NUREG/CR-2015, Vol. 2
UCRL-53021,Vol. 2

Seismic Safety Margins Research Program

Phase I Final Report—Plant/Site Selection and Data Collection (Project I)

T. Y. Chuang

Prepared for
U.S. Nuclear Regulatory Commission

LAWRENCE
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NUREG/CR-2015, Vol. 2
UCRL-53021, Vol. 2
RD, RM

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Manuscript Completed: May 1981
Date Published: July 1981

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NRC FIN No. A0130

ABSTRACT

Project I of Phase I of the Seismic Safety Margins Research Program (SSMRP) comprised two parts: the selection of a representative nuclear power plant/site for study in Phase I and the collection of data needed by the other SSMRP projects. Unit 1 of the Zion Nuclear Power Plant in Zion, Illinois, was selected for the SSMRP Phase I studies.

Unit 1 of the Zion plant has been validated as a good choice for the Phase I study plant. Although no single nuclear power plant can represent all such plants equally well, selection criteria were developed to maximize the generic implications of Phase I of the SSMRP.

On the basis of the selection criteria, the Zion plant and its site were found to be reasonably representative of operating and future plants with regard to its nuclear steam supply system; the type of containment structure (prestressed concrete); its electrical capacity (1100 MWe); its location (the Midwest); the peak seismic acceleration used for design (0.17g); and the properties of the underlying soil (the low-strain shear-wave velocity is 1650 ft/s in a 50- to 100-ft-thick layer of soil overlying sedimentary bedrock).

CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

FOREWORD

The Seismic Safety Margins Research Program (SSMRP) is an NRC-funded, multiyear program conducted by Lawrence Livermore National Laboratory (LLNL). Its goal is to develop a complete, fully coupled analysis procedure (including methods and computer codes) for estimating the risk of an earthquake-caused radioactive release from a commercial nuclear power plant. The analysis procedure is based upon a state-of-the-art evaluation of the current seismic analysis and design process and explicitly includes the uncertainties inherent in such a process. The results will be used to improve seismic licensing requirements for nuclear power plants.

The SSMRP was begun in 1978 when it became evident that an accurate seismic risk analysis must simultaneously consider all the interrelated factors that affect the final probability of radioactive release. In the traditional design procedure, by contrast, each factor is usually analyzed separately. These closely coupled factors are:

- The likelihood and magnitude of an earthquake.
- The transfer of earthquake energy from a fault source to a power plant, a phenomenon that varies greatly with the magnitude of an earthquake.
- Interaction between the soil underlying the power plant and the structural response, a phenomenon that depends on the soil composition under the plant and the location of the fault source relative to the plant.
- Coupled responses of a power plant's buildings and the massive reactor vessels, piping systems, and emergency safety systems within.
- Numerous accident scenarios, which vary according to the types of failures assumed and the success or failure of the engineered safety features intended to mitigate the consequences of an accident.

A nuclear power plant is designed to ensure the survival of all buildings and emergency safety systems in a worst-case ("safe shutdown") earthquake. The assumptions underlying this design process are deterministic. In practice, however, these assumptions are clouded by considerable uncertainty. It is not possible, for example, to accurately predict the worst earthquake that will occur at a given site. Soil properties, mechanical properties of buildings, and damping in buildings and internal structures also vary significantly among plants.

To model and analyze the coupled phenomena that contribute to the total risk of radioactive release it is therefore necessary to consider all significant sources of uncertainty as well as all significant interactions. Total risk is then obtained by considering the entire spectrum of possible earthquakes and integrating their calculated consequences. In the SSMRP this approach to risk analysis is embodied in the seismic analysis chain, comprising five steps: determining seismic input characteristics for a site, calculating the effects of soil-structure interaction, calculating major structure response, calculating subsystem response, and calculating probability of failure.

The seismic input consists of the earthquake hazard in the vicinity of a nuclear power station, defined by an estimate of the seismic hazard function (i.e., the relationship between the probability of occurrence and a measure of the size of an earthquake) and a description of the free-field motion. The soil-structure interaction link in the chain transforms the free-field ground motion into basemat or in-structure response, accounting for the interaction of the soil with the massive, stiff structures present at a nuclear power plant. Determination of the major structure response follows the soil-structure interaction step, where "major structure" commonly denotes a building, but may also include very large components. The final step in the traditional seismic analysis and design process is predicting subsystem structural response. An additional step in the SSMRP is the prediction of failure and subsequent risk of radioactive release.

In the SSMRP this methodology is implemented in three computer programs: HAZARD, which assesses the seismic hazard at a given site, SMACS, which computes in-structure and subsystem seismic responses, and SEISIM, which calculates structural, component, and system failure probabilities and radioactive release probabilities.

The SSMRP Phase I effort was organized into eight projects. In Project I, Unit 1 of the Zion Nuclear Power Plant was chosen as an appropriate "typical" plant. In Project II, we developed the tools and models, including HAZARD, necessary to describe probabilistically the seismic hazard at the Zion site and to generate the appropriate acceleration time histories. Soil-structure interaction was the subject of Project III, in which we provided as input to the first step in the SMACS calculational procedure the characterizations of soil, foundations, and structures at the Zion plant necessary to an analysis of the coupled soil-structure system. Major structure models were developed in Project IV as necessary input to the SMACS computation carried out in Project VIII. In Project V, data were collected and models established for the pertinent piping subsystems to provide input to the SMACS computation. In Project VI we developed fragility curves--normal or lognormal distributions describing the probability of failure as a function of a critical response parameter--necessary for all components and structures whose failure is accounted for in the SEISIM fault trees. In Project VII the SEISIM computer program embodied event/fault trees to systematically describe the possible accident sequences that follow an earthquake and accepted as input the responses computed by SMACS, the set of fragility curves, and a seismic hazard curve for the Zion site to calculate the structural, component, and system failure probabilities and the probabilities of radioactive release. The SMACS computer code was developed in Project VIII to tie together the soil-structure interaction, structure response, and subsystem response calculations.

The results and technical products of each of the eight projects are described in separate volumes of the SSMRP Phase I Final Report. Volume 1 presents an overview of the Phase I effort.

The present volume, dealing with Project I, presents the results of a study performed by Engineering Decision Analysis Company, Inc. (EDAC) under LLNL Contract No. 545-3703, Amendment 3. The purpose of EDAC's analysis was to assess whether Zion is a reasonably representative plant for the Phase I effort.

The NRC technical monitor for Project I was G. Bagchi. We would like to express our thanks to Palmer Van Dyke, the editor of this volume, and to the other members of LLNL's Technical Information Department Staff who contributed their efforts to its production.

EXECUTIVE SUMMARY

Project I of Phase I of the Seismic Safety Margins Research Program (SSMRP) comprised two parts: the selection of a representative nuclear power plant/site for study in Phase I and the collection of data needed by the other SSMRP projects. Unit 1 of the Zion Nuclear Power Plant in Zion, Illinois, was selected for the SSMRP Phase I studies.

Data on the Zion plant were gathered from several sources. The Southwest Research Institute provided system and component data. They collected engineering data on each of 26 systems and 5384 components. Sargent & Lundy Engineers (S&L; the original architect-engineers) and Commonwealth Edison Company (CECo; the operating utility) supplied design information, plant records, and test results. Westinghouse Electric Corporation supplied data on the nuclear steam supply system (NSSS) to S&L, who were responsible for developing a mathematical model of the system.

The Zion Nuclear Power Plant is located on Lake Michigan, about 1.5 miles east of Zion, Illinois and about 40 miles north of Chicago. The plant was designed by S&L for CECo, the owner and builder. It consists of two NSSS units, each with a rated power of 1100 MWe. The first unit was granted an operating license effective April 1973; Unit 2 was licensed to operate in November 1973.

