fold (McQueen et al., 1941).

The borders with the Fluorspar Faulted Complex and the Wabash Valley Seismotectonic Region are discussed above (Sections 2.5.2.3.1.2.4 and 2.5.2.3.1.2.5). The boundaries of the Illinois Basin Random Region to the north, northeast, and northwest are beyond the scope of this report.

2.5.2.3.1.2.7 West Embayment Seismotectonic Region

The West Embayment Seismotectonic Region lies between the New Madrid Seismotectonic Region, as described in Section 2.5.2.3.1.1, and the northwestern edge of the Mississippi Embayment (Section 2.5.1.1.5.1.10). It is a seismotectonic region of low to moderate activity, with a maximum associated event of MMI VI (Figure 2.5-49). Earthquakes in this region cannot be related to known geologic structures. Fault plane solutions in this region exhibit varying mechanisms as shown by Solutions 3, 5, and 21 (Figure 2.5-72). Fault plane Solution 3 is believed to be associated with the north-south fault, which probably bounds the west sides of Anomalies A and B, as discussed in Section 2.5.2.3.1.1.7.

The northwest boundary of this region is delineated by the western edge of the upper Mississippi Embayment, which coincides with the Ozark Escarpment and which also lies along Stearns and Wilson's (1972) Bending Zone 3.

The low to moderate seismic activity of this region contrasts with the strong motion events of the New Madrid Seismotectonic Region to the southeast and with the historically low seismic activity of the Border Region to the northwest. The extent of the West Embayment Region to the southwest is unknown and is beyond the scope of this report.

2.5.2.3.1.2.8 Border Seismotectonic Region

The Border Region is a stable area lying along the southeastern flank of the Ozark Uplift. It is historically of low seismicity with earthquakes being infrequent and of MMI IV or less. This region is bordered on the southeast by the northwestern boundary of the New Madrid Seismotectonic Region along the edge of the upper Mississippi Embayment and coincident with Bending Zone 3 described by Stearns (1974) and discussed in Section 2.5.2.3.1.1.7. To the northeast, the region is bounded by the southwesternmost faulting associated with the Ste. Genevieve Fault System (Section 2.5.1.1.5.2.15). To the northwest, the region is bounded by the core of the St. Francois Mountains along the interface of the northeast trending Greenville Fault (No. 18 on Figure 2.5-66) (McCracken and McCracken, 1965). The extent of the region towards the southwest is unknown and beyond the scope of this report.

2.5.2.3.1.2.9 St. Francois Seismotectonic Region

The St. Francois Seismotectonic Region is a region of low seismicity related to faults on the margin of the St. Francois Mountains. Differential uplift between the St. Francois Mountains and the remainder of the Ozark Uplift probably created the residual stresses that have generated the moderate seismic events. The seismicity of the St. Francois Seismotectonic area is characterized by a maximum intensity of MMI VI.

As shown on Figure 2.5-66, the faults that surround the margin of the St. Francois Mountains include the Simms Mountain Fault Zone (No. 37) to the northeast, the Greenville Fault (No. 18) to the southeast, the Black (No. 4) and the Ellington (No. 14) faults to the southwest, and the Big River Fault System (No. 3) to the northwest.

Comparison of the fault plane solutions of Figure 2.5-72 with the faulting shown on Figure 2.5-66 indicates that the Simms Mountain Fault is coincident with Solution 36; the Black Fault lies northeast of Solutions 13 and 15; and the Ellington Fault appears to be coincident with Solutions 18 and 19. These solutions all indicate that the northwesterly trending faults may have a normal oblique fault mechanism. Solution 16 is coincident with the Ellington Fault but does not match Solutions 18 and 19. Solution 22 does not appear to be related to any known fault.

2.5.2.3.1.2.10 Ste. Genevieve Seismotectonic Region

The Ste. Genevieve Seismotectonic Region is related to and defined by the imbricated Ste. Genevieve Fault System.

The Ste. Genevieve Fault System is discussed in Section 2.5.1.1.5.2.15, by Tikrity (1968), and by Gibbons (1972), and is shown on Figure 2.5-66.

The Ste. Genevieve Fault System, including the Rattlesnake Ferry extension in Illinois, is about 100 miles long from end to end. It has a sinuous trace that has an overall strike trend direction of about North 30° West. Although the system contains some horsts and locally exhibits high angle compensatory normal faults, the main displacements consist of high angle faults. These faults demonstrate uplift of the crustal blocks to the southwest relative to the downthrown crustal blocks to the northeast, which are also tilted into the Illinois Basin. Vertical offsets along the upthrust fault system reach a maximum of nearly 2000 feet near the center of the fault system and diminish considerably along its trace to the northwest and southeast.

Faults and structures that are part of the Ste. Genevieve Fault Zone include the Ditch Creek Fault System (Warfield, 1953), and Valles Mines-Vineland Fault Zone (Parizek, 1949), the Rugley School Fault (Pike, 1929), the Cruise Mill-Fertile Fault Zone (Parizek, 1949), the Menfro faults (Flint, 1926), the Omete Creek Fault (Flint, 1926), the Mahken Branch Fold (Flint, 1926), the Richwoods Fault Zone (Warfield, 1953), Pleasant Creek Monocline (Flint, 1926).

The Ste. Genevieve Fault Zone and its possible extension, the Ditch Creek Fault, end in the vicinity of the town of St. Clair in Franklin County. In this vicinity, the character of the geologic terrane changes along a line trending northeast-southwest, roughly coincident with the course of the Meramec River. Work in this study area appears to indicate that this line demarcates the northwestern boundary of the crustal block that Gibbons (1972) has designated the Potosi Block. We suggest that this line of demarcation, or lineament, be designated as the Meramec River Lineament.

The Meramec River Lineament is a major dividing line separating the Potosi Block--which constitutes one of the main crustal blocks which have been elevated in the heart of the Ozark Uplift--from the other blocks in the northwestern flank of the Ozark Uplift in the area of the Cuba Graben. To the southeast of the Meramec River Lineament, the movement in Paleozoic time along the Ste. Genevieve Fault Zone resulted from differential uplift of blocks in the Ozark Uplift to the southwest and blocks in the Illinois Basin to the northeast.

Strong northeasterly trending features (faults, lineaments in structural contours. change in trends of surface outcrop belts, change in strike of the Leasburg structure) indicate

that a major crustal block boundary transects and terminates the Ste. Genevieve Fault along a zone roughly corresponding to the position of the Meramec River. Further, it is considered significant that the indicated Meramec Lineament is roughly coincident with the northwestern margins of the Chester-Dupo, Ste. Genevieve, and St. Francois Seismotectonic regions shown on Figure 2.5-61. It is probable that the Meramec Lineament constitues the northwestern margin of seismic activity associated with these regions. The Meramec River Lineament nearly coincides with a gravity gradient lineament, the St. Louis Lineament (Figure 2.5-69). Also parallel to these two lineaments are other linear features resulting from structure, alignment of epicenters, outcrop pattern, topographic linears, ERTS imagery linears, cave trends, and alignment of springs.

Analysis of the Bouguer gravity map of southeastern Missouri (Figure 2.5-68) reveals a prominent gravity gradient between St. Louis and Rolla, Missouri, which Phelan (1968) had interpreted as resulting from a difference in crustal thickness. The thin and thick crustal blocks are separated by a structurally weak zone. This corresponds very closely with the structural concepts of Gibbons (1972). Parallel to the lineaments between Rolla and St. Louis is a zone of structural disturbance. Beds are more highly folded as shown by structure contours drawn on top of the Roubidoux Formation. Major fold axes trend northwest, but there is a nosing trend eastnortheastward. Also the major faults trend northwest, but there are some (Virginia Mines Fault, Catawissa Fault, and portions of the Leasburg Fault; Figure 2.5-66) that trend east-northeast near the St. Louis Lineament. Very possibly related to this structurally disturbed zone is a concentration of springs along this zone that extends further southwest across the state (Figure 2.5-23). Also, there is a northeast trend to many ERTS, topographic linears, and to the alignment of some caves.

Earthquakes of the Ste. Genevieve Seismotectonic Region exhibit a characteristic maximum intensity of MMI VI, and there is no direct evidence that the Ste. Genevieve Fault System is capable. No fault plane solutions from Street and Herrmann (1974) and Herrmann (1973, 1979), shown on Figure 2.5-72, are found to coincide with the trace of the Ste. Genevieve Fault.

The boundary of this region with the St. Francois Seismotectonic Region to the southwest is based on a change in seismicity coincident with a change in structure related to the Farmington Block as identified by Gibbons (1972). The seismic events to the south appear to be related to the Simms Mountain and related faults at the north margin of the St. Francois

Mountains. The change in character from the Ste. Genevieve to the St. Francois regions is transitional, but there is a definite structural break along the Simms Mountain Fault (Tikrity, 1968).

The boundary with the Border Region to the south is largely based on the contrast of seismicity and is poorly defined; however, the boundary is spatially related to the seismicity coincident with the Ste. Genevieve Fault System. The boundary to the north with the Illinois Basin Random Region also is based largely on the contrast in seismicity. The boundary with the Chester-Dupo Seismotectonic Region to the north is based upon changes both in seismicity and structure as discussed in Section 2.5.2.3.1.2.11. The southeastern border of the Fluorspar Faulted Complex-Western Kentucky Faulted Belt Seismotectonic Region is not well defined since the Ste. Genevieve Fault System dies out before it reaches the Fluorspar Faulted Complex. A continuation of the Ste. Genevieve Fault System into Tennessee has been hypothesized by Heyl (1965) and Hildenbrand et al. (1977) based on interpretation of geophysical data; however, this has not been substantiated. For the purpose of this report, the Ste. Genevieve Seismotectonic Region is extended along this projected direction of the Ste. Genevieve Fault to its abutment against the northwestern edge of the Fluorspar Faulted Complex. To the northwest, the Ste. Genevieve Seismotectonic Region ends at the Meramec River Lineament.

2.5.2.3.1.2.11 Chester-Dupo Seismotectonic Region

The Chester-Dupo Seismotectonic Region (a name originally proposed by Nuttli, 1973c) encompasses an area underlain by folding and some known faulting in the vicinity of St. Louis, Missouri.

The Dupo Anticline (No. 20 on Figure 2.5-12) together with the Dupo-Waterloo Anticline in Illinois (No. 3 on Figure 2.5-13), and the Florissant Dome (No. 24 on Figure 2.5-12) have an overall axial trend of about North 15° West. The Cheltenham Syncline (No. 13 on Figure 2.5-12) lies to the southwest of the Dupo structure. The St. Louis Fault (No. 39 on Figure 2.5-13; Frank, 1948, Brill et al., 1960) lies in the same area, but is a much smaller structure (discussed as item 39 under Missouri in Table 2.5-3); it has a displacement of only 10 feet, and appears to have a crosscutting relationship to the Dupo Anticline. The St. Louis Fault does, however, lie along the trend of the Plattin Anticline (No. 55 on Figure 2.5-12) (Pike, 1929). The relationship of the faulting and folding to seismicity is not clear; nevertheless, the coincidence of faulting, folding, and epicentral locations provides an overall north-south trend.

The Chester-Dupo Seismotectonic Region is one of moderate seismicity characterized by a maximum MMI of VI. Recent work by Nuttli (1973c) has shown that some of the old historic earthquakes originally attributed to this region actually occurred further east in the Illinois Basin Random Region near Centralia, Illinois. To the south, the Chester-Dupo Seismotectonic Region borders on the Ste. Genevieve Seismotectonic Region. This border is delineated by a change in the trend directions along which the seismic events have occurred. To the north of this boundary, the epicenters are aligned along north-south trends parallel and subparallel to the structures described above. To the south of this boundary, the epicenters appear to be aligned along a southeast trend that parallels the Ste. Genevieve trend and its associated structures such as the Valles Mines-Vineland Fault Zone (Parizek, 1949), the Ditch Creek Fault System (Warfield, 1953) and the Rugley School Fault (Pike, 1929). To the east, the Chester-Dupo Seismotectonic Region is bounded by the transition from the folds described in this section to the deeper portions of the Illinois Basin along the hinge line, which separates the basin from the front elements of the Ozark Uplift. To the north, the Chester-Dupo Seismotectonic Region appears to be bounded by the eastward projection of the Cap au Gres Fault (No. 7 on Figure 2.5-13) along its apparent strike of about South 80° East. To the west, the boundary with the Missouri Random Region is based upon a distinct change in seismicity, coincident with the Meramec River Lineament.

2.5.2.3.1.2.12 Missouri Random Region

The site lies in an area of central Missouri characterized by random seismic events of maximum MMI V which are not associated with known geologic structures. This region is herein designated as the Missouri Random Seismotectonic Region. As shown on Figure 2.5-61, the Missouri Random Region borders upon the Chester-Dupo, Ste. Genevieve, St. Francois, and the Border Seismotectonic regions.

Inspection of the Bouguer gravity anomalies shown on Figure 2.5-68 reveals a mosaic pattern which McGinnis (1974) describes as being characteristic of undisturbed regions of the midcontinent. According to McGinnis, the mosaic pattern is produced by mass concentrations that were emplaced in Precambrian time by mechanisms that are not completely understood. A convective overturn of crust involved in plate motions similar to those occurring at the present time is probably the most likely explanation.

Such mosaic gravity regions of the mid continent are generally associated with regions of random or infrequent

seismicity. These mosaic patterns outline blocks of Precambrian crust that differ slightly in density, a differential of about 0.1 gm/cm3.

Boundaries of the Missouri Random Region to the north, west and south are not herein defined.

2.5.2.3.1.3 Identification and Description of Capable Faults

The term "capable fault" as defined in NRC Guideline 10 CFR 100, December 5, 1973, supersedes previous use of the term "Active fault" for this report. For all practical purposes, the New Madrid Seismotectonic Region, as defined, must be considered capable of producing large earthquakes, although no events can be associated with a specific structure at this time.

Outside of the described New Madrid Seismotectonic Region, there is no irrefutable evidence establishing capability of any known structure in the entire mid-continent region. In the New Madrid Seismotectonic Region, however, capability should be assumed, from a practical standpoint, on the basis of the sheer number and dense distribution of instrumentrecorded events, along as yet unidentified discrete structures (Figure 2.5-74). The capability of near-surface structures near Reelfoot Lake (Russ, 1979; Zoback, 1979) has been suggested and somewhat corroborates the assumption of capable structures in this area of intense seismic activity.

An evaluation of the earthquake potential of such a capable structure is not necessary for this report, since a recurrence of the largest New Madrid event (1812) is assumed for this seismotectonic province. According to Nuttli and Herrmann (1978), its magnitude of 7.5 saturates the mb scale and represents a truly major event, similar to the great earthquakes associated with movements along lithospheric plate boundaries.

Faulting in the Mississippi Embayment area is considered to be capable, as described in Section 2.5.1.1.5.2.13 and in the discussions in Sections 2.5.2.3.1.1 and 2.5.2.3.1.3.

The faults in the New Madrid Seismotectonic Region are discussed in detail in Section 2.5.2.3.1.1.7. The Intensity X to XII New Madrid earthquakes of 1811-1812 altered the topography of 30,000 to 50,000 square miles of unconsolidated alluvial material of the Mississippi Embayment (Section 2.5.1.1.5.1.19) and may have been responsible for the faulting near Reelfoot Lake described by Olive (1969). Recent investigations indicate that little or no near-surface fault movement occurred along the Reelfoot Scarp during the 1811-1812 events (Stearns, 1980;

| Russ, 1979; Zoback, 1979). Similar disruption occurred

during the MMI VIII Charleston, Missouri, earthquake of 1895, but on a much smaller scale.

2.5.2.3.2 Recurrence Intervals

Recurrence intervals for seismic events in the various seismotectonic regions are presented only to demonstrate the contrasting characteristics of frequency of return for different seismotectonic regions. These have been plotted on Figure 2.5-92 as Modified Mercalli Intensity versus the log of the number of earthquakes for a given seismotectonic region, expressed as number of events per 1,000 square kilometers per 100 years. Due to the brevity of the record, the recurrence curves are not intended to be used to calculate exact earthquake return periods. Rather, they are considered to be useful as a way of comparing the characteristics of the various seismotectonic regions. Thus the curves show relative characteristics of size, frequency, and maximum earthquakes for each region. From Figure 2.5-92, it is seen that the frequency of occurrence for seismic events is greatest for the New Madrid Seismotectonic Region and is least for the Missouri Random Region. Although the historical data base is relatively short in comparison to geologic time, the data are not unmeaningful when compared to the projected 40-year operational life of the proposed facility.

Recent work on earthquake recurrence by Nuttli and Herrmann (1978) gives an estimate of the return period of earthquakes in a study area centered in southeast Missouri. These data indicate the recurrence of a New Madrid-type event to be around 800 to 1000 years in the seismically active zone around the Mississippi Embayment. A recent study of fault displacement in younger sediments in western Tennessee (Russ, 1978) concluded that major earthquakes in the area have an average recurrence period of 666 years. Therefore, geologic evidence is in fairly good agreement with seismicity data (Nuttli and Herrmann, 1978). Johnston (in press) incicates that the average recurrence rates (63% probability of occurrence) for large new Madrid earthquakes with body wave magnitudes mb = 7.0 - 7.3 are 912 - 1687 years/events.

2.5.2.4 Maximum Earthquake Potential

In order to establish criteria for the Safe Shutdown Earthquake, an examination has been made of the degree of ground motion that is possible considering both the seismic history and geologic structure of the region and the specific site area. To summarize, the seismogenic regions within 200 miles of the site as discussed in the previous section are listed below, with their maximum historical event and closest approach to the site (see Figure 2.5-49).

REGION	MAX. HIST. EVENT	CLOSEST SITE APPROACH
St. Francois	VI	65 miles
Ste. Genevieve	VI	70 miles
Chester-Dupo	VI	70 miles
Illinois Basin Random	VII	70 miles
Border	IV or less	140 miles
West Embayment	VI	160 miles
New Madrid	XI - XII	175 miles
Wabash Valley	VII	180 miles
Fluorspar Fault Complex	low	180 miles
Reelfoot	VII	185 miles
Missouri Random	V	site

While there are substantial differences in the seismic characteristics of many of the regions listed above, there is perhaps insufficient geologic evidence to define many of them as discrete seismotectonic provinces. The structure and seismicity of the New Madrid area, however, clearly describes a seismotectonic province, the closest approach to the site of which is fairly distinct for purposes of this study, and is consistent with an appropriate level of conservatism. It is also seen that no events outside this seismic zone (within the area of influence of the site) have exceeded Intensity VII. Elsewhere in the Central Stable region of the midcontinent, earthquakes as high as Intensity VII-VIII have been reported, but can be confined to zones or structures that preclude their consideration for recurrence in the site vicinity. Also, there are no geologic structures which would tend to localize earthquakes in the site vicinity.

