Design of Nuclear Power Reactors Against Earthquakes

by

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Introduction. - Nuclear power reactors pose special problems of earthquake safety that are different from those encountered in the earthquake-resistant design of ordinary coal-steam electric power generating stations. For a coal-steam power generator, the consequence of earthquake damage is merely a temporary shortage of electrical power. In the case of the nuclear power reactor, however, the occurrence of earthquake damage could lead to uncontrolled nuclear fission with the possibility of explosion and release of fission products into the atmosphere. Such an incident would be a serious hazard to human life in the immediate area of the reactor and could pose a health problem over an area of thousands of square miles. Because of the serious consequences of a nuclear incident, there has developed a special field of study in nuclear reactor safety, and the problem of safety against earthquakes is one particular aspect of the more general safety problem. Since the nuclear reactor safety expert is not, in general, knowledgeable either in structural dynamics or engineering seismology, the safety of the nuclear reactor against earthquake becomes the responsibility of structural engineers and engineering seismologists.

The special character of the earthquake safety problem of a nuclear power reactor is made clear by comparing with an ordinary coal-steam power generator. In the case of the coal-steam power generator, it is customary to classify the structures and equipment into two categories so far as earthquake-resistant design is concerned:

a. Those components that are essential to the continuing operation of the power generator are designed to resist higher seismic factors than prescribed by the building ordinance. It is common practice in California to design these to resist a seismic loading of the order of 20%g, following the design procedures specified by the California building codes.

b. Those components of the installation that are convenient but are not absolutely essential to the operation are designed according to normal building code requirements which specify a seismic loading of the order of 10%g.

In the case of the nuclear power reactor, the danger to life and the possibility of economic loss are so much greater than in the case of the coal-steam generator that the structures and equipment must be classified in three different categories:

Class 1. Those structures (either buildings or equipment) whose failure might cause a nuclear incident must be given a special design to resist earthquakes. It is imperative that these components be designed so that the probability of failure is essentially zero when they are subjected to the strongest probable earthquake ground motion. These components thus require very special consideration as regards earthquake-resistant design, as discussed below.

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Class 2. Those structures that are essential to the operation of the power generator but whose failure could not cause a nuclear incident must also be given special consideration in their design to resist earthquakes, but not to the degree indicated for the structures of Class 1. For example, in some cases it might be deemed adequate to design for 20%g according to procedures specified by California building codes.*

Class 3. Those structures that are convenient to the operation of the power generator but are not essential to the operation may logically be designed according to the ordinary requirements of the building code.

The structures in Class 1 should be designed so that they will not be damaged by the strongest probable ground motion, and conservatism would dictate that their design should be such that the stresses remain within the elastic limits. The structures in Class 2 should be designed so that they are not significantly damaged by the strongest probable ground motion, but overstressing, that is, plastic yielding, would be permissible. The structures in Class 3 which are designed according to ordinary building code requirements would be expected to have some cracking and plastic yielding during strong ground motion, and possibly to have significant damage in the event of an extremely great earthquake.

Strongest Probable Ground Motion. - Because of the short history of recording strong ground motions, it is not possible to specify the strongest possible ground motion. In the United States various strong ground motions have been recorded and the strongest of these was recorded at El Centro, California during the earthquake of 18 May 1940. This record is usually taken to represent the strongest probable ground motion** in the highly seismic region of the United States (Zone 3). Ground motion one-half as intense is usually taken as the strongest probable ground motion in Zone 2; and the strongest probable ground motion in Zone 1 is taken to be one-half as intense as that in Zone 2.

The intensity of ground motion is defined in terms of the spectrum intensity[1]. The velocity spectrum of the ground motion is defined to be[2, 3, 4]

$$S_v = \left\{ \int_0^t \ddot{z}\, e^{-\zeta \frac{2\pi}{T}(t-\tau)} \sin \frac{2\pi}{T}(t-\tau)\, d\tau \right\}_{max} \quad \ldots .(1)$$

*The actual strength of a structure depends not only on the code specifications, but also upon design procedures, allowable stresses, etc. When mention is made of a 20%g design, it refers to such a structure as would result from applying California design procedures.

**The strongest possible ground motion may be significantly greater than this, perhaps, two or three times as intense.

where

S_v = the velocity spectrum

$\ddot{z}$ = the recorded ground acceleration of the earthquake

ζ = fraction of critical damping

T = period of vibration

The velocity spectrum S_v, is a measure of the maximum vibrational excitation of a structure having period T and damping n. The maximum relative displacement S_d, and the maximum absolute acceleration of a single degree of freedom structure are given in terms of the maximum relative velocity S_v by

$$S_d = \frac{T}{2\pi} S_v$$
$$S_a = \frac{2\pi}{T} S_v \qquad \ldots.(2)$$

The spectrum intensity (SI_n) is defined as:

$$SI_\zeta = \int_{0.1}^{2.5} S_v(\zeta, T)\, dT \qquad \ldots.(3)$$

The spectrum intensity (SI_ζ) is thus a measure of the severity with which the ground vibrated those structures having periods in the range 0.1 to 2.5 seconds and having damping ζ. Some recorded ground motions and their spectrum intensities are listed in Table I.