Engineering Decision Analysis Company, Inc. (EDAC) was contracted to investigate whether Zion and its site are reasonably representative for study in Phase I. More than a hundred currently operating and planned nuclear power plants in the contiguous United States were compared on the basis of a set of pertinent characteristics. Although obviously no single plant can completely reflect the entire range of variance, Zion was selected to maximize the generic implications of Phase I. The following characteristics provided the basis for the comparative study:

- Nuclear steam supply system
- Containment structure
- Electric power generating capacity
- Geographic location
- Site seismicity
- Foundation soil properties.

On the basis of the selection criteria, the Zion plant and its site were found to be reasonably representative of operating and future plants with regard to the design of its NSSS; the type of containment structure (prestressed concrete); its electrical capacity (1100 MWe); its location (the Midwest); the peak seismic acceleration used for design (0.17g); and the properties of the underlying soil (the low-strain shear-wave velocity is 1650 ft/s in a 50- to 100-ft-thick layer of soil overlying sedimentary bedrock). In general, the characteristics of Zion are minimally different from those of other plants; however, it appears that the seismic design criteria for the Zion site were more conservatively estimated than is typical for peer plants.

Seismic Category I building structures at the Zion plant comprise the reactor containment, fuel-handling, auxiliary, and diesel generator buildings, and portions of the turbine and crib house buildings. The plant was designed for a safe shutdown earthquake (SSE) of 0.17g effective peak ground acceleration (EPGA) and an operating basis earthquake (OBE) of 0.08g EPGA. Category I buildings were designed to remain elastic during an OBE, but concrete ultimate strength or steel yield stress design methods were used for the SSE criterion.

Zion was one of the first nuclear power plants to be analyzed for dynamic loads during the design process. At least three different lumped-mass computer models were used to represent the containment and auxiliary-turbine buildings and the interconnected fuel-handling, turbine, and crib house buildings. Damping values assumed in the analysis were 2% for the OBE and 5% for the SSE. Some effects of soil-structure interaction were included.

The results verified that Category I buildings would remain elastic for an OBE and had adequate strength to withstand an SSE. However, the plant was also designed for other load combinations that may have controlled the design but that did not include seismic loads.

Category I piping and component systems at the Zion plant comprise the reactor coolant system and engineered safety-related piping systems. Piping smaller than 10 in. in diameter was subjected to seismic analysis using design curves. Seismic analyses of Category I piping larger than or equal to 10 in. in diameter were performed with lumped-mass models based on the response spectrum method. Reactor coolant components were designed and analyzed in accordance with the ASME code. Components of the NSSS were analyzed by the vendor, Westinghouse, using lumped-mass, multi-degree-of-freedom models.

The Zion emergency core cooling system, designed to ASME and ANSI standards, was analyzed and found to comply with the NRC's final acceptance criteria.

Category I equipment at the Zion plant includes reactor control systems, protection systems, and ventilation systems. Seismic analysis and testing procedures for reactor control systems were similar to those for Category I components. The protection systems were tested by type, using the same methods as for other equipment or components. All components and supports of the control room heating, ventilating, and air conditioning system met Category I requirements.

SECTION 1: INTRODUCTION

Project I of Phase I of the Seismic Safety Margins Research Program (SSMRP) comprised two parts: the selection of a representative nuclear power plant/site for study in Phase I and the collection of data needed by the other SSMRP projects. Unit 1 of the Zion Nuclear Power Plant in Zion, Illinois, was selected for the SSMRP Phase I studies.

Data on the Zion plant were gathered from several sources. The Southwest Research Institute provided system and component data from the Nuclear Plant Reliability Data System.[1] They collected engineering data on each of 26 systems and 5384 components. Sargent & Lundy Engineers (S&L; the original architect-engineers) and Commonwealth Edison Company (CECo; the operating utility) were very cooperative in supplying design information, plant records, and test results. Westinghouse Electric Corporation supplied data on the nuclear steam supply system (NSSS) to S&L, who were responsible for developing a mathematical model of the system.

Section 2 of this volume discusses the comparative study that led to selection of the Zion plant, and Sec. 3 describes its site characteristics, building structures, piping, equipment, and design parameters, including analytical results. Section 4 presents the conclusions.

SECTION 2: COMPARISON OF NUCLEAR POWER PLANT CHARACTERISTICS

Unit 1 of the Zion Nuclear Power Plant was selected for the SSMRP Phase I studies. The purpose of EDAC's investigation was to determine whether Zion and its site are reasonably representative for study in Phase I. In this section we present selection criteria, a summary of EDAC's analyses and evaluations, and specific recommendations. A more detailed account has been previously published.[2]

More than a hundred currently operating and planned nuclear power plants in the contiguous United States were compared on the basis of a set of pertinent characteristics. Although obviously no single plant can completely reflect the entire range of variance, Zion was selected to maximize the generic implications of Phase I. The following characteristics provided the basis for the comparative study:

- Nuclear steam supply system
- Containment structure
- Electric power generating capacity
- Geographic location
- Site seismicity
- Foundation soil properties.

2.1 NUCLEAR STEAM SUPPLY SYSTEM

The two principal types of nuclear steam supply systems (NSSS) used in existing or planned power plants are the pressurized water reactor (PWR) and the boiling water reactor (BWR). From 1960 to 1971, more BWR than PWR plants were built; since that time, however, more than twice as many PWR than BWR plants have been built (Table 1). On the basis of existing or planned plants, it is clear that the PWR is established as the most common type of NSSS. As a PWR plant, Zion is thus typical of the current trend in nuclear steam supply systems.

2.2 CONTAINMENT STRUCTURE

Three basic types of containment structures are used for PWRs: reinforced concrete, prestressed concrete, and welded steel with reinforced

Table 1. Type of nuclear steam supply system versus plant age.[3]

Age	BWR[a]	PWR, by reactor supplier: Combustion Engineering	Westinghouse	Babcock & Wilcox	PWR subtotals	Total[b]
1960-1971	10	1	6	1	8	18
1972-1978	15	6	19[c]	9	34	49
Construction started or permit granted	29	16	41	8	65	94
Planned	8	8	11	9	28	36
Totals	62	31	77	27	135	197

[a]All BWR reactors are supplied by General Electric Co., except for the LaCrosse (48-MWe demonstration) plant by Allis-Chalmers, licensed in 1969.

[b]Total does not include the high-temperature gas reactor at the Fort St. Vrain Station, Platteville, Colorado, built by General Atomic.

[c]Zion is in this category.

concrete shielding. A survey of age distribution by type shows a consistent trend to prestressed concrete (Table 2). Reflecting this trend, the Zion reactors are contained by this type of structure.

2.3 ELECTRIC POWER CAPACITY

The size of a nuclear power plant is generally related to its electric power generating capacity. Electric power capacity per unit has increased steadily since the early 1960s (Fig. 1). The average power produced per unit is currently 728 net MWe, and the average for plants under construction or planned is 1120 net MWe. At a capacity of 1100 net MWe each, the Zion units are thus representative of newer plants or those planned for the near future.

2.4 GEOGRAPHIC LOCATION

The seismic hazard to which a plant is exposed is related to its geographic location. Although the potential for earthquakes is greater on the

Table 2. Type of containment shell versus age, PWR plants.[4]

Age	Welded steel with reinforced concrete shielding: Spherical[a]	Welded steel with reinforced concrete shielding: Cylindrical	Reinforced concrete	Prestressed concrete	Total
1960-1971	3	0	1	4	8
1972-1978	0	5	10	19[b]	34
Construction started or permit granted	5	14	18	28	65
Totals	8	19	29	51	107

[a]All steel containment shells include reinforced concrete shield buildings except for the freestanding steel spherical containment buildings at the Yankee-Rowe plant, licensed in 1961.

[b]Zion is in this category.