Considerations for the maximum potential earthquake, then, include (1) a random Intensity V occurring adjacent to the site (Missouri Random Region), (2) conservatively, an Intensity VII, a minimum distance of 70 miles from the site, and (3) a recurrence of the New Madrid Intensity XI-XII shock 175 miles from the site. On the basis of attenuation studies of the historical effects of the New Madrid event, it is concluded that such a recurrence would supersede the design considerations imposed by the lesser events specified in (1) and (2) above.

It is appropriate, then, to examine the possible site effect from this large candidate event in terms of historical data and recent attenuation studies.

2.5.2.4.1 Attenuation Studies

Attenuation studies for the eastern and central United States have been concerned with the diminuation of Modified Mercalli

Intensity with distance, since the bulk of the data is in terms of intensity or damage. However, later studies, because of the increased instrumental coverage in recent years, have calculated the attenuation of ground motion parameters (acceleration, velocity) directly with distance in various characteristic geologic regimes. To avoid confusion in this study, the intensity at the site from a recurring design event will be addressed initially, while the intimately related levels of ground motion will be addressed in a subsequent section.

The most recent studies of mid-continent attenuation admittedly calculate levels of ground motion that are unrealistic when applied to large events like the New Madrid experience. By way of example, recent relationships for the attenuation of intensity with distance for the mid-continent region have been published by Gupta and Nuttli (1976) and Gupta (1976), and are, respectively, as follows:

$$IR = IO + 3.7 - .0011R - 2.7 \log R \quad (R \geq 20 \text{ km}) \qquad (2.5\text{-}1)$$

$$IR = IO + 2.35 - .00316R - 1.79 \log R \quad (R \geq 20 \text{ km}) \qquad (2.5\text{-}2)$$

where

IR = MM Intensity at distance R from the maximum epicentral Intensity, IO.

Both formulas calculate an intensity of over VIII at the site from a recurrence of a New Madrid event (XI-XII) at 175 miles. However, these formulas were developed from alluvial response to central U.S. earthquakes, the largest of which was Intensity VIII. Thus, as shown in a later section (2.5.2.6), an extrapolation of these correlations to the large New Madrid event is unrealistic, resulting in site intensities for the subject foundation materials that far exceed the actual historical experience discussed below.

It should be also considered that historic attenuation of the New Madrid events is greater to the northwest and southwest than it is to the northeast and east. The formulas above are based on an average radius and would thus yield high values to the northwest (site direction) of the epicentral zone of the 1811-1812 shocks.

In consideration of the recommended limitations of the above relationships, the attenuation for the large New Madrid events can be examined using the actual historic data available from several investigations.

The first curves investigated are those by Weston Geophysical Company for the Stearns and Wilson report (1972), as shown on

Figure 2.5-93. This range is representative of Californiatype earthquakes having relatively rapid attenuation. The same figure, which gives attenuation in various directions from the epicenter, shows the attenuation curves derived from Stearns and Wilson's isoseismal map for the New Madrid earthquake of 1811. Attenuation for the 1812 New Madrid earthquake is shown on Figure 2.5-94. Ranges and composite attenuation in the east and southeast directions where more data points were available are shown on Figures 2.5-95 and 2.5-96. Figure 2.5-97 shows a composite range of attenuations for the major 1811-1812 New Madrid earthquakes.

The attenuation curves developed form the historical data points for the 1811-1812 events are conservative due to the geomorphic and physiographic conditions influencing wave amplification and attenuation within the floodplain valleys throughout the midwest. Application of these curves to determine either bedrock or surface intensity at the power plant site, located on the upland terrain on better-thanaverage foundation support conditions, is also considered to be conservative.

In none of the synthesized New Madrid attenuation studies from Stearns and Wilson (1972) do intensities at the site exceed MMI VI-VII from a recurrence of the New Madrid earthquake either at its historic epicenter or at the margin of the New Madrid Seismotectonic Region, located about 175 miles to the southeast.

2.5.2.4.2 Maximum Intensity at the Site

Recent attenuation studies based on mid-continent events such as the one shown on Figure 2.5-98 apparently overestimate effects at the site when extrapolated to the New Madrid design event of Intensity XI-XII. Thus, the relationships suggest a site intensity of over VIII for an Intensity XI-XII event at 175 miles. However, based on the actual historic site effects, and ground motion levels associated with such an intensity in well instrumented areas at equivalent distances in other areas, the calculated site effect of VII + is considered unrealistic. A design event of maximum Intensity VII at the site more nearly represents a viable, but conservative level of ground motion upon which to determine a design level of acceleration and is compatible with the historic experience in the site area. This will be discussed in a later section.

2.5.2.5 <u>Engineering Properties of Materials Underlying the Site</u>

The subsurface soil and rock at the site were explored through the drilling of 165 test borings, 131 of which were drilled within the immediate area of the proposed Callaway Plant. The

field and laboratory programs and the analyses of the engineering properties of the subsurface materials are discussed in detail in Section 2.5.4.

The soil deposits encountered at the site are primarily of glacial and postglacial origin; the different units are variable in their engineering properties. These deposits are about 25 to 35 feet thick at the location of the proposed plant.

Development of the power plant and appurtenant facilities included earthwork and grading operations. Site preparation and earthwork for Units 1 and 2 consisted of stripping, excavating, dewatering and backfilling operations to attain a nominal plant grade of elevation 840 feet. All glacial and postglacial soils beneath the power plant and associated Category I structures were excavated to the top of the Graydon chert conglomerate. In order to improve foundation support conditions, the overexcavated soils were replaced with compacted granular structural fill consisting of crushed limestone aggregate. All Category I and heavy structures except the Ultimate Heat Sink (UHS) Retention Pond and Category I pipelines are founded directly upon the Graydon Chert conglomerate or granular structural fill. A discussion of the stability of the subsurface materials including plot plans, subsurface sections and engineering properties of the natural deposits and the fill is presented in Section 2.5.4.

2.5.2.6 <u>Safe Shutdown Earthquake</u>

Based on the above discussions, the maximum intensity at the site would be generated by a recurrence of the largest historical events in the New Madrid seismogenic region, at the closest approach of 175 miles from the site. This motion would supersede that from any credible random events (maximum V-VI) in the region surrounding the site, or the attenuated motion from any events which can be restricted to minimum distances from the site.

On the basis of applicable "historical" attenuation studies, the site intensity for the design event would be less than VII, a level which is corroborated by studies of the effects of the New Madrid events in 1811-1812, as discussed previously.

The foundation support conditions for plant construction are considered to be above average since the plant will be supported, as shown on Figures 2.5-120 through 2.5-122, on a thin layer of crushed rock structural fill placed upon the Gradon chert conglomerate.

The ground motion from the Safe Shutdown Earthquake would consist primarily of surface seismic waves with periods between 1 and 3 seconds, having a total duration of between 1 and 2 minutes. The maximum acceleration from these waves would be realized for only a few seconds with the remainder of the ground motion being at considerably lower levels of amplitude (Nuttli, 1975; Herrmann, 1975; Nuttli and Herrman, 1978).

The level of ground motion to which the site will be subjected as a result of the maximum site intensity of Intensity VII is now discussed.

Directly applying recent Intensity/Acceleration correlations to the (conservative) site design intensity of VII (Trifunac and Brady, 1975; O'Brien et al., 1977), a mean peak horizontal acceleration value between 0.10 and 0.13g is calculated for the Safe Shutdown Earthquake (SSE) as shown on Figure 2.5-99. These values are considered conservative for the design event at 175 miles for the following reasons.

Trifunac and Brady (1975), particularly, have based their mean of 0.13g (for Intensity VII) on maximum peak amplitudes of accelerations taken, in many instances, from instruments sited near the epicenter, of a few larger events. Thus, their mean is weighted somewhat toward the near field wherein one or several sharp spikes of acceleration associated with short periods and high frequencies are typical. Such peaks are not usually evident at distances of concern here; rather, at such distances, a significant portion of the seismic energy is in the form of long-period, large amplitude surface waves where spectral accelerations are proportionately reduced so that the velocity (and displacement) characteristics may become more critical to structural response.

Recently, Nuttli and Herrmann (1978) developed a formula for the attenuation of acceleration with epicentral distance from a given magnitude (mb) event. This equation is based largely on their intensity attenuation relationship previously discussed in Section 2.5.2.4 for the midcontinent, and is their Equation (7).

$$\log Ah\ (cm/sec2) = 0.84 + 0.52\ mb - 1.02 \log R\ (R \geq 15km) \qquad (2.5\text{-}3)$$

which results in a calculated site acceleration level of under 18 percent g.

However, the authors state:

> "Equation (7) was based on data from earthquakes and accelerograph sites in the Mississippi Embayment. Thus Equation (7) may not in fact represent bedrock motions. It is also of interest to note that large accelerations result when Equation (7) is extrapolated to estimate accelerations due to the New Madrid earthquakes of 1811-1812. There is no existing data which can be used to verify the extrapolations to such large magnitude earthquakes. However, we can have confidence in the use of Equation (7) for earthquakes of mb = 6 and less."

Earlier, Nuttli (1973a) presented an analysis that gave the following values as maximum horizontal accelerations specifically for a New Madrid-type event at 175 miles: 0.03g for 0.3-second waves, 0.04g for 1-second waves, and 0.02g for 3-second waves. Taking the largest value indicates a maximum horizontal acceleration of 0.04g.

The notable difference between the estimated 0.04g above and an extrapolation of Nuttli and Herrmann's (1978) Equation (7) to a New Madrid-type event (0.18g at 175 miles) suggests that the recommended application only to mb 6.0 or less should be adhered to.

Nuttli (1973c) has observed that velocity may be the best characteristic to directly describe ground motion and seems more correlatable with the Modified Mercalli Intensity (damage) scale. Nuttli further believes that surface waves may have the greatest damaging effect on a location in the far field such as the site's relationship to the New Madrid epicentral zone.

Intensity-velocity relationships may be derived by first obtaining surface wave attenuation in terms of particle velocity and then converting this value to Mercalli Intensity by comparing known particle velocities at specified intensities.

Using Nuttli's (1973a) bedrock formula,

$$mb = 3.75 + 0.9 \log10 \left(\underline{\quad KM \quad} 111.195 \right) + \log10 (A/T) \text{ microns/sec}, \qquad (2.5\text{-}4)$$

a New Madrid event of mb = 7.5 (Intensity XI-XII) will yield a horizontal vector velocity of 3.06 cm/sec at 175 miles (282 km) (after multiplying by a factor of 2 to convert vertical velocity to a horizontal vector of velocity) (Nuttli, 1973; Street, 1978). Relating this velocity to Intensity using the relationship of Trifunac and Brady (1975),

$$\log Vh = 0.25\ I - 0.63, \qquad (2.5\text{-}5)$$

an intensity of IV to V is calculated for the ground motion generated at the site by a New Madrid-type event at 175 miles. This intensity can then be correlated with an acceleration value of a little over 0.02g using appropriate correlations (Figure 2.5-99).

In summary, the attenuation functions of Gupta (1976), Gupta and Nuttli (1976) and Nuttli and Herrmann (1978), as discussed in Section 2.4.2.4.1, would suggest a site intensity of VIII-IX and an acceleration level at the site of 0.18g (respectively) from a recurrence of a New Madrid event 175 miles from the site. However, it is suggested that the ground motion levels thus derived are not realistic on the basis of the following:

a. Nuttli and Herrmann (1978) state that their equation for site acceleration (not verified for body-wave magnitudes greater than 6.0) appears to overestimate site effects from large New Madrid-type events.

b. The attenuation variable in the relationship above is based on essentially similar formulas developed by Gupta (1976) and Gupta and Nuttli (1976), thus suggesting that a similar extrapolation to large, rare events (beyond the maximum intensity of VIII used for the attenuation data) is not verifiable.

c. Gupta (1976) and Gupta and Nuttli (1976) use average isoseismal radius to develop central U.S. attenuation relationships. As a result, the elongation of recorded isoseismals to the northeast from the New Madrid events would distort the calculated attenuation relationships when applied to the northwest (the site direction). Thus, the asymmetry shown by actual historical experience from the design event suggests that a lower intensity would prevail in the northwest (site) direction.

d. Appropriately-referenced conclusions by the Nuclear Regulatory Commission (1977) concerning the Marble Hill Nuclear Generating Station, located 110 miles from the "New Madrid"-type event, cite the following:

    1. Accelerations exceeding 0.20g are unlikely at epicentral distances beyond 60 miles.

    2. Studies in the mid-continent region indicatethat lower acceleration levels are appropriate (at the distances of concern herein).

3. Much of the damage produced by the New Madrid events may have resulted from soil failure; long duration ground motions with relatively low acceleration can produce such failure.

Nuttli's magnitude formula converts the attenuated New Madrid event to a site intensity of IV to V, with an attendent acceleration level a little over 0.02g at the 175 mile distance.

On the basis of the wide disparity between calculated levels of acceleration at the site (0.03 to 0.18g), a recommended SSE level of 0.20g is considered appropriately conservative for the above-average foundation conditions at the site as an anchor for the response spectra presented in Section 2.5.2.8, below.

2.5.2.7 Operating Basis Earthquake

The Operating Basis Earthquake (OBE) is defined as a recurrence of the New Madrid earthquake near its historic epicenter. Such an event produced site intensities a little over VI (Figure 2.5-56). As in the approach for the analysis of the Safe Shutdown Earthquake in Section 2.5.2.6, the Operating Basis Earthquake of MMI XI-XII will be attenuated to an MMI VI-VII. Using the most conservative correlation shown on Figure 2.5-99, the calculated peak horizontal acceleration at foundation level would be about 0.09g as indicated by Nuttli for the New Madrid event at 175 miles as previously discussed. However, the OBE is herein raised to a value of 0.12g, as a conservative measure.

A statistical analysis has been performed by Algermissen and Perkins (1976) for the contiguous United States. The authors' study considered structure and historical seismicity in contouring expected levels of acceleration. In the site area, they show an interpolated acceleration level of about 6 percent of gravity, with a 90 percent probability of not being exceeded (on hard rock) over a 50-year period. The return period for these parameters is 475 years. This converts to only an 8 percent probability of 0.06g being exceeded on the site bedrock during the 40-year operating life o the facility.

An additional study has been accomplished by the Applied Technology Council (197[illegible]) under contract to the National Bureau of Standards. Their "effective" acceleration for the site area is also about 0.06g with an 80 to 95 percent chance of not being exceeded at any one location in a 50-year period.

Therefore, existing studies concerning site specific risk are compatible, and show the value of 12 percent of gravity to be

conservative, demonstrating a low order of probability for the selected OBE.

2.5.2.8 Response Spectra

Design response spectra are presented on Figures 2.5-100 and 2.5-101. The response spectra are scaled or normalized to the design horizontal ground acceleration for the Safe Shutdown Earthquake of 0.20g and for the Operating Basis Earthquake of 0.12g. These spectra are based on recommended criteria by Newmark, Blume, and Kapur (1973), and published as Regulatory Guide 1.60, as revised. The spectra represent the maximum amplitude of motion over the natural frequency range of various structural elements with typical degrees of damping.

The effects of low frequency, long duration ground motion resulting from an occurrence of the Safe Shutdown Earthquake as defined in Section 2.5.2.6 have been evaluated in order to determine the conservatism of the design response spectra. The analysis was performed using the following approach:

a. The accelerograms of two historical earthquakes having long time histories and with predominant energy in the frequency range between 0.33 and 1.0 Hertz were selected for evaluation. The accelerograms were scaled to a conservative maximum historical acceleration level of sustained motion (estimated for the site from the New Madrid event) and were used to compute model response spectra;

b. The model response spectra of the scaled accelerograms were compared to the design response spectra from Regulatory Guide 1.60, anchored at 0.20g; and

c. The design response spectra from Regulatory Guide 1.60, anchored at 0.20g were compared with the aseismic design recommendations for the central United States proposed by Nuttli (1973c).

The accelerograms that were selected for evaluation were those from the 1949 Olympia, Washington, earthquake and the 1968 Tokachioki, Japan, earthquake. These two historical earthquakes are considered to possess seismic characteristics closely approximating the low frequency, long duration ground motion that would be generated by a seismic event of Modified Mercalli Intensity XI-XII postulated to occur at the western boundary of the New Madrid Seismotectonic Region (Mississippi Embayment Seismic Zone).

Nuttli (1975) suggested the Seattle, Washington, record of the 1949 Olympia, Washington, earthquake. The time history (Murphy and Ulrich, 1951) and response spectra of this seismic

event are well known. The Olympia earthquake had an Intensity of VIII (a Gutenberg-Richter magnitude of 7.1) and its epicenter was located about 40 miles from the recording station in Seattle. However, its duration was about 68 seconds. When scaled to the sustained acceleration level of 0.08g, the computed model response spectra for the Olympia event falls well within the entire design response spectra from Regulatory Guide 1.60, anchored at 0.20g.

The Tokachioki, Japan, earthquake of 1968 is considered to be even more representative of the postulated New Madrid earthquake because of its size and long duration. This earthquake has a (Gutenberg-Richter) magnitude of 7.9, and its epicenter was located about 120 miles from the recording station at Hachinohe Harbor. The accelerogram had a duration of 120 seconds, and the predominant energy was in the frequency range of 0.33 to 1.0 Hertz.

The actual time history of this earthquake is presented on Figure 2.5-102. When scaled to a sustained site acceleration of 0.08g, the computed model response spectra for this event also fall within the design response spectra from Regulatory Guide 1.60, anchored at 0.20g as shown on Figure 2.5-103.

Based on the evaluation of these two historical earthquakes, it is concluded that the effect of earthquake duration has been adequately incorporated into the design response spectra from Regulatory Guide 1.60. Comparison of the model response spectra computed from historical accelerograms with the Regulatory Guide spectra indicates that the Callaway plant design response spectra anchored at 0.20g are conservative, even in the frequency range from 0.33 to 1.0 Hertz.

Furthermore, the design response spectra anchored at 0.20g envelope the ground motion spectra proposed by Nuttli (1973a) in the period range of 1 to 3 seconds. Nuttli (1975) has suggested that, in view of the more recent results of Trifunac and Brady (1975), it would be better on the average to double his earlier values of ground motion. A ground motion spectra curve developed using Nuttli's approach would, therefore, consist of the following three points (at an epicentral distance of 175 miles):

a. At period T = 3.3 seconds, resultant displacement = 2 x 5.6 = 11.2 centimeters;

b. At period T = 1.0 second, resultant velocity = 2 x 6.0 = 12 centimeters per second;

c. At period T = 0.33 second, resultant acceleration = 2 x 0.016 = 0.032g.

These resultant values can be broken down into vertical and horizontal components as shown by Mohraz, Hall and, Newmark (1972). Since the vertical component is very small, the horizontal component values and the resultant values are nearly identical, with the resultants being the more conservative.

REFERENCES: SECTION 2.5

Published References

Aggarwal, Y., 1977, Study of earthquake hazards in New York and adjacent states. Lamont-Doherty Geological Observatory, Annual Technical Report, Phase IV (September 30).

Algermissen, S.T., and Perkins, D.M., 1976, A probabilistic estimate of maximum acceleration in rock in the contiguous United States. U.S. Geological Survey Open File Report 76-416, Department of Interior, 45 p.

Allen, W.H., 1973, First-look analysis of geologic ground patterns on ERTS-1 imagery of Missouri. ERTS Symposium 2.

American Association of Petroleum Geologists, 1971, Future petroleum provinces of the United States - their geology and potential. American Association of Petroleum Geologists, Tulsa, Oklahoma, Memoir, Vol. II, no. 15, p. 1214-1217.

Applied Technology Council, 1976, Working draft of recommended comprehensive seismic design provisions for building. Prepared by Applied Technology Council, San Francisco, California, sponsored by National Science Foundation Research Applied to National Needs Program and National Business Standards (January 31).

Army, Department of, 1970, U.S. Army Engineer Manual 1110-2-1906. Washington, D.C.

Atherton, E.T., 1971, Tectonic development of the eastern interior region of the United States, in Background materials for symposium on future petroleum potential of NCP region 9 (Illinois Basin, Cincinnati Arch, and northern part of Mississippi Embayment). Illinois State Geological Survey, Urbana, Illinois, Illinois Petroleum 96, p. 29-43.

Barosh, P.J., 1969, Use of seismic intensity data to predict effects of earthquakes. U.S. Geological Survey, Washington, D.C., Bulletin No. 1279.

Baxter, J.W., and Desborough, G.A., 1965, Areal geology of the Illinois fluorspar district, Part 2. Illinois State Geological Survey, Urbana, Illinois, Circular No. 385. Baxter, J.W., Potter, P.E., and Doyle, F.L., 1963, Areal geology of the Illinois fluorspar district, Part 1. Illinois State Geological Survey, Urbana, Illinois, Circular No. 343.

Baxter, J.W., Desborough, G.A., and Shaw, C.N., 1967, Areal geology of the Illinois fluorspar district, part 3.

Illinois State Geological Survey, Urbana, Illinois, Circular No. 413.

Baxter, J.W., Bradbury, J.C., and Hester, N.C., 1973, A geologic excursion to fluorspar mines in Hardin and Pope counties, Illinois. Illinois State Geological Survey, Urbana, Illinois, guidebook, series 11.

Bell, A.H., 1929, The Dupo oil field. Illinois State Geological Survey, Urbana, Illinois, Illinois Petroleum, no. 17.

_____, 1943, Subsurface structure on the base on the Kinderhook-New Albany Shale in central and southern Illinois. Illinois State Geological Survey, Urbana, Illinois, Report of Investigation No. 92.

Bell, A.H., et al., 1964, Deep oil possibilities of the Illinois Basin. Illinois State Geological Survey, Urbana, Illinois, Circular No. 38, 38 p.

Ben-Menahem, A., and Singh, S.J., 1972, Computation of models of elastic dislocations in the earth, in Methods of computational physics, seismology--body waves and sources. Academic Press, New York, Bruce A. Bolt, editor, vol. 12.

Bieber, C.L., 1946, Structures and structural trends in southwest Missouri. Missouri Geological Survey and Water Resources, Rolla, Missouri, unpublished manuscript.

_____, 1955, The structural geology of southwestern Missouri. Missouri Geological Survey and Water Resources, Rolla, Missouri, unpublished manuscript.

Billings, M.P., 1972, Structural geology, 3rd ed. Prentice Hall, Englewood, New Jersey.

Bishop, A.W., and Henkel, D.J., 1962, The measurement of soil properties in the triaxial test. Edward Arnold Ltd. (Publishers), London, England, 228 p. Bollinger, G.A., 1977, Reinterpretation of the intensity data for the 1886 Charleston, South Carolina, earthquake, in Preliminary Studies of the 1886 Charleston, South Carolina earthquake, U.S. Geological Survey Professional Paper 1028.

Bond, D.C., et al., 1971, Possible future petroleum potential of region 9 - Illinois Basin, Cincinnati Arch, and northern Mississippi Embayment, in Cram, I.H., Future petroleum provinces of the United States--their geology and potential. American Association of Petroleum Geologists, Memoir, vol. II, no. 15.

Brackenridge, H.M., 1814, View of Louisiana.

Bradbury, J.C., and Atherton, E., 1965, The Precambrian basement of Illinois. Illinois State Geological Survey, Urbana, Illinois, Circular No. 382, p. 9.

Bradford's Illustrated Atlas of the United States, 1854.

Braile, L.W., et al., 1978, An integrated geophysical and geological study of the tectonic framework of the 38th Parallel Lineament in the vicinity of its intersection with the extenson of the New Madrid fault zone, in New Madrid seismotectonic study - activities during fiscal year 1978, T.C. Buschbach, editor, NRC, NUREG/CR-0450, p. 16-44.

Braile, L.W., and Hinze, W.J., 1979, What is the northeastern extent of the New Madrid Fault Zone? Geological Society of America, Abstracts with Programs, vol. II, no. 2, p. 145.

Branson, E.B., 1944, The geology of Missouri. University of Missouri, Columbia, Missouri, Studies no. 3, vol. XIX, p. 274-275.

Brazee, R.J., 1969, Attenuation of modified Mercalli intensities with distance for the United States east of latitude 109 . Seismological Society of America, Bulletin.

Brill, K.G., et al., 1960, Middle Mississippian and Pennsylvanian stratigraphy of St. Louis and St. Louis County, Missouri. Association of Missouri geologists, 7th Annual field trip guidebook, 14 p.

Bristol, H.M., 1967, Structure of the base of the Mississippian Beech Creek (Barlow) Limestone in Illinois. Illinois State Geological Survey, Urbana, Illinois, Illinois Petroleum, no. 88, plate 1. Bristol, H.M. and Treworgy, J.D., 1978, The Wabash Valley Fault System in southeastern Illinois, in New Madrid seismotectonic study - activities during fiscal year 1978. T.C. Buschbach, editor, NRC, NUREG/CR-0450, p. 105-111.

Broadhead, G.C., 1889, The geological history of the Ozark Uplift. American Geology, vol. 3, p. 6-13.

Brownfield, R.L., 1954, Structural history of the Centralia area. Illinois State Geological Survey, Urbana, Illinois, Report of Investigation No. 172.

Buschbach, T.C., 1973, Illinois State Geological Survey, unpublished report.

_____, 1978, Geologic setting of the New Madrid area, Abs. of 3rd Ann. A.G.U. Midwest Meeting, Sept. 26-28, 1977, in New Madrid seismotectonic study-activities during fiscal year 1978. NRC, NUREG/CR-0450, p. 123.

Buschbach, T.C., and Ryan, R., 1963, Ordovician explosive structure at Glasford, Illinois. American Association of Petroleum Geologists, vol. 47, no. 12, p. 2015-2022 (December).

Byerly, P., 1926, The Montana earthquake of June 28, 1925. Seismological Society of America, Bulletin No. 16, p. 209-263.

_____, 1928, Nature of first motion in the Chilean earthquake of November 11, 1922. American Journal of Science, no. 16, p. 232-236.

_____, 1930, Love waves and the nature of the motion at the origin of the Chilean earthquake of November 11, 1922. American Journal of Science, no. 19, p. 274-282.

Casagrande, A., 1936, The determination of the preconsolidation load and its practical significance, in Proceedings International Conference on Soil Mechanics and Foundation Engineering, vol. III, p. 60-64.

Charles, H.H., 1927, Oil and gas resources of Anderson County, Kansas. Kansas State Geological Survey, Lawrence, Kansas, Bulletin No. 6.

Clair, J.R., 1943, Oil and gas resources of Cass and Jackson counties, Missouri. Missouri Geological Survey and Water Resources, Rolla, Missouri, vol. 27, 2nd series, p. 208.
Clark, E.L., 1941, Geology of the Cassville Quadrangle, Barry County, Missouri. University of Missouri, Columbia, Missouri, unpublished Ph.D. dissertation.

Clegg, K.E., 1965, The LaSalle anticlinal belt and adjacent structures in east-central Illinois. Illinois State Geological Survey, Urbana, Illinois, reprint 1965-H, p. 13.

Clegg, K.E., and Bradbury, J.C., 1956, Igneous intrusive rocks in Illinois and their economic significance. Illinois State Geological Survey, Urbana, Illinois, Report of Investigation 197, 19 p.

Coffman, J.L., and von Hake, C.A., 1973, Earthquake history of the United States. U.S. Government Printing Office, Washington, D.C., 200 p.

Cohee, G.V., 1940, Recent developments in oil and gas in Illinois. Illinois State Geological Survey, Urbana, Illinois, Circular No. 97, p. 6.

Cole, V.B., 1961, The Cap au Gres Fault, in Guidebook of 26th annual field conference of the Kansas Geological Society. Missouri Geological Survey and Water Resources, Rolla, Missouri, Report of Investigation No. 27, p. 86-88.

_____, 1962, Configuration of top of Precambrian basement rocks in Kansas. Kansas Geological Survey, Lawrence, Kansas, Oil & Gas Investigation No. 26, map.

_____, 1976, Configuration of top of Precambrian rocks in Kansas. Kansas Geological Survey, map M-7.

Cordell, R.J., 1950, Preliminary report on the geology of Grundy County. Missouri Geological Survey and Water Resources, Rolla, Missouri, unpublished manuscript.

Coulter, H.W., Waldron, H.H., and Devine, J.F., 1973, Seismic and design considerations for nuclear facilities. Proceedings of the 5th World Conference on Earthquake Engineering, Rome, Italy, Paper No. 302.

Cushing, E.M., Boswell, E.H., and Hosman, R.L., 1964, General Geology of the Mississippi Embayment. U.S. Geological Survey Professional Paper 448-B.

Dake, C.L., 1927, Early diastrophic events in the Ozarks. (Abstract) Geological Society of America Bulletin, vol. 38, p. 157-158. _____, 1930, The geology of the Potosi and Edgehill quadrangles. Missouri Bureau of Geology and Mines, vol. 23, 2nd series, p. 233.

Dake, C.L., and Bridge, J., 1932, Buried and resurrected hills of central Ozarks. American Association of Petroleum Geologists, Bulletin, vol. 16, p. 629-652.

Dames & Moore, 1975, Report, on-site rock quarry site selection and feasibility study, source of coarse aggregate, Callaway Plant, Units 1 and 2, for Union Electric Company. Dames & Moore, Park Ridge, Illinois (April 11).

_____, 1975, Report, engineering geology investigation, on-site production mine quarry, source of coarse aggregate, Callaway Plant, Units 1 and 2, for Union Electric Company. Dames & Moore, Park Ridge, Illinois (July 31).

_____, 1975, Report, field and laboratory investigations of the crushed stone structural fill, Callaway Plant, Units 1 and 2, for Union Electric Company. Dames & Moore, Park Ridge, Illinois (August 8).

_____, 1976, Report, results of plate load tests on graydon chert conglomerate, unit 1 power block excavation, for Union Electric Company. Dames & Moore, Park Ridge, Illinois (June 24).

_____, 1976, Report, results of plate load tests on graydon chert conglomerate, unit 2 power block excavation, for Union Electric Company. Dames & Moore, Park Ridge, Illinois (October 27).

_____, 1976, Report, esults of detailed excavation mapping, Callaway Plant, Units 1 and 2, for Union Electric Company. Dames & Moore, Park Ridge, Illinois (August 24).

_____, 1977, Report addendum, engineering geology investigation, proposed on-site production mine quarry, source of coarse aggregate, Callaway Plant, Units 1 and 2, for Union Electric Company. Dames & Moore, Park Ridge, Illinois (June 2).

_____, 1979, Interim report, results of detailed excavation mapping, ultimate heat sink excavation, Callaway Plant, Units 1 and 2, for Union Electric Company. Dames & Moore, Park Ridge, Illinois (April 25).

Darby's Universal Gazetteer, 1827. Docekal, J., 1970, Earthquakes of the stable interior with emphasis on the midcontinent. University of Nebraska, unpublished Ph.D. dissertation.

DuBois, E.P., 1951, Geology and coal resources of a part of the Pennsylvanian System in Shelby, Moultrie, and portions of Effingham and Fayette counties. Illinois State Geological Survey, Urbana, Illinois, Report of Investigation No. 156.

DuBois, S.M., and Wilson, F.W., 1978, A revised and augmented list of earthquake intensities for Kansas, 1867-1977. Kansas Geological Survey, Lawrence, Kansas, Environmental Geology Series 2, 56 p.

Eardley, A.J., 1962, Structural geology of North America. Harper and Row, New York, 2nd edition, p. 37.

Ellis, J.F., 1929, The influence of the environment on the settlement of Missouri.

Eppley, R.A., 1965, Earthquake history of the Unit d States, Part 1, stronger earthquakes of the United States (exclusive of California and western Nevada) through 1963. U.S. Coast and Geodetic Survey.

Farrar, W., and McManamy, L., 1937, The geology of Stoddard County, Missouri. Missouri Geological Survey and Water Resources, Rolla, Missouri, 59th Biennial report 19351936, Appendix 6, p. 92.

Fenneman, N.M., 1911, Geology and mineral resources of the St. Louis Quadrangle, Missouri-Illinois. U.S. Geological Survey, Washington, D.C., Bulletin No. 438, map, p. 73.

_____, 1931, Physiography of the Western United States. McGraw Hill, New York, p. 534.

_____,1938, Physiography of the Western United States. McGraw

Hill, New York, 714 p.

_____, 1946, Physical divisions of the United States. U.S. Geological Survey, Washington, D.C., map.

Finch, W.I., 1971, Geologic map of part of the Bondurant quadrangle, Fulton County, Kentucky and New Madrid and Mississippi counties, Missouri. U.S. Geological Survey, Washington, D.C., map GQ-944.

Fischer, J.A., et al., 1970, Seismotectonic relationships of the New Madrid, Missouri, region. Geological Society of America, vol. 2, no. 7, abstracts, p. 551. Fisk, H.N., 1944, Geological investigation of the Alluvial Valley of the lower Mississippi River. U.S. Army Corps of Engineers, Mississippi River Commission, Vicksburg, Mississippi, 1 vol. of text, 78 p., 1 vol. of maps.

Flint, R.F., 1918, The geology of parts of Perry and Cape Girardeau Counties, Missouri. University of Chicago, Chicago, Illinois, unpublished Master's thesis.

_____, 1926, Thrust faults in southeastern Missouri. American Journal of Science, vol. 12, p. 37-40.

Foster, W.H., 1929, Coffeyville oil field, Montgomery County, Kansas. American Association of Petroleum Geologists, Structure of Typical American Oil Fields, vol. 1.

Fox, J.H., 1954, Cryptovolcanic force field. St. Louis University, St. Louis, Missouri, unpublished Ph.D. dissertation.

Frank, A.J., 1945, The earthquake of March 27, 1945, on the Moselle (Missouri) Fault. American Geophysical Union, trans., vol. 26, no. 3, p. 347-351.

_____, 1948, Faulting on the northeastern flank of the Ozarks, Missouri. Geological Society of America, Bulletin, vol. 12, no. 59, Part 2, 1322 p.

Franks, P.C., 1966, Ozark Pre-Cambrian-Paleozoic relations. American Association of Petroleum Geologists, Bulletin, vol. 50, no. 5, 1035 p.

Friedman, M., 1964, Petrofabric techniques for the determination of principal stress directions in rocks, <u>in</u> State of stress of the earth's crust. William R. Judd, ed., Proceedings of the International Conference, June 13-14, 1963, Santa Monica, California, p. 451-552.

Frye, J.C., et al., 1960, Accretion-gley and the gumbotil dilemna. American Journal of Science, vol. 258, no. 3.

_____, 1960, Accretion-gley, and the weathering profile. Illinois Geological Survey, Urbana, Illinois, Circular No. 295.

Fuller, D.L., et al., 1967, Ground water, in Mineral and water resources of Missouri. U.S. Geological Survey, Missouri Division of Geological Survey and Water Resources, Rolla, Missouri, Document, vol. XLII, no. 19, 2nd series, p. 281-313. Fuller, M.L., 1905, The New Madrid earthquake, by Shepard, Edward M., in American geologist, vol. 35. Journal of Geology, vol. 13, p. 45-62.

_____, 1912, The New Madrid earthquake. U.S. Geological Survey, Bulletin, no. 494, pp. 119, and abstracts from Brooks, A.H., Washington Academy of Science, Journal, vol. 2, p. 350-351.

Gealy, J.R., 1955, Geology of the Cape Girardeau and Jonesboro quadrangles, southeastern Missouri. Yale University, New Haven, Connecticut, unpublished Ph.D. dissertation.

Gentile, R.J., 1965, Stratigraphy, sedimentation, and structure of the Upper Cherokee and Lower Marmaton (Pennsylvanian) rocks of Bates County and portions of Henry and Vernon counties, Missouri. University of Missouri, Rolla, Missouri, unpublished Ph.D. dissertation.

_____, 1976, The geology of Bates County, Missouri. Missouri Geological Survey and Water Resources, Rolla, Missouri, Report of Investigation No. 59, 89 p.

Gibbons, J.F., 1972, Tectonics of the eastern Ozarks area, southeastern Missouri. Syracuse University, Syracuse, New York, unpublished Ph.D. dissertation, 70 p.

Gordon, D.W., et al., 1970, The south-central Illinois earthquake of November 9, 1968 - macroseismic studies. Seismological Society of America, Bulletin, vol. 60, p. 221-250.

Graves, H.B., 1938, The Precambrian structure of Missouri. Transactions of the St. Louis Academy of Science, vol. 29, p. 111-161.

Gregory, B.W., 1954, Geology of the Coloma quadrangle, Missouri. University of Missouri, Columbia, Missouri, unpublished Master's thesis.

Grogan, R.M., and Bradbury, J.C., 1968, Fluorite-zinc-lead deposits of the Illinois mining district, in Ore deposits in the United States 1933/1967, V.I. American Institute of Mining Engineers, New York, p. 370-399.

Grohskopf, J.G., 1955, Subsurface geology of the Mississippi

Embayment of southeast Missouri. Missouri Geological Survey and Water Resources, Rolla, Missouri, vol. 37, 2nd series. Grohskopf, J.G., Hinchey, N.S., and Greene, F.C., 1939, Subsurface geology of northeastern Missouri. Missouri Geological Survey and Water Resources, Rolla, Missouri, 60th Biennial report, appedix 1, p. 1-60.