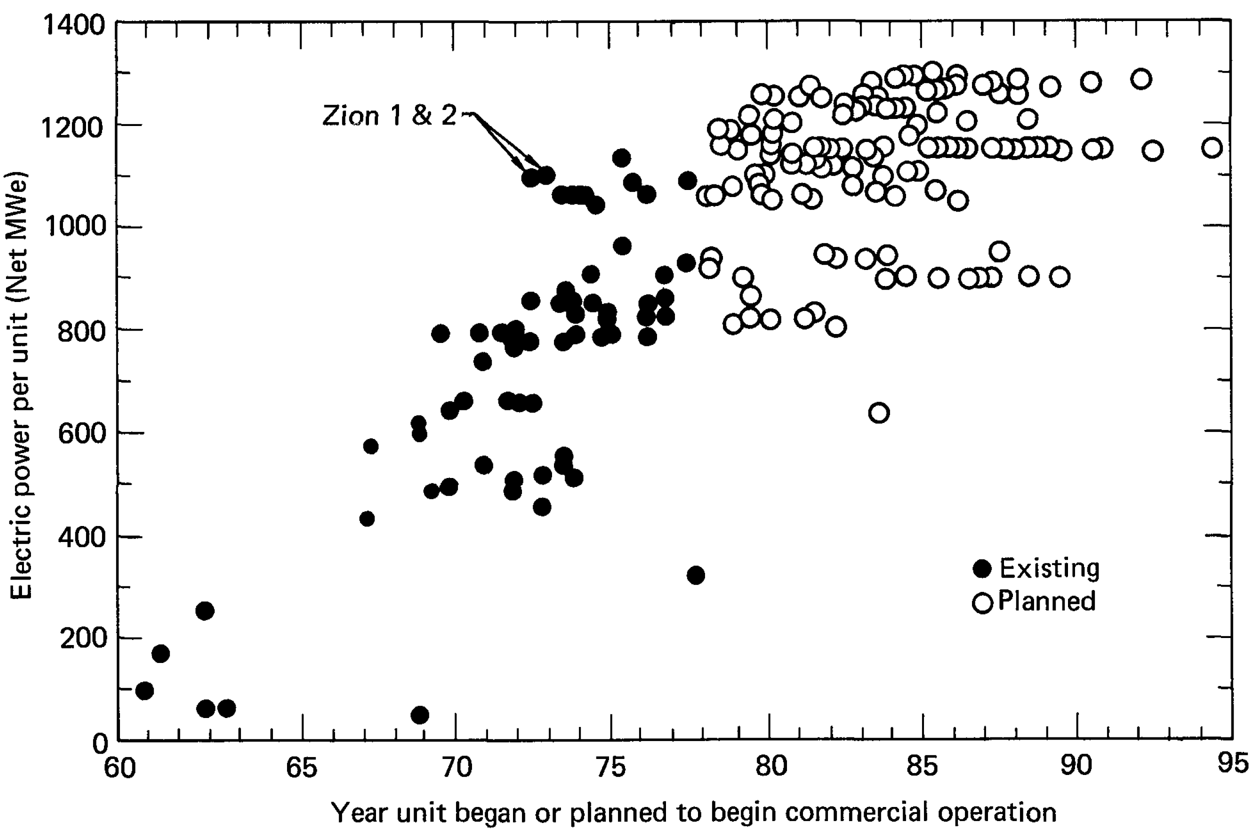

Fig. 1. Electric power capacity versus age of plant.[3]

West Coast than in other parts of the contiguous United States, most existing or planned plants are located east of the Rocky Mountains (Table 3). Zion's location (in Illinois) is thus representative of a large number of plants.

2.5 SITE SEISMICITY

The seismic capacity of a plant is determined in part by the value of the safe shutdown earthquake (SSE) peak ground acceleration used to design it. However, the relationship between the design SSE (related to seismic capacity) and the site seismic hazard (related to seismic demand) will more directly influence the probability of radioactive release than the SSE value alone. Thus, even though a plant may be located in a region of low seismicity, both the seismic capacity and the site hazard are necessary to identify seismic risk.

The average design SSE acceleration of licensed nuclear power plants is 0.16g; the Zion plant was designed for 0.17g (Fig. 2). With regard to seismic capacity, then, Zion is representative of plants in the United States.

Table 3. Geographic distribution versus age, nuclear power plants.[3]

Year operation began or is anticipated	West of Rockies	East of Rockies	Total
1960-1971	2	16	18
1972-1978	2	48[a]	50
Beyond 1978:			
Construction started or permit granted	12	82	94
Beyond 1978:			
Planned	6	30	36
Totals	22	176	198

NOTE: Table does not include the following plants: Clinch River breeder reactor, NORCO-1 (Puerto Rico), or Hanford-N (Richland, Wash.).

[a]Zion is in this category.

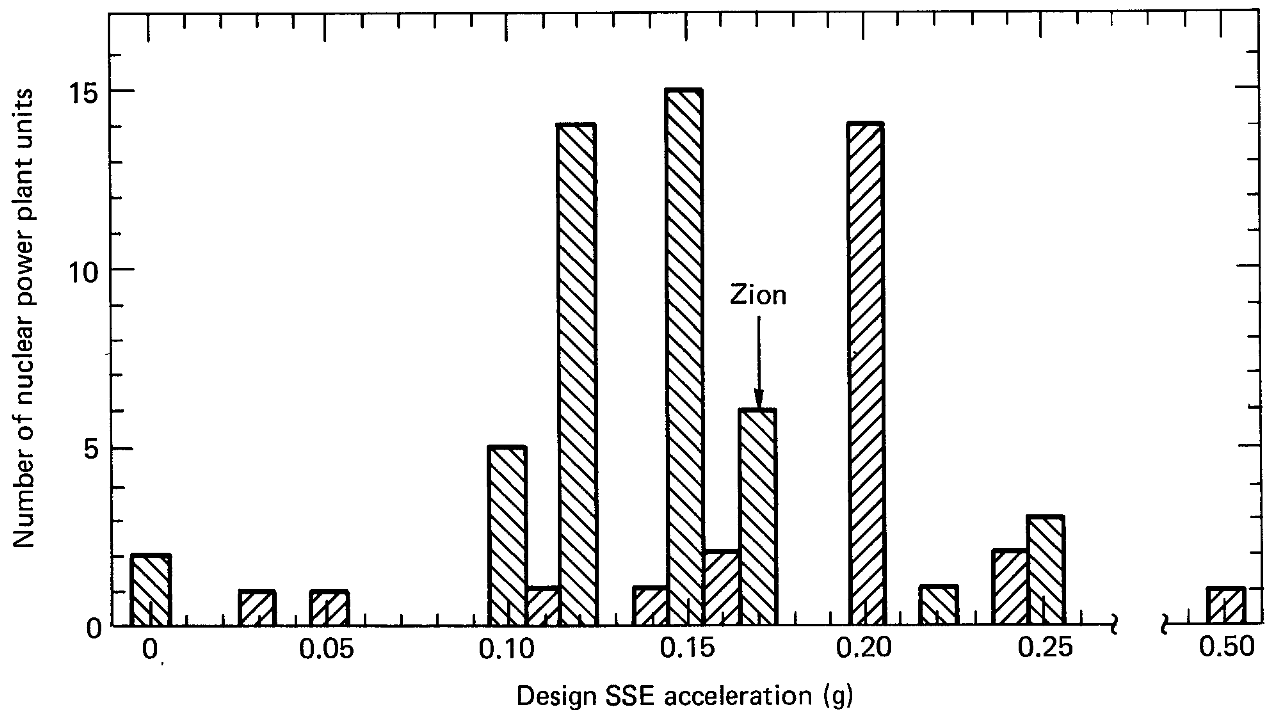

Fig. 2. Histogram of design SSE accelerations for licensed nuclear power plant units.