Gross, R.E., 1949, The geology of the southwestern quarter of the Elsberry quadrangle, Missouri. University of Iowa, Iowa City, Iowa, unpublished Master's thesis.

Gubin, I.E., 1967, Earthquakes and seismic zoning. International Institute of Seismology, Bulletin, vol. 4, p. 107-126.

Gupta, I.N., 1976, Attenuation of intensities based on isoseismals of earthquakes in central United States. Earthquake Notes, vol. 47, no. 3, p. 13-20.

Gupta, I.N., and Nuttli, O.W., 1976, Spatial attenuation of intensities for central United States earthquakes. Bulletin Seismological Society of America, vol. 66, p. 743-752.

Gutenberg, B., and Richter, C.F., 1942, Earthquake magnitude, intensity, energy, and acceleration. Seismological Society of America, Bulletin, vol. 32, p. 163-191.

Harlan, J.L., 1951, The geology of the east-central portion of the Jefferson City quadrangle, Missouri. University of Missouri, Columbia, Missouri, unpublished Master's thesis.

Harris, S.E., and Parker, M.C., 1964, Stratigraphy of the Osage Series in southeastern Iowa. Iowa Geological Survey, Iowa City, Iowa, Report of Investigation No. 1, p. 52.

Harrison, J.A., 1951, Subsurface geology and coal resources of the Pennsylvanian System in White County, Illinois. Illinois State Geological Survey, Urbana, Illinois, Report of Investigation No. 153.

Hayes, W.C., Jr., 1960, Reconnaissance mapping in Christian, Douglas, Stone, and Reynolds counties, Missouri. Missouri Geological Survey and Water Resources, Rolla, Missouri, unpublished maps.

Hayes, W.C., 1962, Precambrian lineament map of Missouri. Missouri Geological Survey, Rolla, Missouri, open file.

Heflin, L.H., 1961, The geology of the southern half of Warrenton quadrangle. University of Missouri, Columbia, Missouri, unpublished Master's thesis. Heigold, P.C., 1968, Notes on the earthquake of November 9, 1968, in southern Illinois. Illinois Geological Survey, Environmental Geology Notes No. 24, 16 p.

Heinrich, R.R., 1941, A contribution to the seismic history of Missouri. Seismological Society of America, Bulletin, vol. 31, no. 3, p. 187-204 (July), and Master's thesis, 1938, St. Louis University, St. Louis, Missouri, unpublished.

Hendricks, H.E., 1942, Geology of the Macks Creek quadrangle, Missouri. University of Iowa, Iowa City, Iowa, unpublished master's thesis.

_____, 1954, Geology of the Steelville quadrangle, Missouri. Missouri Geological Survey and Water Resources, Rolla, Missouri, vol. 36, 2nd series, p. 52-72.

Herrmann, R.B., 1978, A seismological study of the northern extent of the New Madrid seismic zone, <u>in</u> New Madrid seismotectonic study - activities during fiscal year 1978, T.C. Buschbach, editor. NRC, NUREG/CR-0450, p. 94-104.

_____, 1979, Surface wave focal mechanisms for eastern North American earthquakes with tectonic implications, <u>in</u> Journal Geophysical Research, vol. 84 (in press).

Hershberger, J., 1956, A comparison of earthquake accelerations with intensity ratings. Seismological Society of America, Bulletin, vol. 46, no. 4, p. 317-320.

Heyl, A.V., et al., 1965, Regional structure of the southeast Missouri and Illinois-Kentucky mineral districts. U.S. Geological Survey, Bulletin No. 1202-B, p. 20.

_____, 1972, The 38th parallel lineament and its relationship to ore deposits. Economic Geology, vol. 67, p. 885-887, and abstracts, p. 879-894.

_____, 1977, Some major lineaments in the central United States. Geological Society of America, Abstracts with Programs, vol. 9, no. 5, p. 605 (March).

Hildenbrand, T.G., et al., 1977, Magnetic and gravity anomalies in the northern Mississippi Embayment and their spatial relation to seismicity, miscellaneous field studies map, MF-914. U.S. Geological Survey, Ecological Survey.

Hinds, H., 1912, Coal deposits of Missouri. Missouri Bureau of Geology and Mines, vol. 11, 2nd series, 503 p. Hinds, H., and Greene, F.C., 1915, The stratigraphy of the Pennsylvanian Series in Missouri. Missouri Bureau of Geology and Mines, vol. 13, 2nd series, p. 407.

Hinze, W.J., et al., 1977, A tetonic overview of the central midcontinent. U.S. NRC publication NUREG-0382, R6A, p. 106.

History of Callaway County, Missouri, 1884.

Hopper, M.G., and Algermissen, S.T., 1980, An evaluation of the effects of the October 31, 1985, Charleston, Missouri, earthquakes: U.S. Geological Survey, Open-File Report 80-778, 43 p.

Howe, W.B., et al., 1961, The stratigraphic succession in Missouri. Missouri Geological Survey and Water Resources, Rolla, Missouri, Report, no. 40, 2nd series, p. 10-136.

Howe, W.B., and Fellows, L.D., 1977, The resources of St. Charles County, Missouri, land, water and minerals. Missouri Geological Survey and Water Resources, Rolla, Missouri, 233 p.

Howe, W.B., and Heim, G.E., Jr., 1968, The Ferrelview Formation of Missouri. Missouri Geological Survey and Water Resources, Rolla, Missouri, Report of Investigations, no. 42, p. 17.

Howell, B.F., Jr., 1959, Introduction of geophysics, isoseismal map of Charleston, South Carolina, 1886. McGraw-Hill Book Company, New York.

Illinois State Geological Survey, 1971, Background materials for symposium on future petroleum potential of NPC region 9. Illinois State Geological Survey, Urbana, Illinois, Illinois Petroleum 96, 63 p.

Indiana Geological Survey, 1974, Earthquake list. Department of Natural Resources, Geological Survey, Bloomington, Indiana, 18 p.

James, J.A., 1951, The relationship of regional structural geology to the ore deposits in the southeastern Missouri mining district. University of Missouri, Columbia, Missouri, unpublished Ph.D. dissertation.

Janbu, N., 1967, Settlement calculations based on the tangent modulus concept, in Soil mechanics and foundation engineering. Th Technical University of Norway, Trondheim, Norway.

Jewett, J.M., 1951, Geologic structures in Kansas. Kansas State Geological Survey, Lawrence, Kansas, Bulletin, no. 90. Jewett, J.M., and Abernathy, G.E., 1945, Oil and gas in eastern Kansas. Kansas State Geological Survey, Lawrence, Kansas, Bulletin No. 57, p. 244.

Jewett, J.M., and Merriam, D.F., 1959, Geological framework of Kansas -- a review of geophysicists, in Symposium on geophysics in Kansas. Kansas State Geological Survey, Lawrence, Kansas, Bulletin No. 137.

Jewett, J.M., and Newell, N.O., 1935, The geology of Wyandotte

County, Kansas. Kansas State Geological Survey, Lawrence, Kansas, Bulletin No. 21.

Johnston, A.C., in press, On the use of the frequency - magnitude relation in earthquake risk assessment: Submitted for presentation for the conference on Earthquakes and Earthquake Engineering: The Eastern U.S. - Knoxville, Tennessee, September 14 - 16, 1981.

Kane, M.F., 1977, Correlation of major eastern earthquake epicenters with mafic/ultramafic basement masses. U.S. Geological Survey, Professional Paper 1028, p. 199-204.

Keller, G.R., and Austin, C.B., 1977, Gravity studies of features along the 38th Parallel lineament. Geological Society of America, Abstracts with Programs, vol. 9, no. 5, 1977, p. 614, (March).

Keyes, C.R., 1894, Crustal adjustment in the Upper Mississippi Valley. Geological Society of America, Bulletin, vol. 5, p. 231-242.

Kiilsgaard, T.H., et al., 1963, The Crooked Creek disturbance, southeast Missouri. U.S. Geological Survey, Professional Paper 450-E, p. 14-19.

King, P.B., 1959, Evolution of North America. Princeton University Press, Princeton, New Jersey, p. 10.

Kisslinger, C., and Nuttli, O.W., 1965, The earthquake of October 20, 1965, and Precambrian structure in Missouri. Earthquake Note No. 36, p. 32-36.

Kisvarsanyi, E.B., 1974a, Operation basement-buried Precambrian rocks of Missouri - their petrography and structure. American Association of Petroleum Geologists, vol. 58, no. 4, p. 674-684.

______, 1974b, Ortho-polygonal tectonic patterns in the exposed and buried Precambrian basement of southeast Missouri, in Proceedings of the First International Conference on the new basement tectonics, Salt Lake City, Utah (June 3-7). Utah Geological Association Public, no. 5, p. 169-182.

Koenig, J.W., 1960, Reconnaissance mapping in Stone and Taney counties for state geologic map. Missouri Geological Survey and Water Resources, Rolla, Missouri, unpublished quadrangle maps. Kolata, D.R., 1978, Structural framework of the Mississippi Embayment of southern Illinois, in New Madrid seismotectonic study - activities during fiscal year 1978, T.C. Buschbach, editor, NRC, NUREG/CR-0450, p. 75-90.

Kolata, D.R., Treworgy, J.D., and Masters, J.M., 1979,

Structural Framework of the Mississippi Embayment in southernmost Illinois. Geolological Society of America, Abstracts with Programs, vol. II, no. 2, p. 150-151.

Kolata, D. R., Treworgy, J. D., and Masters, J. M., 1981, Structural Framework of the Mississippi Embayment of southern Illinois: Illinois State Geological Survey, Circular 516, 38p.

Knight, R.D., 1962, Map of the groundwater areas of Missouri. Missouri Geological Survey and Water Resources, Rolla, Missouri.

Krey, F., 1924, Structural reconnaissance of the Mississippi Valley area from Old Monroe, Missouri, to Nauvoo, Illinois. Illinois State Geological Survey, Urbana, Illinois, Bulletin, no. 45, pp. 38-39. Missouri Bureau of Geology and Mines, vol. 18, 2nd Series, map, p. 86.

Kukla, G.J., and Opdyke, N.D., 1973, Paleomagnetic correlation of Early Pleistocene in the glaciated American midwest. Unpublished discussion paper presented at 7th Annual Meeting, North Central Division, Geological Society of America.

Kulp, J.L., 1961, Geologic timescale <u>in</u> Science, vol. 133, p. 1105-1114.

Laclede Gas Company, no date, Hallsville underground storage, Browns Station Anticline, contour map on base of Chouteau Limestone.

Lamb, T.W., and Whitman, R.V., 1969, Soil mechanics. John Wiley & Sons, Inc., New York, 553 p.

Lee, W., 1914, The geology of the Rolla quadrangle. Missouri Bureau of Geology and Mines, 2nd ser., vol. 12, 111 p.

_____, 1943, The stratigraphy and structural development of the Forest City basin in Kansas. Kansas State Geological Survey, Lawrence, Kansas, Bulletin No. 51, p. 13.

Lidiak, E.G., and Zietz, I., 1976, Interpretation of aeromagnetic anomalies between latitudes 37 N and 38 N in the eastern and central United States. Geological Society of America, Spec. Paper 167, 37 p. _____, 1977, Aeromagnetic lineaments along the 38th Parallel lineament in the eastern and central United States. Geol. Soc. of America, Abstracts with Programs, vol. 9, no. 5, p. 622 (March).

Lobeck, A.K., 1950, Physiographic diagram of North America. The Geographical Press, Columbia University, New York.

Lyell, C., 1849, A second visit to the United States of North

America. London, vol. 2, 2nd and 3rd editions, p. 228-239.

Marbut, C.F., 1907, The geology of Morgan County. Missouri Bureau of Geology and Mines, Rolla, Missouri, vol. 7, 2nd series, 97 p.

Mateker, E.J., Jr., 1956, Gravity survey of the Cap au Gres structure in the Hardin-Brussels quadrangle, Illinois. St. Louis University, St. Louis, Missouri, unpublished Bachelor's thesis.

McCracken, E., 1938, Structure map - base of Roubidoux Formation. Missouri Geological Survey and Water Resources, Rolla, Missouri, unpublished map.

_____, 1956, Northeast Missouri oil possibilities improve. Missouri Geological Survey and Water Resources, Rolla, Missouri, reprint from Oil and Gas Journal, Report of Investigation No. 21, p. 3.

McCracken, E., and McCracken, M.H., 1965, Subsurface maps of the Lower Ordovician (Canadian series) of Missouri. Missouri Geological Survey and Water Resources, maps, scale 1:1,000,000.

McCracken, M.H., 1961, Geologic map of the state of Missouri. Missouri Geological Survey and Water Resources, Rolla, Missouri.

_____, 1964, The Cambro-Ordovician rocks of northeastern Oklahoma and adjacent areas. Tulsa Geological Society, Digest, vol. 32, p. 49-75.

_____, 1967, Structure, <u>in</u> Mineral and water resources of Missouri. Missouri Geological Survey and Water Resources, Rolla, Missouri, Bulletin No. 43, 2nd series, p. 20-21.

_____, 1971, Structural features of Missouri. Missouri Geological Survey and Water Resources, Rolla, Missouri, Report of Investigations No. 49, 99 p. McGinnis, L.D., 1970, Tectonics and the gravity field in the continental interior. Journal of Geophysical Research, vol. 75, no. 2.

McGinnis, L.D., and Ervin, C.P., 1974, Earthquakes and block tectonics in the Illinois basin. Geology, vol. 2, no. 10, p. 517-519.

McMillan, N.J., 1956, Petrology of the Nodaway Underclay (Pennsylvanian), Kansas. Kansas State Geological Survey, Lawrence, Kansas, Bulletin No. 119.

McQueen, H.S., 1943, Geology of the fire clay districts of east central Missouri. Missouri Geological Survey and Water

Resources, Rolla, Missouri, vol. XXVIII, 2nd series, pp. 250.

McQueen, H.S., and ·id, K., 1940, Map of top of Bethany Falls Limestone in vicinity of Blackburn School, Livingston County. Missouri Geological Survey and Water Resources, Rolla, Missouri, unpublished map.

McQueen, H.S., and Greene, F.C., 1938, The geology of northwestern Missouri. Missouri Geological Survey and Water Resources, Rolla, Missouri, vol. 25, 2nd series, 217 p.

McQueen, H.S., et al., 1939, Notes on Paleozoic, Mesozoic, and Cenozoic stratigraphy of southeastern Missouri. Kansas Geological Society, 13th annual field conference guidebook, p. 59-76.

McQueen, H.S., et al., 1941, The Lincoln fold in Lincoln, Pike, and Ralls counties, northeastern Missouri. Kansas Geological Society, 15th annual field conference guidebook, p. 9?-110 (reprinted in 26th annual field conference guidebook, 1961, p. 81-85).

Medvedev, S.V., Sponheuser, W., and Karnik, V.T., 1963, Seimicheskala. Proceedings of the 3rd World Conference on Earthquake Engineering.

Meents, W.F., and Swann, D.H., 1965, Grand Tower Limestone (Devonian) of southern Illinois. Illinois State Geological Survey, Urbana, Illinois, Circular No. 389.

Merriam, D.F., 1963, The geologic history of Kansas. Kansas State Geological Survey, Lawrence, Kansas, Bulletin No. 162, p. 160, 179, 180, 182, 223, 253.

Miller, J.C., 1967, Geology and groundwater resources of Saline County, Missouri. University of Missouri, Columbia, Missouri, unpublished Master's thesis. Missouri Geological Survey and Water Resources, 1961, The stratigraphic succession in Missouri. Rolla, Missouri, vol. XL, 2nd series, John W. Koenig, editor.

Mitchell, B.J., 1973, Radiation and attenuation of Rayleigh waves from the southeastern Missouri earthquake of October 21, 1965. Journal Geophysical Research, vol. 78, no. 5, p. 886-899.

Mohraz, B., Hall, W.J., and Newmark, N.M., 1972, A study of vertical and horizontal earthquake spectra. Nathan M. Newmark, Consulting Engineering Service, Urbana, Illinois, U.S. AEC Contract No. AT(49-5)-2667.

Monette, J., 1846, The influence of the environment on the settlement of Missouri.

Moore, R.C., and Landes, K.K., 1937, Geologic map of Kansas. Kansas State Geological Survey, Lawrence, Kansas.

Muehlberger, W.R., 1966, Ozark Pre-Cambrian-Paleozoic relations; A discussion. American Association of Petroleum Geologists, Bulletin, vol. 50, no. 5, p. 1043.

Murphy, L.M., and Ulrich, F.P., 1951, United States earthquakes, 1949. U.S. Coast and Geodetic Survey, Washington, D.C.

Nakano, H., 1923, Notes on the nature of the forces which give rise to the earthquake motions. Central Meteorological Observatory, Japan, Seismological Bulletin No. 1, p. 92-130.

_____, 1930, Some problems concerning the propagation of the disturbances in and on a semi-infinite elastic solid. Geophysical Magazine, no. 2, p. 189-348.

National Oceanic and Atmospheric Administration, 1973, Earthquake history of the United States, Coffman, J.L., and von Hake, C.A. (eds.). NOAA, 1977 reprint, 208 p.

Naval Facilities Engineering Command, 1971, Design manual soil mechanics, foundations, and earth structures. Department of the Navy, Washington, D.C., DM-7 (March).

Newmark, N.M., Blume, J.A., and Kapur, K.K., 1973, Design response spectra for nuclear power plants. American Society of Civil Engineers, annual meeting, San Francisco, California. Nuclear Regulatory Commission, 1977, Safety evaluation report (section 2.5.2.1) for the Marble Hill nuclear generating station. Dockets 50-546 and 50-547 (June).

Nuttli, O.W., 1973a, The Mississippi Valley earthquakes of 1811 and 1812, intensities, ground motion and magnitudes. Seismological Society of America, Bulletin, vol. 63, no. 1, p. 227-248.

_____, 1973c, State of the art for assessing earthquake hazards in the United States, report 1, design earthquakes for the central United States. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

_____, 1974 On the recurrence rate of lower Mississippi Valley earthqu[illegible]. Seismological Society of America, annual meeting [illegible]y).

_____, 1978, Working draft of earthquake list of midcontinent region.

Nuttli, O.W., Bollinger, S.A., and Griffith, D.W., 1979, On the

relation between modified Mercalli intensity and body-wave magnitude, in Bulletin, Seismological Society of America, vol. 69 (in press).

Nuttli, O.W., and Herrmann, R.B., 1978, State of the art for assessing earthquake hazards in the United States, report 12, credible earthquakes for the central United States. U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi, Misc. Paper 5-73-1, 99 p.