2.6 FOUNDATION SOIL PROPERTIES

Site soil characteristics were obtained from a report prepared for General Atomic Company.[5] Five types of sites were defined by thickness of soil layers beneath the plants and by type of base rock (Table 4). There is a reasonably uniform distribution of soil sites for the 69 plants studied. However, sites underlain by sedimentary rock, including Zion, are more numerous than those underlain by plutonic rock.

Shear wave velocities at Type III sites were also compared (Fig. 3). This parameter is related to soil stiffness, which affects dynamic response characteristics. The average shear-wave velocity at the type of site that includes Zion is 1630 ft/s. The shear-wave velocity at the Zion site is 1450 ft/s; as a design value of 1650 ft/s was used, Zion appears to be typical of sites in the United States.

Table 4. Soil characteristics of nuclear power plant sites (based on categories in Dames & Moore report).[5]

Soil type	Rock category: Underlying rock is plutonic	Underlying rock is sedimentary	Total
Type I: Soil cover 20 ft or less	6	10	16
Type II: Soil cover 20 ft to 40 ft	4	5	9
Type III: Soil cover 50 ft to 100 ft	4	12[a]	16
Type IV: Soil cover 100 ft to 400 ft	3	11	14
Type V: Soil cover more than 400 ft	14 sites (categories not applicable)		14

[a]Zion is in this category.

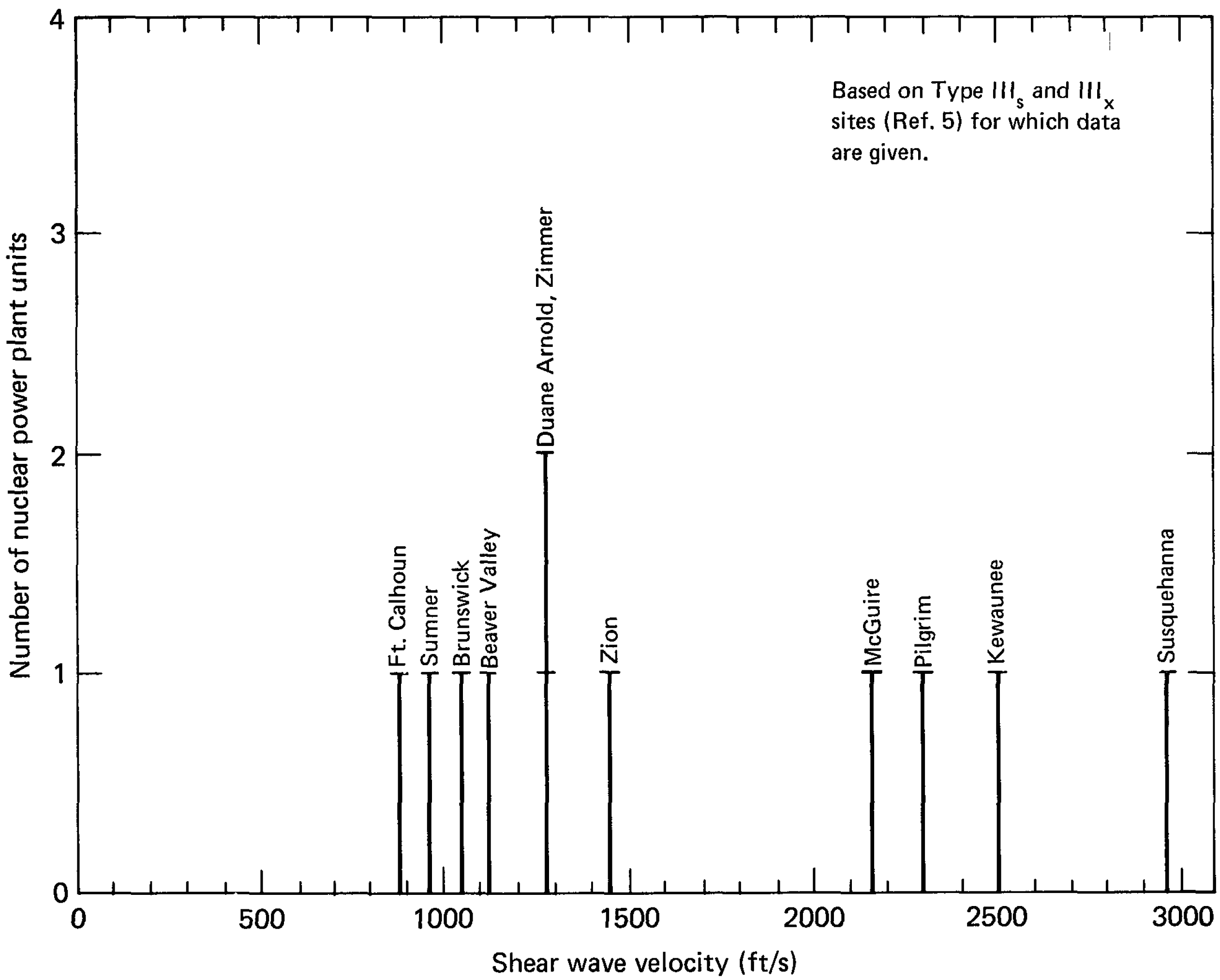

Fig. 3. Distribution of shear-wave velocities for nuclear power plant sites with soil cover of 50 to 100 feet over bedrock.[5]

SECTION 3: DESCRIPTION OF ZION NUCLEAR POWER PLANT

In this section we describe the general background of the Zion plant, site characteristics; seismic Category I building structures, piping, and equipment; and design parameters. Our discussion is based on the Final Safety Analysis Report (FSAR)[6] and the information received from S&L.

3.1 GENERAL BACKGROUND

The Zion Nuclear Power Plant is located on Lake Michigan, about 1.5 miles east of Zion, Illinois, and about 40 miles north of Chicago. The plant was designed by S&L for CECo, the owner and builder. It consists of two NSSS units, each with a rated power of 1100 MWe. The first unit was granted an operating license effective April 1973; Unit 2 was licensed to operate in November 1973.

3.2 SITE CHARACTERISTICS

Characteristics pertinent to the site are its geology and seismicity, types of foundation soils, and types of construction foundations.

3.2.1 Geology and Seismicity

Geology and seismicity characteristics pertinent to the Zion plant comprise rock types, faulting, and historical seismicity.[6,7]

Bedrock in the region surrounding the Zion plant generally consists of Paleozoic sedimentary rock overlying Precambrian basement rock. This rock base is covered by a mantle of glacial drift about 80 to 150 feet thick. Recent layers of unconsolidated sand, silt, and peat were removed during excavation.

Although there are several faults in the region, there is no evidence of recent seismic activity. Approximately 25 miles southwest of the site, near Des Plaines, there is a highly complex faulted zone that appears to have no relationship to the regional structure. There are several faults in southern Wisconsin; the one closest to the site is about 45 miles away. There are also faults in northeastern Illinois, although none is within 50 miles of the site. All of these faults are covered by glacial drift, and there is no evidence of faulting at the ground surface.

The Zion site is in a region of only minor seismic activity. Figure 4 shows the location of earthquake epicenters. The largest historical seismic events were the 1804 Ft. Dearborn, Illinois, and the 1909 Beloit, Wisconsin, earthquakes. Both were reported to have modified Mercalli intensities (MMIs) of VII (later modified to VI for the 1804 event).

An earthquake on 14 September 1972 was the only seismic event observed in the region since the Zion plant began operation.[8] The epicenter was located near Holcomb, Illinois. A Richter magnitude of 3.7 was recorded; the epicentral intensity was estimated at MMI VI. The intensity at Zion was estimated to be in the range of MMI I to III.[9]

3.2.2 Soils

Soils at the Zion site were investigated before construction of the plant through both laboratory and site tests. Samples were used to perform direct shear tests, confined and unconfined compression tests, consolidation tests, and tests for density and particle size. The site tests included geophysical refraction surveys, shear-wave velocity surveys, and uphole velocity surveys. Typical soil conditions are shown in Fig. 5.

3.2.3 Foundations

Information on foundation types, bearing pressures, and excavation details was based on recommendations made before construction.[10] Recommended soil bearing pressures served as acceptance criteria for the soil pressure calculations.

The reactor containment and turbine buildings are constructed on separate mat foundations. Conventional spread footings were recommended for the service building and other light structures. Some bearing pressures recommended for foundations are given in Table 5.

It was recommended that the banks of excavated areas be constructed at a slope of 1 vertical to 1.5 horizontal or flatter. Sheet piles were used for construction of the crib house.

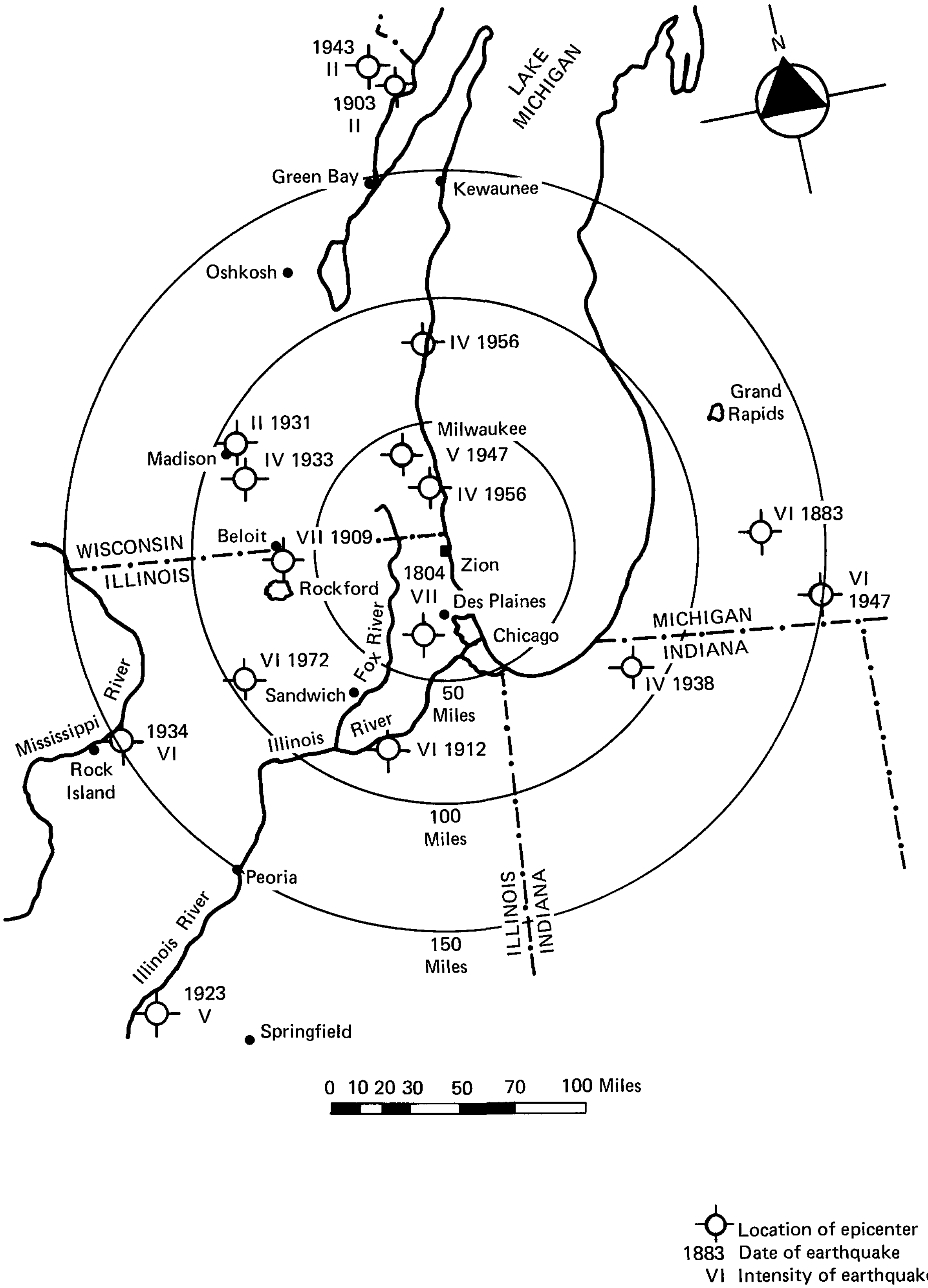

Fig. 4. Historical earthquakes in the region of the Zion site.[7]

Depth (ft)	Log symbols	Description	Compressional wave velocity (ft/s)	Poisson's ratio	Shear wave velocity (ft/s)	Unit weight (lbs/ft^3)
0 – 24–33		Granular lake (beach) deposits (Fine to medium sand with coarse sand and gravel and pockets of organic material) Moderately dense to dense	2,240	0.39	920	122
24–33 – 102–116		Pleistocene glacial till, outwash, and Lacustrine deposits (Silty clay, clayey silt, silt, sand, and gravel) Firm to hard	6,000	0.46	1,650	142
102–116 –		Niagara dolomite (250′ thick)	16,500	0.27	9,200	150

Fig. 5. Typical soil conditions at the Zion site.[7]

Table 5. Soil bearing pressures recommended for building structures of Zion plant.[10]

Foundation type	Elevation (ft)	Recommended bearing pressure (psf)
Reactor building mat	554	6000 to 7000
Condenser pit and turbine generator pedestal	548	3000 to 5000
Turbine building mat	588	3000 to 6000
Auxiliary building mat	538 to 563	2500 to 4000
Fuel-handling building mat	577 to 583	2000 to 5000
Crib house	545	3000 to 3000
Spread foundations on granular lake deposits	Above 575 Below 575	3000 to 4000[a] 5000 to 8000[a]
Spread foundations on controlled compacted fill	Above 575 Below 575	3000 to 4000[a] 5000 to 8000[a]
Foundations on glacial till	--	15,000

[a]Recommended value depends upon depth of embedment.

3.3 CATEGORY I BUILDING STRUCTURES

Seismic Category I building structures at the Zion plant comprise the reactor containment, fuel-handling, auxiliary, and diesel generator buildings, and portions of the turbine and crib house buildings (Fig. 6).

The two identical reactor containment buildings are constructed of prestressed concrete with ungrouted tendons. Each consists of a cylindrical exterior wall with a shallow domed roof and a flat foundation mat. The reactor containment shell is approximately 140 feet in diameter by 212 feet high, with three-foot-thick walls and a nine-foot-thick foundation mat. The containment structures are lined with 0.25-inch welded steel plate to provide vapor tightness.[6]

3.3.1 Design Criteria

Comprehensive data on peak ground accelerations and response spectra, load combinations, and acceptance criteria used to design the Zion structures