Nuttli, O. W., 1981, Catalog of central United States earthquakes since 1800 m ½ 3.0 in Barstow, N. L., Brill, K. G., Nuttli, O. W. and Pomeroy, P. W., An approach to seismic zonation for siting nuclear electric power generating facilities in the eastern United States: U.S. Nuclear Regulatory Commission, NUREG/CR-1577, Appendix B , pp. B-2-1 to B2-31.

O'Brien, L.J., Murphy, J.R., and LaHoud, J.A., 1977, The correlation of peak ground acceleration amplitude with seismic intensity and other physical parameters. Prepared by Computer Sciences Corp. for the U.S. Nuclear Regulatory Commission, Office of Standards Development, Contract No. AT (49-245)-0148, NUREG-0143.

O'Connor, H.G., 1960, Geology and groundwater resources of Douglas County, Kansas. Kansas State Geological Survey, Lawrence, Kansas, Bulletin No. 148, p. 200.

O'Leary, D.W., and Hildenbrand, T.G., 1979, Structural significance of lineament and aeromagnetic patterns in the Mississippi embayment. Proceedings, 3rd International Conference on Basement Tectonics, 1980 (in press). Olive, W.W., 1969, Geologic map of parts of the Bandana and Olmsted quadrangles, McCracken and Ballard counties, Kentucky, in Geologic quadrangle maps of the United States. U.S. Geological Survey, Department of the Interior, Washington, D.C., map GQ-799.

_____, 1972, Geology of the Jackson Purchase region, Kentucky. Geological Society of Kentucky, Spring Field Conference (April 6-8), 11 p.

Parizek, E.J., 1949, Geology of the Vineland and Tiff quadrangles of southeast Missouri. University of Iowa, Iowa City, Iowa, unpublished Ph.D. dissertation.

Peck, R.B., 1974, The selection of soil parameters for the design of foundations. Second Nabor Carillo Lecture, Mexican Society for Soil Mechanics, Mexico City, Mexico.

Peterschmidtt, E., 1952, Sur la variation de l'intensite microse'smique avec la distance epicentral. Bureau Central Seismologique Internationale, publication series A, no. E,

p. 183-208.

Phelan, M.J., 1968, Crustal structure in the central Mississippi valley earthquake zone from geophysical measurement. Washington University, St. Louis, Missouri, unpublished Ph.D. dissertation.

Pike, R.W., 1929, The geology of the Crystal City Quadrangle. University of Chicago, unpublished Master's thesis.

Prucha, J.J., Graham, J.A., and Nickelsen, R.P., 1965, Basement controlled deformation in the Wyoming province of the Rocky Mountain front range. American Association of Petroleum Geologists, Bulletin, vol. 49, p. 966-992.

Robertson, F.S., 1940, Flow sequence in the felsite rocks in the eastern Ironton Quadrangle. Washington University, St. Louis, Missouri, unpublished Ph.D. dissertation.

Ross, C.A., 1963, Structural framework of southernmost Illinois. Illinois State Geological Survey, Urbana, Illinois, Circular, no. 351.

Rubey, W.W., 1952, Geology and mineral resources of the Hardin and Brussels quadrangles (Illinois). U.S. Geological Survey, Professional Paper, no. 218, p. 179.

Russ, D.P., 1978, Recent surface faulting and earthquake recurrence in the Reelfoot Lake area, northwestern Tennessee. Abstracts, Midwest Annual American Geophysical Union Meeting, St Louis, Missouri (September).

_____, 1979, Late Holocene faulting and earthquake recurrence in the Reelfoot Lake area, northwestern Tennessee. Bulletin, Geological Society of America, in press.

Russ, D.P. and Crone, A.J., 1979, New stratigraphic information from a deep test well in New Madrid County, Missouri. Geolological Society of America, Abstracts with programs, vol. 11, no. 2, p. 165.

Rutledge, R.B., 1924, McDonald County map with geologic reconnaissance. Missouri Bureau of Geology and Mines, Rolla, Missouri, unpublished map.

_____, 1929, Geologic map of Lawrence County, Missouri. Missouri Bureau of Geology and Mines.

Satterfield, I.R., and Ward, R.A., 1978, Structural geologic study of southeastern Missouri, in New Madrid seismotectonic study - activities during fiscal year 1978, Buschbach, T.C. (editor). NRC, NUREG/CR-0450, p. 53-63.

Schroeder, E.R., 1950, The geology of a portion of the

Hermitage quadrangle, Missouri. University of Iowa, Iowa City, Iowa, unpublished Master's thesis.

Schuchert, C., 1910, Paleogeography of North America. Geological Society of America, Bulletin, vol. 20, p. 427-606.

Schwalb, H.R., 1978, Geology of the Reelfoot Basin; abstract of 3rd annual A.G.U. midwest meeting, September 26-28, 1977, in New Madrid seismotectonic study - activities during fiscal year 1978, Buschbach, T.C. (editor). NRC, NUREG/CR-0450, p. 123.

Searight, T.K., 1954, The geology of the Humansville Quadrangle, Missouri: Missouri Geological Survey and Water Resources, Rolla, Missouri, Report of Investigation No. 15, p. 50.

Searight, T.K., and Searight, W.V., 1961, Pennsylvanian geology of the Lincoln Fold, in Guidebook of 26th regional field conference of the Kansas Geological Society: Missouri Geological Survey and Water Resources, Rolla, Missouri, Report of Investigation No. 27, p. 168. Searight, W.V., et al., 1953, Classification of Desmoinesian (Pennsylvanian) of the northern midcontinent. American Association of Petroleum Geologists, Bulletin, vol. 37, no. 12, p. 2747-2749.

Seed, H.B., and Idriss, I.M., 1971, Simplified procedure for evaluating soil liquifaction potential, in Journal of soil mechanics and foundations division. American Society of Civil Engineers, vol. 97, no. SM9 (September).

Seed, H.B., and Whitman, V.R., 1970, Design of earth retaining structures for dynamic loads. Cornell University, 1970 Specialty conference on lateral stresses in the ground and design of earth-retaining structures (June).

Shepard, E.M., 1898, A report on Greene County, Missouri. Missouri Geological Survey, vol. 12, 1st series, part 1, p. 147, 160.

Sinclair, V.R., 1956, Geologic map of the Mineola area Montgomery County, Missouri. Missouri Geological Survey and Water Resources, Rolla, Missouri, unpublished map.

Skillman, M.W., 1948, Pre-upper Cambrian sediments of Vernon County, Missouri. Missouri Geological Survey and Water Resources, Rolla, Missouri, Report of Investigation 7, 18 p.

Smart, B., 1957, Geologic study and mapping of Pennsylvanian rocks in western Missouri. University of Iowa, Iowa City, Iowa, unpublished Master's thesis.

Snyder, F.G., 1968, Tectonic history of midcontinental United States. University of Missouri at Rolla Journal, no. 1, p. 70-72.

Snyder, F.G., and Gerdemann, P.E., 1965, Explosive igneous activity along an Illinois-Missouri-Kansas axis. American Journal of Science, vol. 263, p. 465-493.

Soderberg, R.K., and Keller, G.R., 1981, Geophysical evidence for deep basin in western Kentucky: American Association Petroleum Geologists Bulletin, Volume 65-2, pp. 226-234.

Stauder, W., 1973, Seismicity study of the site of Meramec Lake, Missouri. U.S. Geological Survey, St. Louis University contract 14-08-0001-12860.

_____, 1977, Microearthquake-array studies of the seismicity in southeast Missouri. Earthquake Information Bulletin, vol. 9, no. 1, p. 8-13 (January-February).

Stauder, W., et al.,1975, Relation of microearthquakes in southeast Missouri to structural features (abstract). EOS Transactions of the American Geophysical Union, vol. 56, no. 6, p. 398. Stauder, W., et al., 1976, Seismic characteristics of southeast Missouri as indicated by a regional telemetered microearthquake array. Bulletin of the Seismological Society of America, vol. 66, no. 6, p. 1953-1964.

Stearns, R.G., 1958, Cretaceous, Paleocene, and lower Eocene geologic history of the northern Mississippi Embayment. Tennessee Division of Geology, Report of Investigations No. 6.

_____, 1973, Geology and seismic hazard in and east of the New Madrid fault zone. Geological Society of America, meeting.

Stearns, R.G., and Marcher, M.V., 1962, Late Cretaceous and subsequent structural development of the northern Mississippi Embayment area. Tennessee Division of Geology, Report of Investigations 18 (reprinted from Geological Society of America Bulletin, vol. 75, p. 1387-1394.)

Stearns, R.G., and Wilson, C.W., 1972, Relationship of earthquakes and geology in west Tennessee and adjacent areas. Tennessee Valley Authority.

Stearns, R.G., and Zurawski, A., 1976, Post-Cretaceous faulting in the head of the Mississippi Embayment. Southeastern Geology, vol. 17, no. 4, p. 207-229.

Stearns, R.G., 1980, Monoclinical structure and shallow faulting of the reelfoot Scharp as estimated from drill holes with variable spacings: U.S. Nuclear Regulatory

Commission, NUREG/CR-1501, 37 pp.

Steward, D.R., 1942, Mesozoic and Cenozoic geology of southeastern Missouri. Missouri Geological Survey and Water Resources, Rolla, Missouri, unpublished Master's thesis.

Stonehouse, H.B., and Wilson, G.M., 1955, Faults and other structures in southern Illinois - a compilation. Illinois State Geological Survey, Urbana, Illinois, Circular 195, 4 p.

Street, R.L., 1978, A note on the horizontal to vertical Lg wave-amplitude ratio. Earthquake Notes, vol. 49, p. 15-20.

Street, R.L., and Herrmann, R.C., 1974, Map showing fault plane solutions for seismic events in the region of interest for the period 1962 to 1973. Refuge Site PSAR manuscript, figure 25-21.

Street, R.L., Herrmann, R.B., and Nutti, O.W., 1974, Earthquake mechanics in the central United States. Science, vol. 184, no. 4143, p. 1285-1287.

Street, R.L., 1980, The southern Illinois earthquake of September 27, 1981: Bulletin seismological Society America, Volume 70, No. 3, pp. 915-920.

Stryker, W.L., 1925, Subsurface geology of Wilson County, Kansas. American Association of Petroleum Geologists, Bulletin, vol. 9, p. 1207-1214.

Sutton, P.G., 1953, A geological review of the Rough Creek fault system. Kentucky Geological Survey, Special Paper 3, Series 9, p. 17-20.

Swann, D.H., 1951, Waltersburg Sandstone oil pods of lower Wabash area, Illinois and Indiana. American Association of Petroleum Geologists, Bulletin, vol. 35, no. 2.

Tarr, A.C., 1977, Recent seismicity near Charleston, South Carolina, and its relationship to the August 31, 1886 earthquake, in Studies related to the Charleston, South Carolina earthquake of 1886 - a preliminary report. U.S. Geological Survey Professional Paper 1028.

Terzaghi, K., and Peck, R.B., 1967, Soil mechanics in engineering practice. John Wiley and Sons, Inc., New York, 2nd ed., 729 p.

Theil, J.M., 1924, Lawrence County exposure and outcrop maps (includes written description of area). Missouri Bureau of Geology and Mines, unpublished manuscript.

Thornbury, W.D., 1965, Regional geomorphology of the United States. Wiley and Sons, New York, p. 251, 268, 269.

Tikrity, S.S., 1968, Tectonic genesis of the Ozark Uplift. Washington University, St. Louis, Missouri, unpublished Ph.D. dissertation.

Timoshenko, S., and Goodier, J.N., 1951, Theory of elasticity. McGraw-Hill, New York, 506 p.

Trifunac, M.D., and Brady, A.G., 1975, On the correlation of seismic intensity scales with the peaks of recorded strong ground motion. Seismological Society of America, Bulletin, abstract in Earthquake Notes, vol. 46, nos. 1-2, p. 46.

Twenhofel, W.H., 1926, Intrusive granite of the Rose Dome, Woodson City, Kansas. Geological Society of America, Bulletin, vol. 37, p. 403-412.

Unklesbay, A.G., 1952, Geology of Boone County, Missouri. Missouri Geological Survey and Water Resources, Rolla, Missouri, vol. 33, 2nd series, p. 159. _____, 1955, The geology of the Fulton quadrangle, Missouri. Missouri Geological Survey and Water Resources, Rolla, Missouri, Report of Investigations No. 19, p. 7, 10.

U.S. Army Corps of Engineers, 1970, Engineering and design stability of earth and rock-fill dams, Washington, D.C., EM 1110-2-1902.

U.S. Bureau of Reclamation, 1973, Design of small dams. United States Department of the Interior, Washington, D.C., 2nd ed., 816 p.

U.S. Geological Survey and Missouri Division of Geological Survey and Water Resources, 1967, Mineral and water resources of Missouri. U.S. Geological Survey and Missouri Division of Geological Survey and Water Resources, Rolla, Missouri, Document, vol. XLIII, no. 19, p. 13-20.

Wagner, R.E., and Kisvarsanyi, E.B., 1969, Lapilli tufts and associated pyroclastic sediments in Upper Cambrian strata along Dent Branch, Washington County, Missouri. Missouri Geological Survey and Water Resources, Rolla, Missouri, Report of Investigation No. 43, p. 80.

Wagner, R.J., 1961, Geology of the barite deposits in Washington County, Missouri. St. Louis University, St. Louis, Missouri, unpublished Master's thesis.

Wanless, H.R., undated Pennsylvanian correlations in the eastern interior and Appalachian coal fields. Geological Society of America, Special Paper No. 17, p.130.

Ward, J.R., 1968, A study of the joint patterns in gently dipping sedimentary rocks of south-central Kansas. Kansas State Geological Survey, Lawrence, Kansas, Bulletin No. 191, Part 2.

Warfield, R.G., 1953, Stratigraphy and structure of the northeast quarter of the Richwoods quadrangle, Missouri. University of Iowa, Iowa City, Iowa, unpublished Master's thesis.

Wayman, N.L., 1968, A pictorial history of St. Louis.

Weller, J.M., Grogan, R.M., and Tippie, F.E., 1952, Geology of the fluorospar deposits of Illinois. Illinois State Geological Survey, Urbana, Illinois, Bulletin No. 76, 147 p. Weller, S., and St. Clair, S., 1928, Geology of Ste. Genevieve County, Missouri. Missouri Bureau of Geology and Mines, 2nd Ser., vol. 22.

Wheeler, H.E., 1965, Ozark Precambrian-Paleozoic relationships. American Association of Petroleum Geologists, Bulletin, vol. 49, p. 1647-1666.

Whiting, L.L., and Stevenson, D.L., 1965, The Sangamon Arch. Illinois State Geological Survey, Urbana, Illinois, Circular No. 383, p. 20.

Williams, J.H., 1966, Reconnaissance mapping in the Doniphan Quadrangle, Missouri. Missouri Geological Survey and Water Resources, Rolla, Missouri, unpublished map.

Williams, J.H., and Vineyard, J., 1969, Perennial groundwater level map. Federal Water Pollution Control Administration, Springfield, Missouri, James River-Wilson Creek Study, vol. 2, appendix D.

Willman, H.B., and Payne, J.N., 1942, Geology and Mineral resources of Marseilles, Ottawa, and Streator quadrangles. Illinois State Geological Survey, Urbana, Illinois, Bulletin No. 66, p. 195, 197, 203.

Willman, H.B., et al., 1967, Geologic map of Illinois. Illinois State Geological Survey, Urbana, Illinois.

Wilson, M.E., 1922, The occurrence of oil and gas in Missouri. Missouri Bureau of Geology and Mines, vol. 16, 2nd series, p. 294.

Wong, R.T., 1971, Deformation characteristics of gravel and gravelly soils under cyclic loading conditions. University of California, Berkeley, California, Ph.D. dissertation.

Zartman, R.E., et al., 1967, K-Ar and Rb-Sr ages of some alkalic intrusive rocks from central and eastern United

States. American Journal of Science, vol. 265, p. 848-870.

Zoback, M.D., 1979, Reactivation of late Cretaceous faulting in the vicinity of Reelfoot Lake, northwestern Tennessee. Geological Society of America, Bulletin, in press.

Zoback, M.D., et al., 1979, Seismic reflection profiling to delineate tectonic features of the New Madrid seismic region. Unpublished paper delivered at SSA annual meeting, Golden, Colorado, Abstract. Earthquake Notes, vol. 49, no. 4, p. 27-28. Zollweg, J., et al., 1974, Some preliminary results from a seismograph network in the New Madrid, Missouri region. Paper presented at the 46th annual meeting of the Eastern Section of the Seismological Society of America, abstract in Earthquake Notes, vol. 46, nos. 1-2, p. 46.

Zollweg, J.E., and Johnston, A.C., 1980, Memphis Area Regional Seismic Network, annual progress report - fiscal year 1979 in Buschbach, T.C., ed., New Madrid Seismotectonic Study; Activities during fiscal year 1979: U.S. Nuclear Regulatory Commission, NUREG/CR-0977, pp. 117-125.

Personal Communications

Allen, W.H., 1973, Missouri Geological Survey, Rolla, Missouri, personal communication.

Andreas, 1973, Present owner of Daniel Boone's home, personal communication.

Atherton, E.T., 1973, Illinois Geological Survey, Urbana, Illinois, personal communication.

Baxter, J.W., 1973, Illinois Geological Survey, Urbana, Illinois, personal communication.

Bechtel Power Corporation, 1976, personal communication (April 19).

_____, 1979a, personal communication (April 3).

_____, 1979b, personal communication (April 19).

_____, 1979c, personal communication (April 20).

_____, 1979d, personal communication (April 24).

_____, 1979e, personal communication (September 10).

Beveridge, T.C., 1973, Former state geologist of Missouri, University of Missouri, Rolla, Missouri, personal communication.

TABLE 2.5-7

EARTHQUAKE EPICENTERS*

1795 to 1980

35 - 42 N LATITUDE
87 - 96 W LONGITUDE

	DATE	MODIFIED MERCALLI INTENSITY	LOCATION	NORTH LATITUDE	WEST LONGITUDE	FELT AREA (SQ MI)	REFERENCE
1.	1795 Jan 8	IV-V	Kaskaskia, IL	39.0	89.9	4,500	1,2
2.	1804 Aug 20,24	V-VI	Fort Dearborn, IL	42.0	87.8	30,000	1,2,3
3.	1811 Dec 16	X-XI	New Madrid, MO	36.0	90.0	2,000,000	1,4
4.	1812 Jan 23	X-XI	New Madrid, MO	36.3	89.6	2,000,000	1,4
5.	1812 Feb 7	XI-XII	New Madrid, MO	36.5	89.6	2,000,000	1,4
6.	1820 Nov 9	IV-V	Cape Girardeau, MO	37.3	89.5	2,000,000	1
7.	1838 Jun 9	VI	St. Louis, MO	38.6	90.2	300	1
8.	1841 Dec 27	V	Nr. Hickman, KY	36.5	89.2	5,000	1,2
9.	1843 Jan 4	VIII	Western TN	35.2	90.0	800,000	1
10.	1848 Jan 24	V	Hickman, KY	36.6	89.2	---	2

* Earthquakes of Intensity V and greater only are tabulated beyond a distance of 60 miles from the site up to the limits of the study. All known epicenters located within 60 miles of the site are listed.

REFERENCES:
1) NOAA, 1973.
2) Docekal, 1970.
3) Indiana Geological Survey, 1974.
4) Nuttli and Herrmann, 1978.
5) NOAA, 1978.
6) Nuttli, 1978.
7) DuBois and Wilson, 1978.
8) NOAA, 1981.
9) St. Louis Univ. Geophys. Obs., 1981.
10) Nuttli and Brill, 1981.
11) Street, 1980.
12) Hopper and Algermissen, 1980.

TABLE 2.5-7 (cont'd)

	DATE	MODIFIED MERCALLI INTENSITY	LOCATION	NORTH LATITUDE	WEST LONGITUDE	FELT AREA (SQ MI)	REFERENCE
11.	1853 Dec 18	IV-V	Hickman, KY	36.6	89.2	40,000	2
12.	1857 Oct 8	VI	St. Louis, MO	38.5	90.3	35,000	1
13.	1858 Sep 21	VI	Line Shore, KY	36.5	89.2	---	2
14.	1860 Aug 7	V	Henderson, KY	37.8	87.6	30,000	2
15.	1865 Aug 17	VII	Southeast MO.	36.5	89.5	24,000	1
16.	1867 Apr 24	VII	Manhattan (Wamego), KS felt in MO	39.5	96.7	300,000	1,2,7
17.	1875 Nov 8	V	Topeka, KS	39.3	95.5	9,000	1,2
18.	1876 Sep 25	VI	Evansville, IN	38.5	87.7	60,000	1
19.	1878 Mar 12	V	Columbus, KY	36.8	89.2	local	1
20.	1878 Nov 18	VI	Southeastern MO	36.7	90.4	150,000	1
21.	1882 Jul 20	V	Charleston, MO	38.0	90.0	3,000	1
22.	1882 Sep 27	VI	Southern IL	39.0	90.0	40,000	1
23.	1882 Oct 15	V	Southern IL	39.0	90.0	40,000	1
24.	1882 Oct 22	VI-VII	AR	35.0	94.0	135,000	1
25.	1883 Jan 11	VI	Cairo, IL	37.0	89.2	80,000	1
26.	1883 Apr 12	VI-VII	Cairo, IL	37.0	89.2	---	1
27.	1883 Dec 5	V	Izard County, AR	36.3	91.8	local	1,2
28.	1886 Aug 31	X	Charleston, SC felt in MO	32.9	80.0	2,000,000	1
29.	1887 Feb 6	V-VI	Vincennes, IN	38.7	87.5	75,000	1
30.	1887 Aug 2	V	Cairo, IL	37.0	89.0	---	1
31.	1889 Jul 19	VI	Memphis, TN	35.2	90.0	local	1,2
32.	1891 Jul 26	VI	Evansville, IN	37.9	87.5		1

TABLE 2.5-7 (cont'd)

	DATE	MODIFIED MERCALLI INTENSITY	LOCATION	NORTH LATITUDE	WEST LONGITUDE	FELT AREA (SQ MI)	REFERENCE
33.	1891 Sep 27	VII	Mt. Vernon, IL	38.3	88.5	200,000	2,10,11
34.	1895 Oct 31	VIII	Charleston, MO	37.0	89.4	1,000,000	1,8,10,12
35.	1899 Apr 29	VI-VII	IN/IL	38.5	87.0	40,000	1
36.	1901 Jan 3	V	Eldorado Springs, MO	37.5	94.0	2,000	2
37.	1902 Jan 24	VI	MO	38.6	90.3	40,000	1
38.	1903 Feb 8	VI	Murphysboro, IL	38.5	90.3	65,000	1,2
39.	1903 Oct 4	V-VI	St. Louis, MO	38.5	90.3	45,000	2
40.	1903 Nov 4	VI-VII	Charleston, MO	36.9	89.3	135,000	1,2
41.	1903Nov 27	V	New Madrid, MO	36.5	89.5	70,000	1
42.	1905 Apr 13	V	Keokuk, IA	40.4	91.4	5,000	1
43.	1905 Aug 21	VI-VII	Sikeston, MO	36.8	89.5	125,000	1,2
44.	1906 May 11	V	Petersburg, IN	38.5	87.2	800	1
45.	1906 May 21	V	Flora, IL	37.5	88.5	---	1
46.	1907 Jan 30	V	Greenville, IL	38.9	89.5	1,200	2
47.	1907 Jul 4	IV-V	Farmington, MO	37.7	90.4	400	1
48.	1908 Sep 28	IV-V	New Madrid, MO	36.6	89.6	5,000	1
49.	1908 Oct 27	V	Cairo, IL	37.0	89.2	5,000	1
50.	1909 May 26	VII	Aurora, IL	41.8	89.3	500,000	1
51.	1909 Jul 18	VII	IL	40.2	90.0	40,000	1
52.	1909 Aug 16	---	Southwest IL	---	---	not plotted	
53.	1909 Sep 27	VII	IN	39.0	87.7	3[illegible] 000	1
54.	1909 Oct 23	V	Robinson, IL	39.0	87.7	8,000	1
55.	1909 Oct 23	V	Southeastern MO	37.0	89.5	40,000	1

TABLE 2.5-7 (cont'd)

	DATE	MODIFIED MERCALLI INTENSITY	LOCATION	NORTH LATITUDE	WEST LONGITUDE	FELT AREA (SQ MI)	REFERENCE
56.	1912 Jan 2	VI-V	IL	41.5	88.5	40,000	1
57.	1915 Apr 28	IV-V	New Madrid, MO	36.5	89.5	200	1
58.	1915 Oct 26	V	Mayfield, KY	36.7	88.6	local	1,2
59.	1915 Dec 7	V-VI	Ohio River	36.7	39.1	60,000	1
60.	1916 Dec 18	VI-VII	Hickman, KY	36.6	89.2	local	1,2
61.	1917 Apr 9	VI	Eastern MO	38.1	90.6	210,000	1,2
62.	1918 Oct 13	V	Noxie, AR	36.1	91.0	1,800	1,2
63.	1918 Oct 15	V	Western TN	35.2	89.2	40,000	1,2
64.	1919 May 25	V	Princeton, IN	38.4	87.5	25,000	1,2
65.	1919 Nov 3	IV-V	AR	36.2	90.9	local	1,2
66.	1920 May 1	V	MO	38.5	90.5	10,000	1
67.	1922 Jan 10	IV-V	Mt. Vernon, IN	37.9	87.8	9,500	2
68.	1922 Mar 22	V	Southern IL	37.3	88.6	60,000 (2 shocks)	2
69.	1922 Mar 30	IV-V	Memphis, TN	36.0	89.6	15,000	2
70.	1922 Nov 27	VI-VII	El Dorado, IL	37.8	88.5	50,000	2,8
71.	1923 Oct 28	VII	AR	35.5	90.4	40,000	1
72.	1923 Nov 9	V	Cass County, IL	40.0	90.5	600	1,2
73.	1923 Dec 31	V	AR	35.4	90.3	60,000	1,2
74.	1924 Mar 2	V	KY	36.9	89.1	30,000	2
75.	1925 Apr. 26	VI	Princeton, IN	38.3	87.6	100,000	1
76.	1925 May 13	V	KY	36.7	88.6	3,000	1
77.	1925 Jul 13	V	Edwardsville, IL	38.8	90.0	---	2
78.	1925 Sep 2	V-VI	KY	37.8	87.5	75,000	1

TABLE 2.5-7 (cont'd)

	DATE	MODIFIED MERCALLI INTENSITY	LOCATION	NORTH LATITUDE	WEST LONGITUDE	FELT AREA (SQ MI)	REFERENCE
79.	1927 Mar 18	VI	White Cloud, KS	40.0	95.3	300	1,7
80.	1927 May 7	VII	Mississippi Valley	35.7	90.6	130,000	1
81.	1927 Aug 13	V	Tiptonville, TN	36.4	89.5	25,000	2
82.	1930 Sep 1	V	Marston, MO	36.6	89.4	4,000	2
83.	1931 Jan 5	V	Elliston, IN	39.0	87.0	500	1
84.	1931 Aug 9	VI	Turner, KS	39.1	94.7	300	2,7
85.	1933 Dec 9	V	Manila, AR	35.8	90.2	100	2
86.	1934 Aug 19	VI	Rodney, MO	36.9	89.2	33,000	2
87.	1934 Nov 12	VI	Rock Island, IL	41.5	90.5	---	1
88.	1937 May 16	IV-V	Northeastern AR	35.9	90.4	25,000	1
89.	1937 Nov 17	V	Centralia, IL	38.6	89.1	20,000	1,2
90.	1938 Feb 12	V	Lake Michigan	41.6	87.0	6,500	2
91.	1938 Sep 16	IV-V	Northeastern AR	35.5	90.3	90,000	1
92.	1939 Nov 23	V	Griggs, IL	38.2	90.1	150,000	1
93.	1940 Nov 23	VI	Griggs, IL	38.2	90.1	150,000	2
94.	1941 Nov 16	VI	Covington, TN	35.5	89.7	20,000	2
95.	1943 July 25	IV-V	East central MO	38.1	91.3	---	2
96.	1945 Mar 27	III	Moselle, MO	38.4	90.9	3,000	2
97.	1946 Oct 7	IV-V	Chloride, MO	37.5	90.6	32,000	2
98.	1947 June 29	VI	St. Louis, MO	38.4	90.2	15,000	1
99.	1947 Dec 15	V	Lepanto, AR	35.6	90.1	6,000	2
100.	1949 Jan 13	V	TN-AR-MO Border	36.3	89.7	15,000	2
101.	1949 Aug 26	III	Defiance, MO.	38.6	90.8	---	2

TABLE 2.5-7 (cont'd)

	DATE	MODIFIED MERCALLI INTENSITY	LOCATION	NORTH LATITUDE	WEST LONGITUDE	FELT AREA (SQ MI)	REFERENCE
102.	1950 Feb 8	V	Lebanon, MO	37.7	92.7	5,500	1.2
103.	1952 Feb 20	V	TN-MO Border	36.4	89.5	13,000	2
104.	1952 Jul 16	VI	Dyersburg, TN	36.2	89.6	---	1
105.	1953 Sep 11	VI	Southwestern, IL	38.6	90.1	---	1
106.	1954 Feb 2	VI	Poplar Bluff, MO	36.7	90.3	32,000	1,2
107.	1954 Apr 26	V	Memphis, TN	35.1	90.1	16,000	1,2
108.	1955 Mar 29	VI	Finley, TN	36.0	89.5	10,000	1,10
109.	1955 Apr 9	VI	Sparta, IL	38.1	89.9	20,000	1
110.	1955 Sep 5	V	Finley, TN	36.0	89.5	---	1
111.	1955 Dec 13	V	Dyer County, TN	36.0	89.5	---	1
112.	1956 Jan 28	VI	TN-AR Border	35.6	89.6	5,000	1,2
113.	1956 Oct 29	V	Caruthersville, MO	36.1	89.7	---	1
114.	1956 Oct 30	VII	Northeastern OK	36.2	95.9	10,000	2,10
115.	1956 Nov 25	VI	Wayne County, MO	37.1	90.6	27,000	2
116.	1957 Mar 26	V	Paducah, KY	37.0	88.6	[illegible]00	1,2
117.	1958 Jan 26	V	Caruthersville, MO	35.2	90.0	6,500	2
118.	1958 Jan 27	V	IL-KY-MO Border	37.0	89.0	15,000	2
119.	1958 Apr 8	V	Obion County, TN	36.2	89.1	800	2
120.	1958 Apr 26	V	Lake County, TN	36.4	89.5	700	2
121.	1958 Nov 7	VI	IL-IN Border	38.4	87.9	33,000	2
122.	1959 Feb 13	V	Bogota, TN	36.2	89.5	170	2
123.	1959 Dec 21	V	Finley, TN	36.0	89.5	400	2
124.	1960 Jan 28	V	Dyer County, TN	36.0	89.5	300	2

TABLE 2.5-7 (cont'd)

	DATE	MODIFIED MERCALLI INTENSITY	LOCATION	NORTH LATITUDE	WEST LONGITUDE	FELT AREA (SQ MI)	REFERENCE
125.	1960 Apr 21	V	Lake County, TN	36.3	89.5	local	2
126.	1961 Apr 27	V	Southeastern OK	34.5	95.2	8,000	2
127.	1961 Dec 25	V	Excelsior Springs, MO	39.1	94.6	16,000	2
128.	1962 Feb 2	VI	New Madrid, MO	36.5	89.6	45,000	2
129.	1962 Jun 26	V	Southern IL	37.7	88.5	17,500	2
130.	1962 Jul 23	VI	TN	36.1	89.8	4,000	2
131.	1963 Mar 3	VI	Southeast MO	36.7	90.1	125,000	2
132.	1963 Aug 2	V	IL-KY Border	37.0	88.8	2,600	2
133.	1965 Mar 6	VI	Eastern MO	37.8	91.2	---	3
134.	1965 Aug 13	VI	Southwestern IL	36.3	89.5	---	3
135.	1965 Aug 14	VII	Tamms, IL	37.1	89.2	400	2
136.	1965 Aug 15	V	Southwestern IL	37.4	89.5	2 shocks not plotted	1
137.	1965 Oct 20	VI	Eastern MO	37.8	91.1	245,000	2
138.	1967 Jul 21	VI	MO	37.5	90.4	---	1,2
139.	1968 Nov 9	VII	Southcentral Il	38.0	88.5	580,000	1
140.	1970 Nov 16	VI	North AR	35.9	89.9	30,000	1
141.	1971 Oct 1	V	Sedgwick, AR	35.8	90.4	---	3
142.	1972 Feb 1	V	AR-MO Border	36.4	90.8	10,200	3
143.	1972 Mar 29	V	New Madrid, MO	36.1	89.9	felt in 6 states	3
144.	1972 Apr 4	II	Washington, MO	38.5	91.1	---	
145.	1972 Sep 15	VI	Northern IL	41.6	89.4	---	3
146.	1974 Jan 8	V	MO-TN Border	36.2	89.4	---	5

TABLE 2.5-7 (cont'd)

	DATE	MODIFIED MERCALLI INTENSITY	LOCATION	NORTH LATITUDE	WEST LONGITUDE	FELT AREA (SQ MI)	REFERENCE
147.	1974 April 3	VI	Olney, IL	38.6	88.1	252,800	5,10
148.	1974 May 13	VI	Charleston, MO	36.7	89.4	---	5
149.	1974 Jun 5	V	Belleville, IL	38.6	89.9	---	5
150.	1974 Aug 11	V	Fremont, MO	36.9	91.2	---	5
151.	1975 Feb 13	V	New Madrid, MO	36.5	89.6	---	5
152.	1975 Jun 13	V-VI	New Madrid, MO	36.5	89.7	---	5,8,9,10
153.	1975 Dec 3	V	New Madrid, MO	36.5	89.6	---	5
154.	1976 Mar 25	VI	Marked Tree, AR	35.6	90.5	112,000	5,10
155.	1976 Apr 15	V	Greenville, KY	37.4	87.3	---	5
156.	1976 May 22	V	Dunklin, MO	36.0	89.8	---	5
157.	1976 Sep 25	V	Marked Tree, AR	35.6	90.4	---	5
158.	1976 Dec 13	V	Farmington, MO	37.8	90.2	---	5
159.	1977 Jan 3	VI	Jackson, MO	37.5	89.8	---	5
160.	1978 Jun 2	V	Fairfield, IL	38.4	88.5	---	8,9
161.	1978 Aug 31	V	Dyersburg, TN	36.1	89.4	---	8,9
162.	1978 Sep 20	V	Webster Groves, MO	38.6	90.3	---	8,9
163.	1978 Dec 5	V	Flora, IL	38.6	88.4	---	8,9
164.	1979 Feb 27	VI	Strawberry, AR	35.9	91.2	---	8,9
165.	1979 Jun 11	V	Caruthersville, MO	36.2	89.7	---	8,9
166.	1979 Jun 25	V	Marked Tree, AR	35.5	90.4	---	8,9
167.	1979 Jul 8	V	Charleston, MO	36.9	89.3	---	8,9
168.	1979 Jul 13	V	Hayti, MO	36.1	89.8	---	8,9
169.	1979 Nov 5	V	Warm Springs, AR	36.4	91.0	---	8,9

TABLE 2.5-8

HISTORIC EARTHQUAKES SIGNIFICANT TO THE SITE

DATE	LOCATION	MAXIMUM MMI	MMI AT SITE
1811-1812	New Madrid, MO	XI-XII	VI-VII
1843 Jan. 4	Western TN	VIII	Unknown (Probably II)
1867 Apr. 24	Manhattan (Wamego), KS	VII	IV-V
1878 Nov. 18	Southeastern MO	VI	I-III
1886 Aug. 31	Charleston, SC	X	II-III
1891 Sep. 27	Mt. Vernon, IL	VII	Unknown (No Reports)
1895 Oct. 31	Charleston, MO	VIII	V-VI, VI[a]
1902 Jan. 24	MO	VI	II-III
1903 Feb. 8	Murphysboro, IL	VI	I
1903 Nov. 4	Charleston, MO	VII	II-III
1905 Aug. 21	Sikeston, MO	VI-VII	I
1917 Apr. 9	Eastern MO-St. Louis	VI	IV
1920 May 1	MO	V	III-IV
1939 Nov. 23	Griggs, IL	V	I-III
1946 Oct. 7	Chloride, MO	V	I-III
1955 Apr. 9	Sparta, IL	VI	I
1956 Nov. 25	Wayne Co., MO	VI	I-III
1963 Mar. 3	Southeastern MO	VI	II-III
1965 Oct. 20	Eastern MO-St. Louis	VI	IV-V
1968 Nov. 9	Southcentral IL	VII	IV
1971 Oct. 1	Sedgwick, AR	V	I-III
1974 Apr. 3	Olney, IL	VI	IV
1974 Jun. 5	Belleville, IL	V	III[b]
1976 Mar. 25	Marked Tree, AR	VI	I-III
1976 Dec. 13	Farmington, MO	V	II[b]
1977 Jan. 3	Jackson, MO	VI	IV[b]
1978 June 2	Fairfield, IL	V	II[b]
1978 Sep. 20	Webster Groves, MO	V	III[b]
1979 Feb. 27	Strawberry, AR	VI	II-III[b]

[a]MMI VI according to Hopper and Algermissen, 1980, Plate 1.