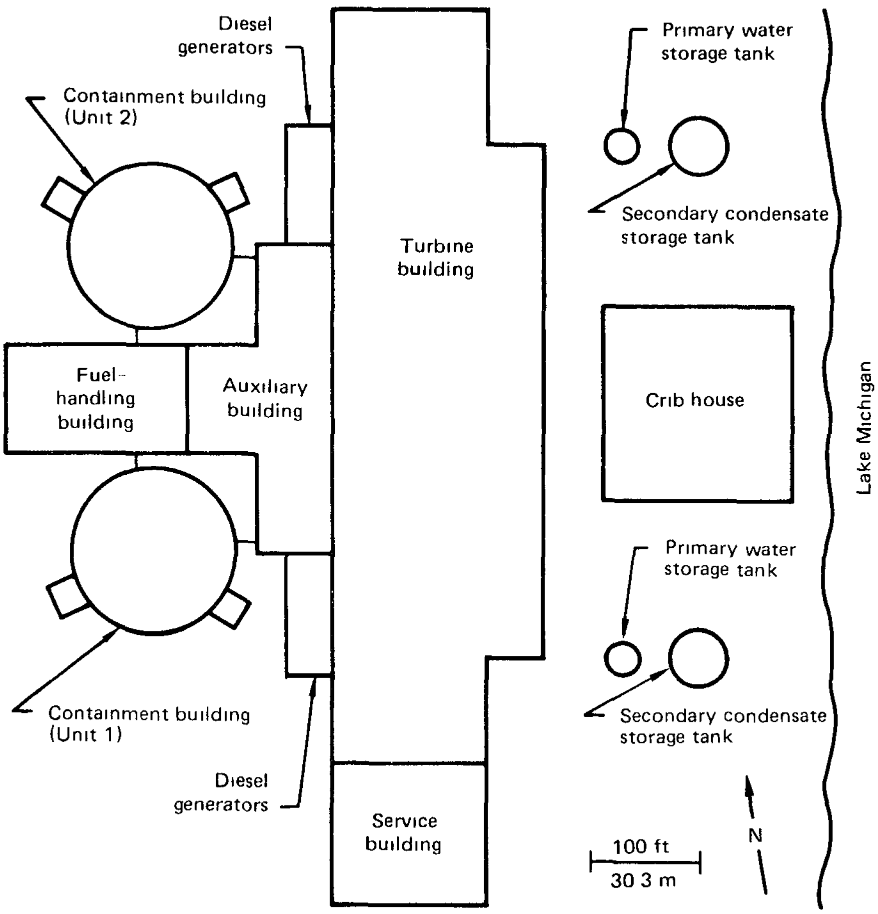

Fig. 6. Arrangement of major building structures at the Zion plant.

are given in the Final Safety Analysis Report.[6] In this section we summarize the criteria associated with potential seismic hazard.

The Zion plant was designed for an SSE of 0.17g effective peak ground acceleration (EPGA) and an operating basis earthquake (OBE) of 0.08g EPGA. The design response spectra anchored to the SSE EPGA are shown in Fig. 7. The corresponding spectra for the OBE are equal to one-half of the SSE spectra.

For Category I buildings other than the containment structures, earthquake loads were considered in combination with dead, thermal, and pressure or pipe rupture loads. Examples of seismic load combinations used in the design of most structural members are given in Table 6.

Acceptance criteria for Category I buildings were based on the provisions of the American Concrete Institute and the American Institute of Steel Construction codes applicable at the time of design.[11,12] The buildings were designed to remain elastic during the OBE, but concrete ultimate strength

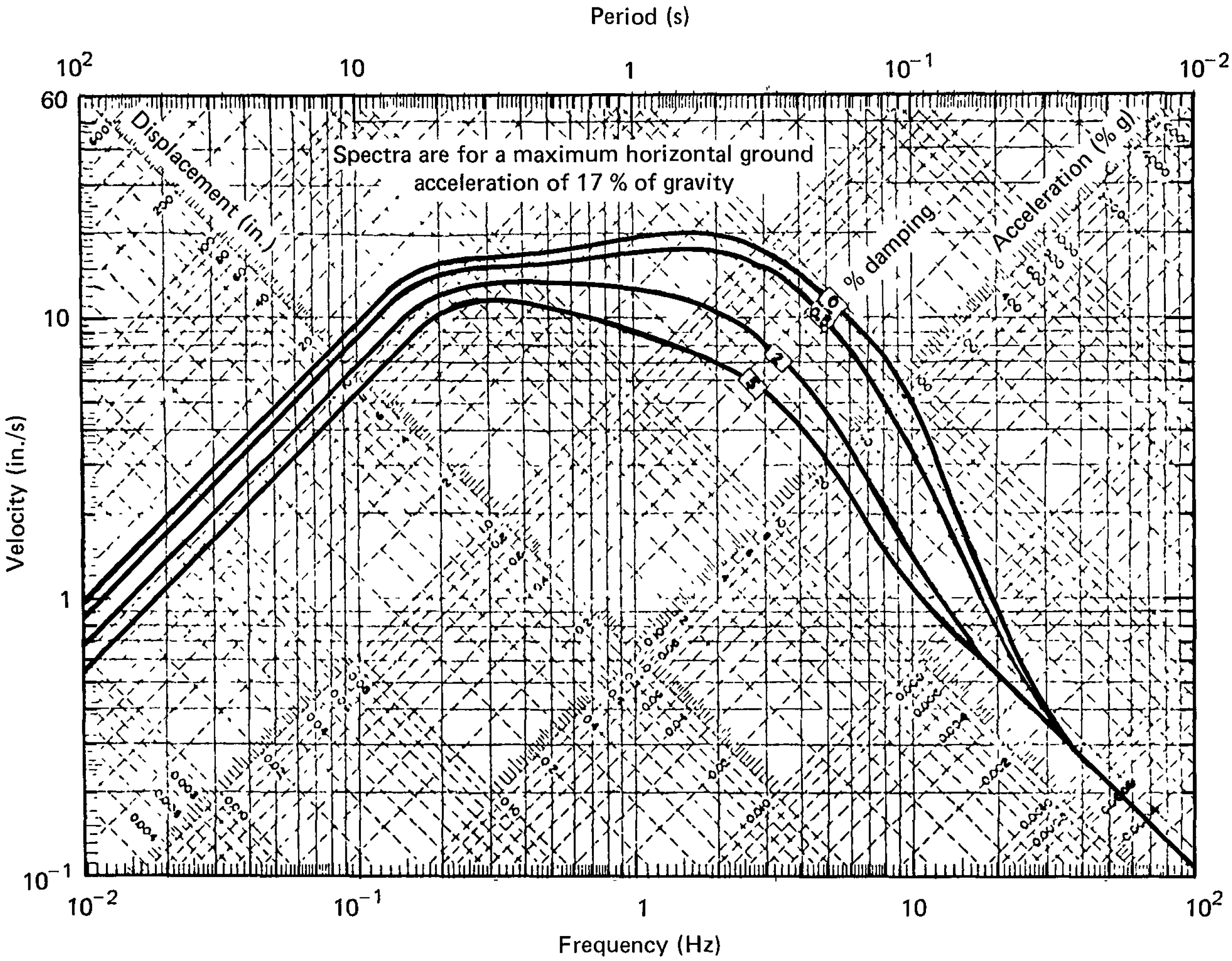

Fig. 7. SSE design response spectra, Zion plant.[6]

or steel yield stress design methods were used for the SSE criteria, as noted in Table 6.

Load combinations and acceptance criteria for the containment buildings were somewhat different from those for other Category I buildings. As shown in Table 7, a "yield limit design" method was used for certain load combinations; this method prohibits redistribution of loads at strains beyond yielding. A more complete account of this approach is given in Ref. 6.

The steel liner plates of the containment building were designed using the first load combination equation given in Table 7.

Table 6. Seismic load combinations and acceptance criteria, Zion plant Category I buildings other than containment building.[6]

Load combination[a]	Acceptance criteria	
$D + T_O + E + P'$	Working stress	ACI 318-63; AISC 6th edition
$D + T_O + E' + R$	Ultimate strength	ACI 318-63 USD; Yield strength of steel

NOTE: D = Dead load and permanent equipment load

T_O = Thermal loading

P' = Reactor internal structures design load (14 psi)

R = Pipe rupture including dynamic effects

E = OBE load

E' = SSE load

[a]Load combinations given governed the design of most structural members.