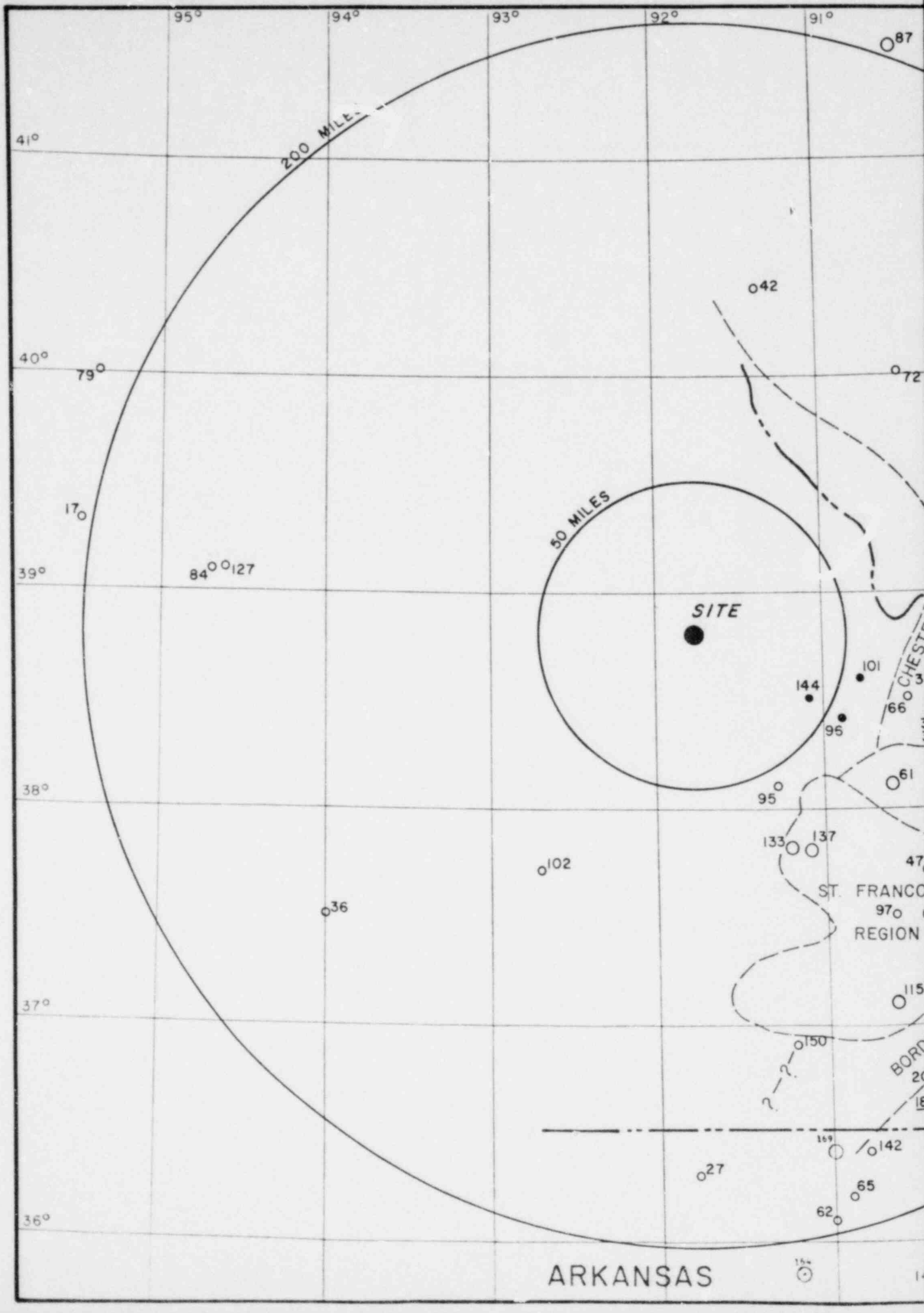
[b]Estimated attenuation obtained using equation from Gupta and Nuttli (1976). No felt reports from site area.

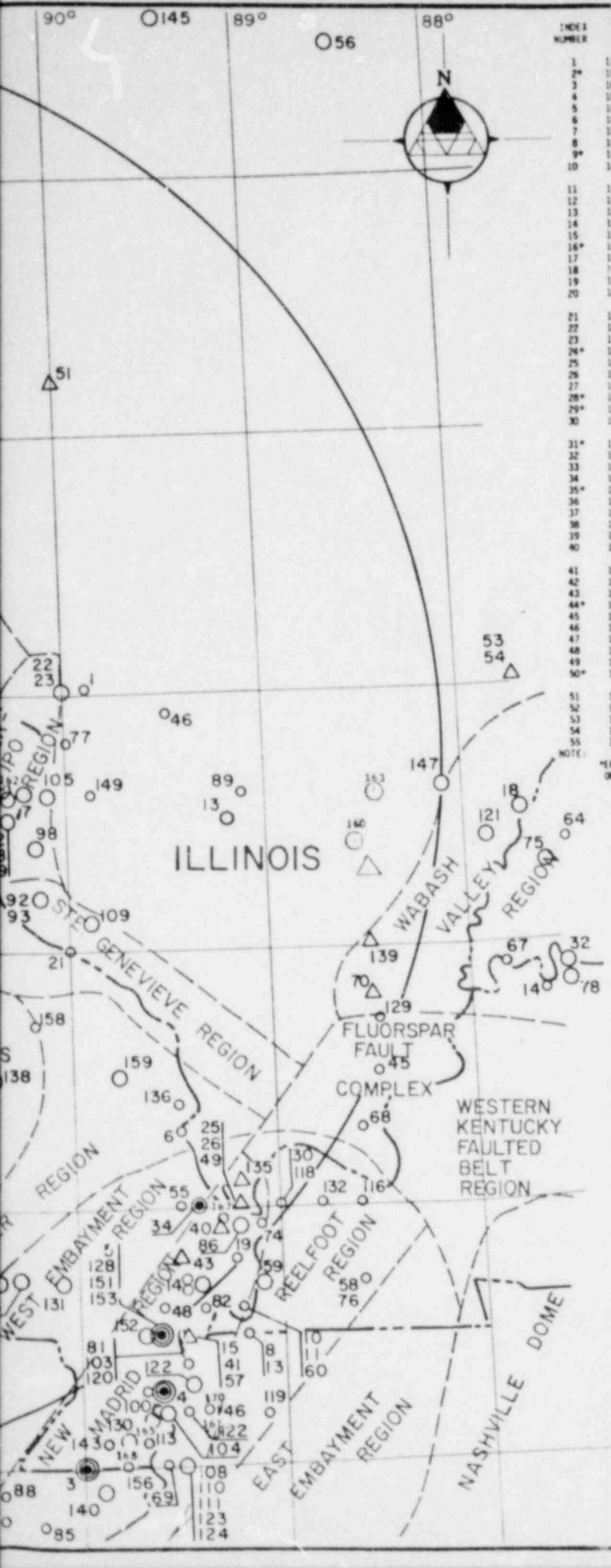
TABLE 2.5-10 (cont'd)

YEAR	MODIFIED MERCALLI INTENSITY	LATITUDE	LONGITUDE
1975	V	36.5	89.6
1975	VI	36.5	89.7
1975	V	36.5	89.6
1976	IV	35.9	92.1
1976	VI	35.6	90.5
1976	V	36.1	89.8
1976	V	35.6	90.5
1977	II	36.5	89.5
1978	V	36.1	89.4
1979	IV	35.8	90.1
1979	VI	35.9	91.2
1979	V	36.2	89.7
1979	V	35.5	90.4
1979	V	36.9	89.3
1979	V	36.1	89.8
1980	IV	36.6	89.6
1980	V	36.2	89.4

TABLE 2.5-7 (cont'd)

	DATE	MODIFIED MERCALLI INTENSITY	LOCATION	NORTH LATITUDE	WEST LONGITUDE	FELT AREA (SQ MI)	REFERENCE
170.	1980 Dec 2	V	Miston, TN	36.2	89.4	---	8,9


95°
94°
93°
92°
91°
41°
40°
39°
38°
37°
36°
200 MILES
50 MILES
SITE
ST. FRANCO
REGION
CHESTE
BORD
ARKANSAS
87
42
72
79
17
84
127
101
144
96
66
61
95
133
137
102
47
36
97
115
150
142
27
65
62



INDEX NUMBER	DATE	MMI	INDEX NUMBER	DATE	MMI	INDEX NUMBER	DATE	MMI
1	1795 JAN 8	IV-V	56	1912 JAN 2	VI	111	1955 DEC 13	V
2*	1804 AUG 20, 24	V-VI	57	1915 APR 28	IV-V	112*	1956 JAN 28	VI
3	1811 DEC 16	X-XI	58	1915 OCT 26	V	113	1956 OCT 29	V
4	1812 JAN 23	X-XI	59	1915 DEC 7	V-VI	114*	1956 OCT 30	VII
5	1812 FEB 7	XI-XII	60	1916 DEC 18	VI-VII	115	1956 NOV 25	VI
6	1820 NOV 9	IV-V				116	1957 MAR 26	V
7	1838 JUN 9	VI	61	1917 APR 9	VI	117*	1958 JAN 26	V
8	1841 DEC 27	V	62	1918 OCT 13	V	118	1958 JAN 27	V
9*	1843 JAN 4	VIII	63*	1918 OCT 15	V	119	1958 APR 8	V
10	1848 JAN 24	V	64	1919 MAY 25	V	120	1958 APR 26	V
			65	1919 NOV 3	IV-V			
11	1853 DEC 18	IV-V	66	1920 MAY 1	V	121	1958 NOV 7	VI
12	1857 OCT 8	VI	67	1922 JAN 10	IV-V	122	1959 FEB 13	V
13	1858 SEP 21	VI	68	1922 MAR 22	V	123	1959 DEC 21	V
14	1860 AUG 7	V	69	1922 MAR 30	IV-V	124	1960 JAN 28	V
15	1865 AUG 17	VII	70	1922 NOV 27	VI-VII	125	1960 APR 21	V
16*	1867 APR 24	VII				126*	1961 APR 27	V
17	1875 NOV 8	V	71*	1923 OCT 28	VII	127	1961 DEC 25	V
18	1876 SEP 25	VI	72	1923 NOV 9	V	128	1962 FEB 2	VI
19	1878 MAR 12	V	73*	1923 DEC 31	V	129	1962 JUN 26	V
20	1878 NOV 18	VI	74	1924 MAR 2	V	130	1962 JUL 23	VI
			75	1925 APR 26	VI			
21	1882 JUL 20	V	76	1925 MAY 13	V	131	1963 MAR 3	VI
22	1882 SEP 27	VI	77	1925 JUL 13	V	132	1963 AUG 2	V
23	1882 OCT 15	V	78	1925 SEP 2	V-VI	133	1965 MAR 6	VI
24*	1882 OCT 22	VI-VII	79	1927 MAR 18	V	134	1965 AUG 13	VI
25	1883 JAN 11	VI	80*	1927 MAY 7	VII	135	1965 AUG 14	VII
26	1883 APR 12	VI-VII				136	1965 AUG 15	V
27	1883 DEC 5	V	81	1927 AUG 13	V	137	1965 OCT 20	VI
28*	1886 AUG 31	IX-X	82	1930 SEP 1	V	138	1967 JUL 21	VI
29*	1887 FEB 6	V-VI	83*	1931 JAN 5	V	139	1968 NOV 9	VII
30	1887 AUG 2	V	84*	1931 AUG 9	IV-V	140	1970 NOV 16	VI
			85	1933 DEC 9	V			
31*	1889 JUL 19	VI	86	1934 AUG 19	VI	141	1971 OCT 1	V
32	1891 JUL 26	VI	87	1934 NOV 12	VI	142	1972 FEB 1	V
33	1891 SEP 27	VII	88	1937 MAY 16	IV-V	143	1972 MAR 29	V
34	1895 OCT 31	VIII	89	1937 NOV 17	V	144	1972 APR 4	II
35*	1899 APR 29	VI-VII	90*	1938 FEB 12	V	145	1972 SEP 15	VI
36	1901 JAN 3	V				146	1974 JAN 8	V
37	1902 JAN 24	VI	91*	1938 SEP 16	IV-V	147	1974 APR 3	VI
38	1903 FEB 8	VI	92	1939 NOV 23	V	148	1974 MAY 13	VI
39	1903 OCT 4	V-VI	93	1940 NOV 23	VI	149	1974 JUN 5	V
40	1903 NOV 4	VI-VII	94*	1941 NOV 16	VI	150	1974 AUG 11	V
			95	1943 JUL 25	IV-V			
41	1903 NOV 27	V	96	1945 MAR 27	III	151	1975 FEB 13	V
42	1905 APR 13	V	97	1946 OCT 7	IV-V	152	1975 JUN 13	V-VI
43	1905 AUG 21	VI-VII	98	1947 JUN 29	VI	153	1975 DEC 3	V
44*	1906 MAY 11	V	99*	1947 DEC 15	V	154	1976 MAR 25	VI
45	1906 MAY 21	V	100	1949 JAN 13	V	155	1976 APR 15	V
46	1907 JAN 30	V				156	1976 MAY 22	V
47	1907 JUL 4	IV-V	101	1949 AUG 26	III	157	1976 SEP 25	V
48	1908 SEP 28	IV-V	102	1950 FEB 8	V	158	1976 DEC 13	V
49	1908 OCT 27	V	103	1952 FEB 20	V	159	1977 JAN 3	VI
50*	1909 MAY 26	VII	104	1952 JUL 16	VI	160	1978 Jun 2	V
			105	1953 SEP 11	VI	161	1978 Aug 31	V
51	1909 JUL 18	VII	106	1954 FEB 2	VI	162	1978 Sep 2?	V
52	1909 AUG 16	---	107*	1954 APR 26	V	163	1978 Dec 5	V
53	1909 SEP 27	VII	108	1955 MAR 29	VI	164	1979 Feb 27	VI
54	1909 OCT 23	V	109	1955 APR 9	VI	165	1979 Jun 11	V
55	1909 OCT 23	V	110	1955 SEP 5	V	166	1979 Jun 25	V
						167	1979 Jul 8	V
						168	1979 Jul 13	V
						169	1979 Nov 5	V
						170	1980 Dec 2	V

NOTE:

*EPICENTERS LOCATED OUTSIDE OF MAP; SEE TABLE 2.5-7 FOR LOCATION OF THESE POINTS.

LEGEND:

- ● II - IV
- ○ V
- ◯ VI
- △ VII
- ◉ VIII
- ◎ IX OR GREATER
- —·—·— STATE BOUNDARIES
- — — — SEIMOGENIC BOUNDARIES

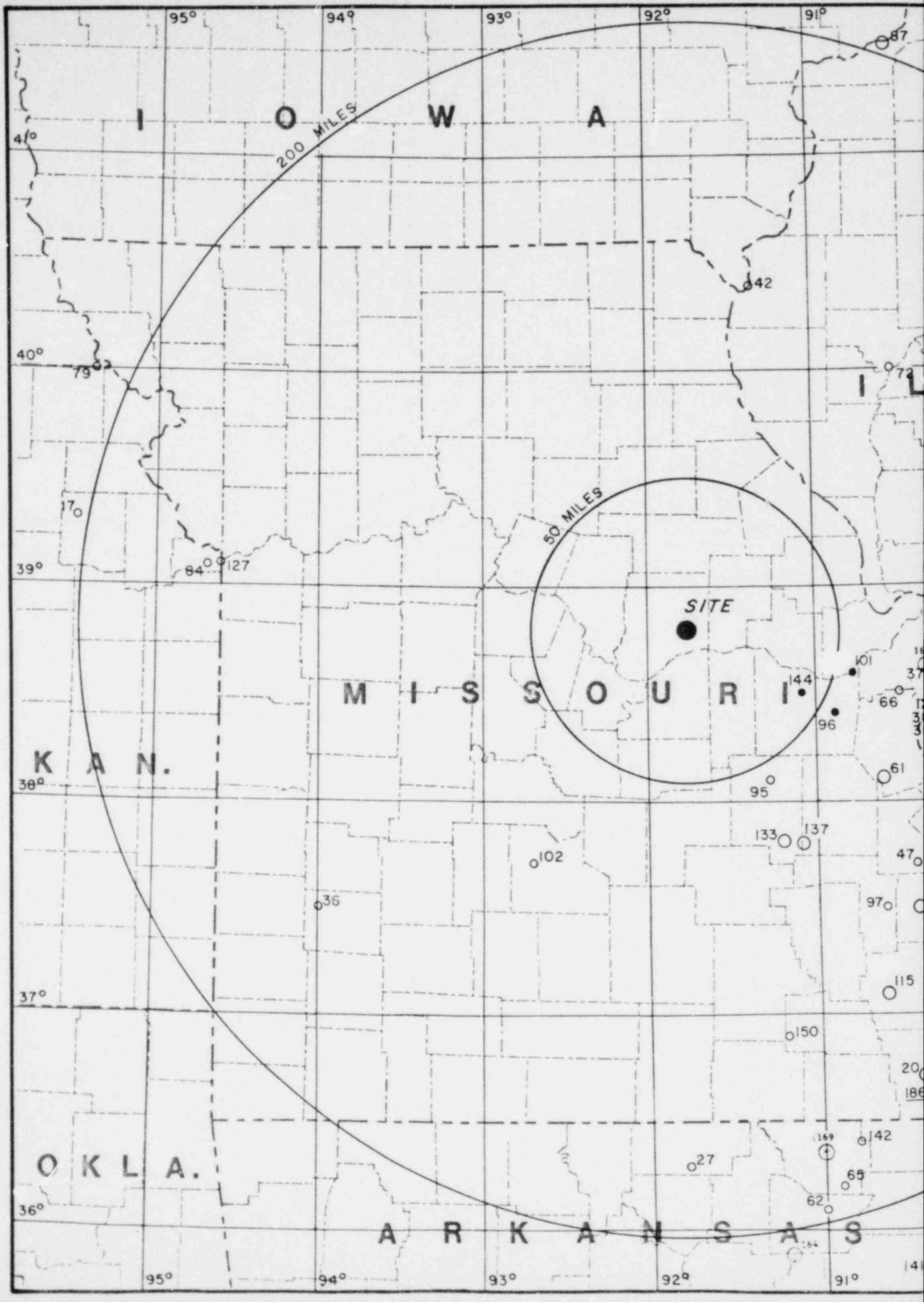
25 0 25 50 75

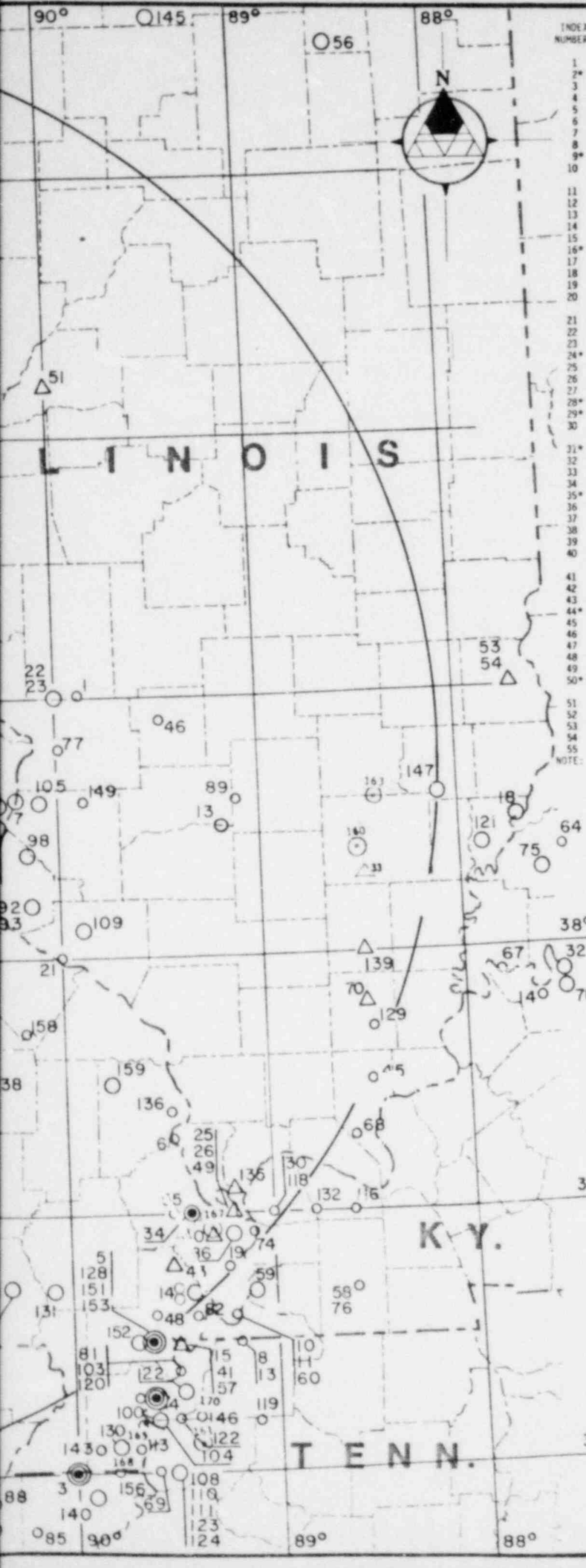
MILES

UNION ELECTRIC COMPANY
CALLAWAY PLANT UNITS 1 AND 2
FINAL SAFETY ANALYSIS REPORT

FIGURE 2.5-62

EARTHQUAKE EPICENTERS AS RELATED TO SEISMOTECTONIC REGIONS


95°
94°
93°
92°
91°
I O W A
200 MILES
41°
40°
39°
38°
37°
36°
50 MILES
SITE
M I S S O U R I
IL
KAN.
OKLA.
A R K A N S A S
87
42
79
72
17
84
127
101
144
66
96
61
95
133
137
102
47
36
97
115
150
20
186
169
142
27
65
62
164



INDEX NUMBER	DATE	MMI
1	1795 JAN 8	IV-V
2*	1804 AUG 20, 24	V-VI
3	1811 DEC 16	X-XI
4	1812 JAN 23	X-XI
5	1812 FEB 7	XI-XII
6	1820 NOV 9	IV-V
7	1838 JUN [illegible]	VI
8	1841 DEC 27	V
9*	1843 JAN 4	VIII
10	1848 JAN 24	V
11	1853 DEC 18	IV-V
12	1857 OCT 8	VI
13	1858 SEP 21	VI
14	1860 AUG 7	V
15	1865 AUG 17	VII
16*	1867 APR 24	VII
17	1875 NOV 8	V
18	1876 SEP 25	VI
19	1878 MAR 12	V
20	1878 NOV 18	VI
21	1882 JUL 20	V
22	1882 SEP 27	VI
23	1882 OCT 15	V
24*	1882 OCT 22	VI-VII
25	1883 JAN 11	VI
26	1883 APR 12	VI-VII
27	1883 DEC 5	V
28*	1886 AUG 31	IX-X
29*	1887 FEB 6	V-VI
30	1887 AUG 2	V
31*	1889 JUL 19	VI
32	1891 JUL 26	VI
33	1891 SEP 27	VII
34	1895 OCT 31	VIII
35*	1899 APR 29	VI-VII
36	1901 JAN 3	V
37	1902 JAN 24	VI
38	1903 FEB 8	VI
39	1903 OCT 4	V-VI
40	1903 NOV 4	VI-VII
41	1903 NOV 27	V
42	1905 APR 13	V
43	1905 AUG 21	VI-VII
44*	1906 MAY 11	V
45	1906 MAY 21	V
46	1907 JAN 30	V
47	1907 JUL 4	IV-V
48	1908 SEP 28	IV-V
49	1908 OCT 27	V
50*	1909 MAY 26	VII
51	1909 JUL 18	VII
52	1909 AUG 16	---
53	1909 SEP 27	VII
54	1909 OCT 23	V
55	1909 OCT 23	V

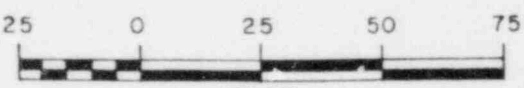
INDEX NUMBER	DATE	MMI
56	1912 JAN 2	VI
57	1915 APR 28	IV-V
58	1915 OCT 26	V
59	1915 DEC 7	V-VI
60	1916 DEC 18	VI-VII
61	1917 APR 9	VI
62	1918 OCT 13	V
63*	1918 OCT 15	V
64	1919 MAY 25	V
65	1919 NOV 3	IV-V
66	1920 MAY 1	V
67	1922 JAN 10	IV-V
68	1922 MAR 22	V
69	1922 MAR 30	IV-V
70	1922 NOV 27	VI-VII
71*	1923 OCT 28	VII
72	1923 NOV 9	V
73*	1923 DEC 31	V
74	1924 MAR 2	V
75	1925 APR 26	VI
76	1925 MAY 13	V
77	1925 JUL 13	V
78	1925 SEP 2	V-VI
79	1927 MAR 18	V
80*	1927 MAY 7	VII
81	1927 AUG 13	V
82	1930 SEP 1	V
83*	1931 JAN 5	V
84*	1931 AUG 9	IV-V
85	1933 DEC 9	V
86	1934 AUG 19	VI
87	1934 NOV 12	VI
88	1937 MAY 16	IV-V
89	1937 NOV 17	V
90*	1938 FEB 12	V
91*	1938 SEP 16	IV-V
92	1939 NOV 23	V
93	1940 NOV 23	VI
94*	1941 NOV 16	VI
95	1943 JUL 25	IV-V
96	1945 MAR 27	III
97	1946 OCT 7	IV-V
98	1947 JUN 29	VI
99*	1947 DEC 15	V
100	1949 JAN 13	V
101	1949 AUG 26	III
102	1950 FEB 8	V
103	1952 FEB 20	V
104	1952 JUL 16	VI
105	1953 SEP 11	VI
106	1954 FEB 2	VI
107*	1954 APR 26	V
108	1955 MAR 29	VI
109	1955 APR 9	VI
110	1955 SEP 5	V

INDEX NUMBER	DATE	MMI
111	1955 DEC 13	V
112*	1956 JAN 28	VI
113	1956 OCT 29	V
114*	1956 OCT 30	VII
115	1956 NOV 25	VI
116	1957 MAR 26	V
117*	1958 JAN 26	V
118	1958 JAN 27	V
119	1958 APR 8	V
120	1958 APR 26	V
121	1958 NOV 7	VI
122	1959 FEB 13	V
123	1959 DEC 21	V
124	1960 JAN 28	V
125	1960 APR 21	V
126*	1961 APR 27	V
127	1961 DEC 25	V
128	1962 FEB 2	VI
129	1962 JUN 26	V
130	1962 JUL 23	VI
131	1963 MAR 3	VI
132	1963 AUG 2	V
133	1965 MAR 6	VI
134	1965 AUG 13	VI
135	1965 AUG 14	VII
136	1965 AUG 15	V
137	1965 OCT 20	VI
138	1967 JUL 21	VI
139	1968 NOV 9	VII
140	1970 NOV 16	VI
141	1971 OCT 1	V
142	1972 FEB 1	V
143	1972 MAR 29	V
144	1972 APR 4	II
145	1972 SEP 15	VI
146	1974 JAN 8	V
147	1974 APR 3	VI
148	1974 MAY 13	VI
149	1974 JUN 5	V
150	1974 AUG 11	V
151	1975 FEB 13	V
152	1975 JUN 13	V-VI
153	1975 DEC 3	V
154	1976 MAR 25	VI
155	1976 APR 15	V
156	1976 MAY 22	V
157	1976 SEP 25	V
158	1976 DEC 13	V
159	1977 JAN 3	VI
160	1978 Jun 2	V
161	1978 Aug 31	V
162	1978 Sep 20	V
163	1978 Dec 5	V
164	1979 Feb 27	VI
165	1979 Jun 11	V
166	1979 Jun 25	V
167	1979 Jul 8	V
168	1979 Jul 13	V
169	1979 Nov 5	V
170	1980 Dec 2	V

NOTE:
*EPICENTERS LOCATED OUTSIDE OF MAP; SEE TABLE 2.5-7 FOR LOCATION OF THESE POINTS.

LEGEND:

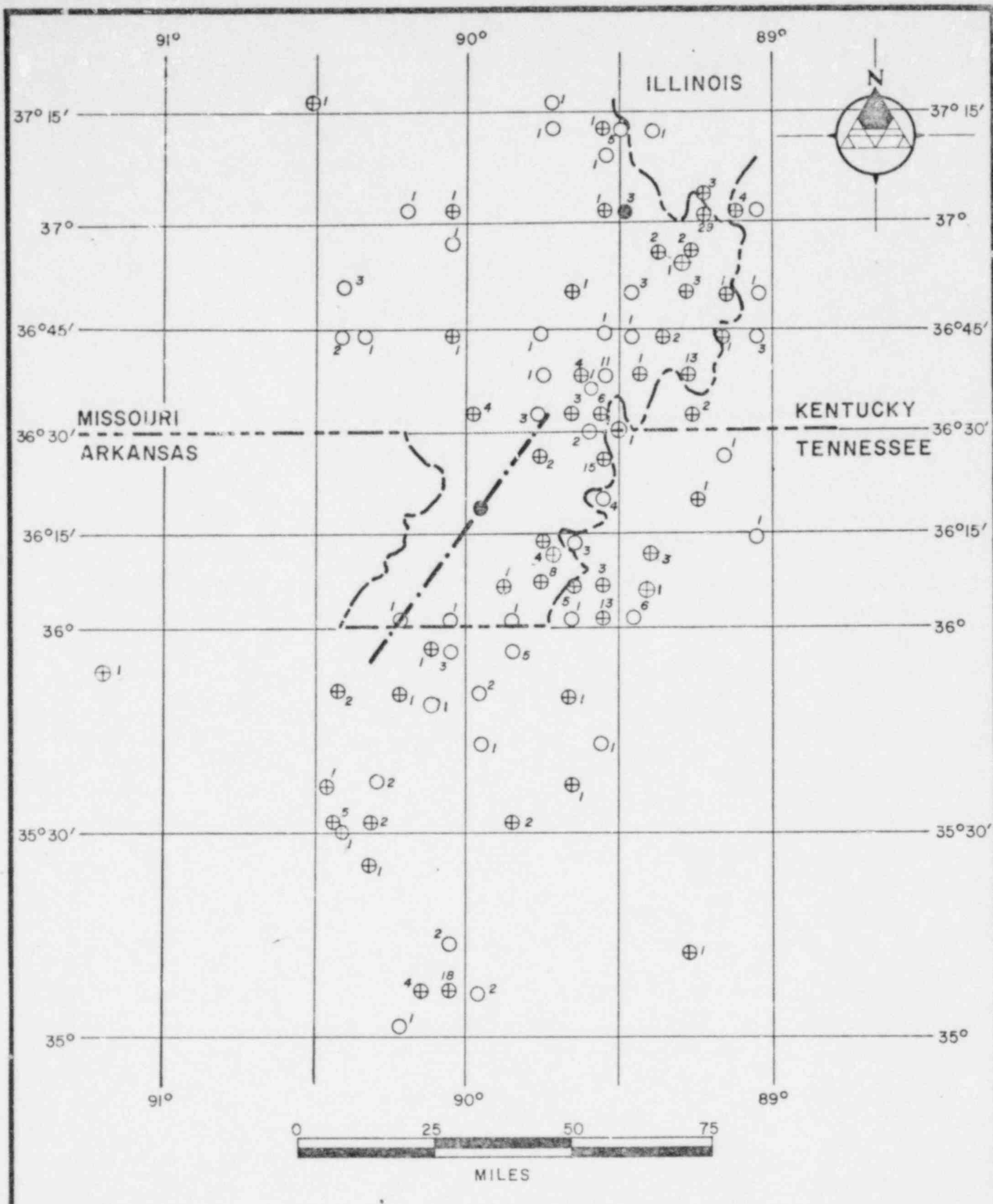
- ● II - IV
- ○ V
- ◯ VI
- △ VII
- ◉ VIII
- ◎ IX OR GREATER



UNION ELECTRIC COMPANY
CALLAWAY PLANT UNITS 1 AND 2
FINAL SAFETY ANALYSIS REPORT

FIGURE 2.5-49

EPICENTER LOCATIONS



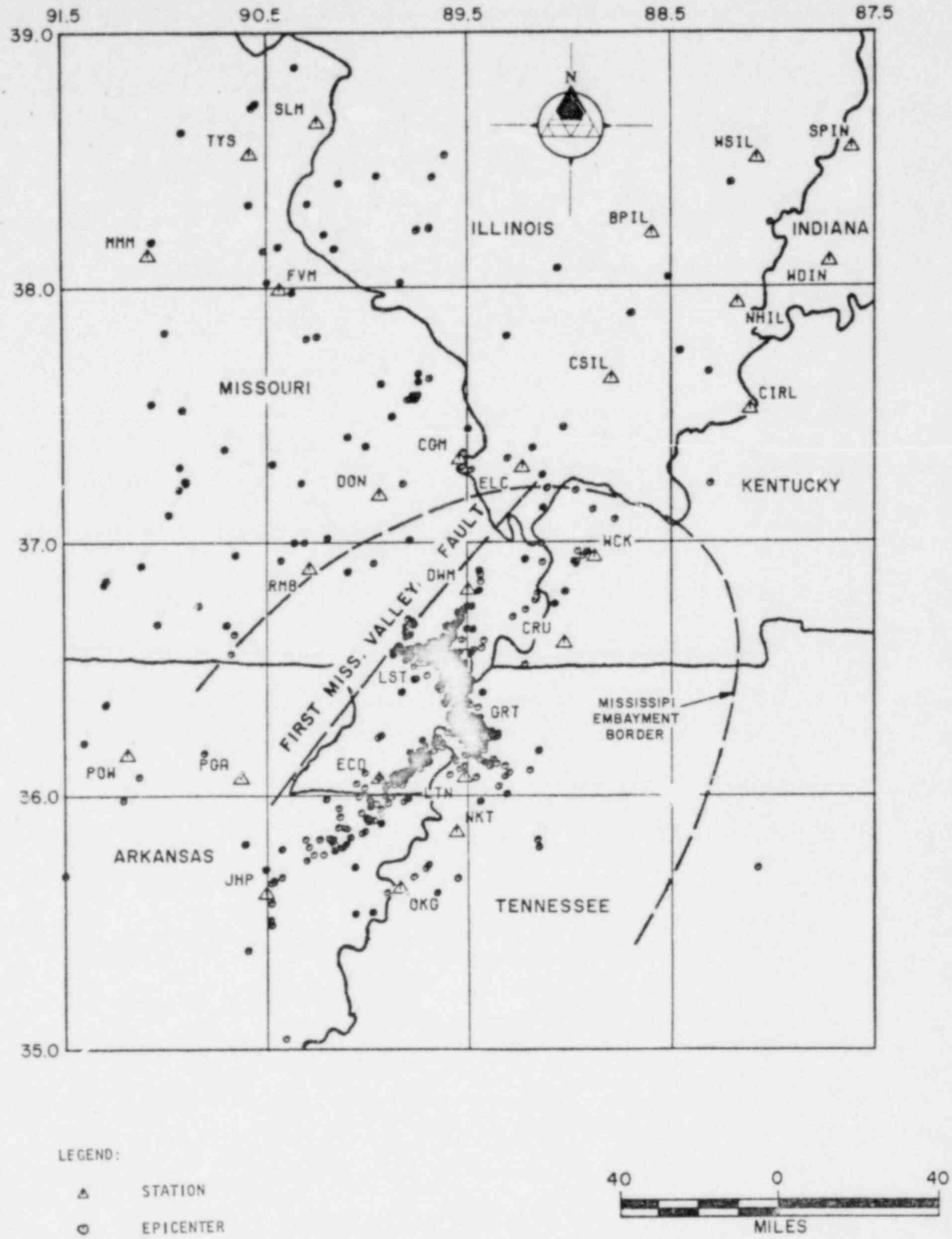
EXPLANATION:
INTENSITY OF GREATEST SINGLE EVENT

- ○ ≤MMI-IV
- ⊕ MMI V-VII
- ● ≥MMI-VIII
- —·—· EPICENTRAL LINE OF 1811-12 EARTHQUAKES (FULLER, 1912)

NUMERALS INDICATE NUMBER OF EVENTS

UNION ELECTRIC COMPANY
CALLAWAY PLANT UNITS 1 AND 2
FINAL SAFETY ANALYSIS REPORT

FIGURE 2.5-63
EPICENTERS OF PERCEPTIBLE SEISMIC EVENTS NEAR NEW MADRID
1811–1980



UNION ELECTRIC COMPANY
CALLAWAY PLANT UNITS 1 AND 2
FINAL SAFETY ANALYSIS REPORT

FIGURE 2.5-74

REGIONAL EPICENTER LOCATIONS
CUMULATIVE EVENTS 01 JUL 1974
TO (END DATE FOR LATEST QUARTERLY REPORT)

REFERENCE:
CENTRAL MISSISSIPPI VALLEY EARTHQUAKE
BULLETIN, QUARTERLY REPORT NO.