Table 7. Seismic load combinations and acceptance criteria, Zion plant containment buildings.[6]

Load combination[a]	Acceptance criteria
$D + F + P + T_A + E$	Working stress (ACI 318-63)
$D + F + 1.25P + T_A + 1.25E$	Yield limit design--concrete strain held to ultimate, steel allowed to just yield
$D + F + P_A + T + E'$	

NOTE: D = Dead load

F = Prestress load

P = Accident pressure load

T_A = Accident thermal load

E = SSE load

E' = OBE load

[a]Load combinations given governed the design of most structural members.

3.3.2 Analytical Methods and Results

Zion was one of the first nuclear power plants to be analyzed for dynamic loads during the design process. At least three different lumped-mass computer models were used to represent the containment and auxiliary-turbine buildings, and the interconnected fuel-handling, turbine, and crib house buildings.[6] Damping values assumed in the analysis were 2% for the OBE and 5% for the SSE. Some effects of soil-structure interaction were included.

Design forces were obtained by the response spectrum method, except that vertical forces were assumed to be two-thirds of the peak horizontal ground acceleration times the building mass. Time-history analyses were performed to generate horizontal floor response spectra. Vertical floor response spectra were assumed to be two-thirds of the corresponding horizontal spectra.

The results[6] verified that Category I buildings would remain elastic for an OBE and had adequate strength to withstand an SSE. However, the plant was also designed for other load combinations that may have controlled the design but that did not include seismic loads.

3.4 CATEGORY I PIPING AND COMPONENT SYSTEMS

Piping systems classified as seismic Category I are listed in Table 8. In terms of seismic safety, the most important are the reactor coolant system and those required for other engineered safety-related functions.

3.4.1 Reactor Coolant System

The piping and components of the primary coolant systems consist of four heat-transfer loops connected to the reactor pressure vessel (RPV). Each includes a circulating pump, two isolation valves, and a steam generator.

The RPVs for both Zion units were designed to the criteria of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III.[13] Detailed stress analyses performed included seismic loads.[6]

Piping design data for the primary coolant system are presented in Table 9. Seismic analyses of piping smaller than 10 inches in diameter were performed using design curves. In addition, large primary piping runs were designed for loss-of-coolant accident (LOCA) loads combined with seismic

Table 8. Zion plant category I piping systems.[6]

Reactor pressure vessel and cooling systems
Emergency core cooling systems
Containment spray systems
Penetration pressurization piping
Isolation valve seal water piping
Main steam and feedwater piping and penetration (including isolation valve)
Main steam relief valve piping
Component cooling system
Chemical and volume control system
Residual heat removal system
Spent fuel cooling system
Service water piping
Waste gas piping
Fire water piping
Liquid radwaste piping

Table 9. Data on primary coolant piping and components.[6]

Item	Data value
System design pressure	2,485 psig
Nominal operating pressure	2,235 psig
Coolant temperature at reactor inlet	530 ^{o}F
Coolant temperature at reactor outlet	594 ^{o}F
Total coolant flow rate (four loops)	1.35×10^{8} lb/hr
Reactor vessel inside diameter of shell	173 in.
Reactor vessel thickness of shell	8.44 in. (min.)
Closure head thickness	6.50 in.
Vessel design temperature	650 ^{o}F
Piping inside diameter, reactor inlet	27.50 in.
Nominal thickness at inlet	2.38 in.
Piping inside diameter, reactor outlet	29.00 in.
Nominal thickness at outlet	2.50 in.
Piping inside diameter, coolant pump suction	31.00 in.
Nominal thickness at coolant pump suction	2.66 in.
Piping design temperature	650 ^{o}F

loads. Seismic analyses of all seismic Category I piping larger than or equal to 10 inches in diameter were performed with lumped-mass models based on the response spectrum method.

In general, reactor coolant components associated with the primary coolant system were designed and analyzed in accordance with the ASME code.[13] Table 10 lists the codes applied to the RPV and associated components. NSSS components, including the heat exchangers, pressurizers, pumps, tanks, valves, and RPV, were analyzed by Westinghouse (the NSSS vendor) using lumped-mass multi-degree-of-freedom models. Seismic Category I components not supplied by Westinghouse were analyzed or tested using procedures that depended on the complexity and size of the component. Some of the more complex components were subjected to shake tests.

3.4.2 Engineered Safety-Related Piping Systems

Engineered features are provided at Zion to ensure plant safety in the event of a LOCA. These comprise the emergency core cooling, auxiliary feedwater, containment isolation, and containment spray systems.

Table 10. Codes applied to components of Zion primary coolant system.[6]

Component	Code
Reactor vessel	ASME B & PV Code, Section III, Class A
Rod driving mechanism housing	ASME B & PV Code, Section III, Class A
Steam generators:	
Tube side	ASME B & PV Code, Section III, Class A
Shell side	ASME B & PV Code, Section III, Class C
Reactor coolant pump casing	No code, designed in accordance with ASME B & PV Code, Section III, Article 4
Pressurizer	ASME B & PV Code, Section III, Class A
Pressurizer relief tank	ASME B & PV Code, Section III, Class C
Loop isolation valves	ASME B & PV Code, Section III
Other valves	ASA B16.5, MSS-SP-66, and ASME B & PV Code, Section III, 1968 Edition

The emergency core cooling system (ECCS) in the Zion plant, designed to criteria developed to prevent prevent reactor core damage in the event of a LOCA,[14] operates in two phases. In the safety injection phase, cooling water is injected immediately following a LOCA. In the second phase, the system operates in a recirculation mode to provide long-term cooling. Preoperational tests evaluated the capability of the system to perform these functions;[4] the ECCS's performance has since been reanalyzed and found to comply with the NRC's final acceptance criteria. ASME and American National Standards Institute (ANSI) codes were used to design the ECCS,[13,15] summarized in Table 11.

The auxiliary feedwater system provides cooling water to the steam generators in the event of a reactor trip along with a loss of offsite power. This system consists of two subsystems, one using a turbine-driven pump and the other using two motor-driven pumps.

The containment isolation system provided for each Zion unit seals off the containment building from the outside in the event of a LOCA. It consists of protective barriers together with or in lieu of isolation valves for all lines that penetrate the containment structure, except for lines needed for service during an accident. To ensure effectiveness, each isolation valve includes a valve seal water system designed to provide water to the valve seats and stem packing or to piping between valves, depending on valve type.

The containment spray system removes fission products from the containment building's atmosphere and limits the pressure to below the design

Table 11. Codes applied to components of Zion emergency core coolant system.[6]

Component	Code
Refueling water storage tank	Not applicable
Residual heat exchanger:	
Tube side	ASME B & PV Code, Section III, Class C
Shell side	ASME B & PV Code, Section VIII
Accumulators	ASME B & PV Code, Section III, Class C
Valves	ANSI B16.5 or MSS-SP-66, and ASME B & PV Code, Section III, 1968 Edition
Boron injection tank	ASME B & PV Code, Section III, Class C

level in the event of an accident by spraying an NaOH solution inside the structure. The system is triply redundant.

3.5 CATEGORY I EQUIPMENT

Equipment and systems may be roughly categorized by design operating conditions, the extremes of which are normal operating and accident conditions. Between these extremes are certain abnormal conditions that by virtue of protective systems do not result in accident conditions. The systems most important to seismic safety are the reactor control systems, equipment associated with primary coolant or engineered safety systems, and protection and ventilation systems.

3.5.1 Reactor Control Systems

The reactor's automatic control systems perform during normal plant operation. They are designed to prevent fuel damage due to changes in plant load. Manual operation is used below 15% of nominal power and is available at all times.

Control is achieved by the movement of control rod cluster assemblies and changes in boron moderator concentration. Input signals include neutron flux, coolant temperature, and turbine load. In addition to signals from dedicated instrumentation and measurement devices, control systems receive signals from protective systems. Isolation amplifiers are provided at interfaces between the protection and control systems so that the former will not be affected by disturbances in the latter.

The cables connecting elements of the control systems are normally supported in cable trays that are laterally braced to resist seismic loads. Where convenient, trays are braced with horizontal struts designed to resist maximum floor-slab accelerations. Otherwise, cross bracing is used, with trays designed to withstand the peak acceleration from the applicable floor response spectra.

3.5.2 Primary Coolant and Engineered Safety Systems Equipment

Equipment for the engineered safety systems is entirely independent of equipment for the primary coolant system, although in most cases both systems use the same type of equipment.

Seismic analysis and testing procedures were similar to those described for Category I components. Because the equipment tends to be smaller than Category I components, much of it was tested rather than analyzed. For equipment supplied by Westinghouse, specifications of similar equipment supplied to other plants were checked to see that loading was more severe than at Zion. Otherwise, new analyses or tests were performed.

3.5.3 Protection Systems

Reactor protection systems are designed to help prevent unsafe operating conditions, defining allowable regions of power and coolant pressure and temperature. If an approach to unsafe conditions is indicated, the system actuates alarms, prevents withdrawal of control rods, and initiates load cutback. One or more of the engineered safety systems may be activated. Alternatively, or in combination with these measures, the reactor trip breakers may be opened.

For reliability, each protective function is provided with redundant instrumentation channels that are electrically isolated and physically separated. Loss of voltage in a channel generally results in a signal to trip the reactor.

The Zion protection systems are designed in accordance with proposed criteria of the IEEE.[16] Seismic qualification was by type testing, using methods previously described for testing of other equipment or components.

3.5.4 Ventilation and Cooling Systems

Air-handling systems are especially important to safety in two areas at Zion, the control room and the containment buildings. The latter includes containment fan cooling, considered an engineered safety feature.

Control Room

The heating, ventilating, and air conditioning (HVAC) system for the control room is designed to provide filtered air at the proper temperature and humidity under any plant condition, normal or abnormal, thus permitting occupancy during a safe shutdown of the plant. The control-room HVAC consists of high-efficiency particulate air (HEPA) and activated-charcoal filters, a cooling and heating coil package, a humidifier, and an axial fan. Circulated air is mixed with outside air as necessary to meet minimum ventilation and cooling requirements. Outside air is brought in through a missile-protected wall opening, or if high radiation is detected, from the turbine room. Turbine room air is automatically passed through the HEPA and activated charcoal filters. All components and supports of the control-room HVAC system met seismic Category I requirements.[6]

Containment Buildings

Two air-handling systems are provided for each containment building, the reactor containment fan cooler system (CFCS) and the containment purge system. Each is designed to operate under normal and postaccident conditions.

Each CFCS, designed for both cooling and filtering air, consists of five units, each of which is composed of a motor and a fan, control and backdraft dampers, roughing and HEPA filters, and a moisture separator. Under normal operating conditions, only four of the five units are employed.

Under postaccident conditions, each CFCS limits the containment atmosphere to design pressure following a LOCA, assuming that core residual heat is released as steam. Furthermore, the moisture eliminators are designed to remove 95% of free water particles of 10 μm or more in size, protecting the HEPA filters, which in turn remove radioactive airborne particulates. In the postaccident mode, a minimum of three CFCS units are needed to achieve these functions.

The containment purge systems reduce airborne particulates in the containment atmosphere before release to the outside environment and also provide make-up air. Each includes supply and exhaust fans, heating and cooling coils, and supply and exhaust filters, including HEPA and activated charcoal filters for exhaust. Seismic Category I equipment in the containment purge systems is listed in Table 12. Under normal operating conditions, the containment purge systems allow personnel access to the containment building within three hours of reactor shutdown.

Under accident and postaccident conditions, the systems operate differently from during normal operation. Monitors that sense high radiation levels automatically seal the containment building, providing safety for fuel handling and other activities in addition to reactor operation. In addition, the system is designed to remove hydrogen gas from the containment atmosphere and to keep its concentration below the lower flammability limit for 30 days, when hydrogen recombiners are activated. After radiation levels decay, the system vents the containment air through HEPA and activated charcoal filters to remove particulate matter.

Table 12. Seismic Category I equipment, Zion containment building purge systems.[6]

Air-sampling systems
High efficiency particulate air filters
Activated-charcoal filters
Purge isolation valves
Vacuum isolation valves
Hydrogen purge fans

SECTION 4: CONCLUSIONS

Unit 1 of Zion has been validated as an optimum choice for the Phase I study plant. Although no single nuclear power plant can represent all such plants equally well, selection criteria were developed to maximize the generic implications of Phase I of the SSMRP.

On the basis of the selection criteria, the Zion plant and its site were found to be reasonably representative of operating and future plants with regard to the design of its nuclear steam supply system; the type of containment structure (prestressed concrete); its electrical capacity (1100 MWe); its location (the Midwest); the peak seismic acceleration used for design (0.17g); and the properties of the underlying soil (the low-strain shear-wave velocity is 1650 ft/s in a 50- to 100-ft-thick layer of soil overlying sedimentary bedrock). In general, the characteristics of Zion are minimally different from those of other plants; however, it appears that the seismic design criteria for the Zion site were more conservatively estimated than is typical for peer plants.

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*Available for purchase from the NRC/GPO Sales Program, U.S. Nuclear Regulatory Commission, Washington, DC 20555, and/or the National Technical Information Service, Springfield, VA 22161.

NRC FORM 335
(7-77)

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

1. REPORT NUMBER *(Assigned by DDC)*
NUREG/CR-2015, Vol. 2
UCRL-53021, Vol. 2

4. TITLE AND SUBTITLE *(Add Volume No., if appropriate)*
Seismic Safety Margins Research Program
Phase I Final Report -- Plant/Site Selection and
Data Collection (Project I)

2. *(Leave blank)*

3. RECIPIENT'S ACCESSION NO.

7. AUTHOR(S)
T. Y. Chuang

5. DATE REPORT COMPLETED

MONTH	YEAR
May	1981

9. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, California 94550

DATE REPORT ISSUED

MONTH	YEAR
July	1981

6. *(Leave blank)*

8. *(Leave blank)*

12. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Washington, DC 20555

10. PROJECT/TASK/WORK UNIT NO.

11. CONTRACT NO.
FIN A0130

13. TYPE OF REPORT
Technical

PERIOD COVERED *(Inclusive dates)*

15. SUPPLEMENTARY NOTES

14. *(Leave blank)*

16. ABSTRACT *(200 words or less)*

Project I of Phase I of the Seismic Safety Margins Research Program (SSMRP) comprised two parts: the selection of a representative nuclear power plant/site for study in Phase I and the collection of data needed by the other SSMRP projects. Unit 1 of the Zion Nuclear Power Plant in Zion, Illinois, was selected for the SSMRP Phase I studies.

Unit 1 of the Zion plant has been validated as a good choice for the Phase I study plant. Although no single nuclear power plant can represent all such plants equally well, selection criteria were developed to maximize the generic implications of Phase I of the SSRMP.

On the basis of the selection criteria, the Zion plant and its site were found to be reasonably representative of operating and future plants with regard to its nuclear steam supply system; the type of containment structure (prestressed concrete); its electrical capacity (1100 MWe); its location (the Midwest); the peak seismic acceleration used for design (0.17g); and the properties of the underlying soil (the low-strain shear-wave velocity is 1650 ft/s in a 50- 50 100-ft-thick layer of soil overlying sedimentary bedrock).

17. KEY WORDS AND DOCUMENT ANALYSIS

17a. DESCRIPTORS

17b. IDENTIFIERS/OPEN-ENDED TERMS

18. AVAILABILITY STATEMENT
UNLIMITED

19. SECURITY CLASS *(This report)*
UNCLASSIFIED

20. SECURITY CLASS *(This page)*
UNCLASSIFIED

21. NO. OF PAGES

22. PRICE
$

NRC FORM 335 (7-77)