It is found that the shapes of the spectrum curves for strong ground motions of various California earthquakes are similar and average spectrum curves[4] are shown in Figs. 1 and 2. The average spectrum curves have been drawn to an arbitrary scale such that the ordinates must be multiplied by the following factors to represent the average of the two components of the ground motions listed:

El Centro, 1940	2.7
El Centro, 1934	1.9
Olympia, 1949	1.9
Taft, 1952	1.6

For a one-degree-of-freedom structure with period T and damping n, the values of S_a, S_v, and S_d, specify the maximum acceleration, maximum velocity and maximum displacement of the structure for that earthquake. Similarly, from S_a, S_v, or S_d the maximum response of a mode of vibration of a more complex structure can be determined[3].

The average spectrum curves of Fig. 1 thus permit a dynamic design to be made of Class 1 structures so that they will not be overstressed by ground motion whose spectrum intensity is, say, $SI_o = 8$.

For Class 2 structures the same spectrum curves define the ground motion for which the design is to be made but, in this instance, the structures may undergo yielding with an appropriate factor of safety against failure; for example, a factor of safety of three. It has been proposed that the plastic design be made on the basis of the equation[5]:

$$D = \frac{1}{2} m S_v^2 - V \qquad \ldots.(4)$$

where D is the energy that must be dissipated by the structure, m is the mass of the structure[6], and V is the potential energy left in the structure after the last overstress has occurred. For certain simple structures the maximum D of which the structure is capable of absorbing can be calculated quite accurately, but for many structures the maximum possible D cannot be calculated with any degree of precision, and hence care must be taken that the design procedures are conservative.

Principal Features of Nuclear Power Generators. - A nuclear power generator is similar, in broad features, to a coal-steam electric power generator, the chief difference being in the heat generating unit where a nuclear reactor is used in place of a conventional furnace. The principal features of a nuclear power generator* are:

a. The core in which the nuclear reaction takes place and heat is generated. The principal parts of the core are:

1) The reactive material.
2) The moderating material that slows the nuclear reaction. (Some types of reactors do not have moderators)
3) The control rods with which the rate of reaction is controlled or stopped.
4) The coolant material which maintains the core at a proper temperature.
5) The core pressure containment vessel whose function it is to contain the reactor core under pressure without allowing the escape of fission products.

b. The primary coolant loop abstracts the heat from the core and transmits it to the secondary coolant loop. A failure of the primary coolant loop that was not counteracted would cause a rapid rise in core temperature with a probability of melting down and a release of fission products.

c. The secondary coolant loop serves to transfer the heat from the primary coolant loop to the electric power generating system.

d. An adequate water supply system is essential. Strict temperature control is required even in the event of malfunctions, accidents, etc.

e. A biological shield is required around the core to shield operating personnel from harmful radioactivity.

f. A pressure containment structure is used to house the reactor. This is usually a cylindrical or spherical steel-plate pressure vessel of large diameter that is designed to withstand an internal pressure rise that might be associated with a nuclear incident.

*Much of the following information on nuclear reactors was taken from an unpublished handbook of which the writer was one of the authors.

In Table II there is given a list of some different types of nuclear reactors and the elements of which they are composed.

Elements Particularly Sensitive to Seismic Damage. - Some of the elements of which particular care must be taken when making an aseismic design are listed below. In each case the number in parentheses indicates the classification of the element, that is (1) indicates that damage to the element might lead to the release of fission products; (2) indicates that damage to this element could lead to prolonged shut down of the reactor

a. Reactor core (1)
   1. The fuel elements (1)
   2. The moderator (1)
   3. Control rods and safety rods (1)
   4. Supporting and positioning members (1)

b. Reactor pressure vessel (1)

c. Primary coolant loop (1)
   1. Piping system (1)
   2. Heat exchanger (1)
   3. Pressurizer (1)

d. Secondary coolant system (2)
   1. Heat exchanger (2)
   2. Condenser (2)
   3. Cooling water system (2)
   4. Turbo-generator (2)

e. Instrumentation (1), (2)

f. Electric power system (2)

g. Safety devices (1)

h. Emergency water system (1)

i. Fuel handling and storage system (2)

j. Containment building or vessel (1)

k. Biological shield (2)

l. Water storage tanks (2)

m. Chimneys (2)

It will be noted that many of the above items refer not to buildings and such like structures, but rather to machinery, equipment, piping, etc. This means that it is just as important to design, say, the piping of the coolant system to resist earthquakes as to design the large pressure vessel that houses the reactor. The engineer who is responsible for the earthquake-resistant design must therefore extend his attention to all the important elements of the reactor as well as to the structures and buildings. The possibility of rupturing connecting pipes by the relative motion of two pieces of equipment during an earthquake is an example of possible seismic damage.

Types of Nuclear Reactors. - At the present time, many different types of nuclear reactors are being used or studied.[7] Six basic types are:

a. Pressurized water reactor (PWR)

b. Boiling water reactor (BWR)

c. Sodium-graphite reactor (SGR)

d. Gas-cooled reactor (GCR)

e. Fast breeder reactor (FBR)

f. Homogeneous reactor (HRT)

The Pressurized Water Reactor has water in its primary coolant loop under a high pressure and this serves both as a coolant and as a moderator. The pressure vessel surrounding the core must contain very high pressure, and hence the wall of the vessel is very thick. Steam is formed in the secondary coolant loop and is used in a conventional manner to generate electric power.

The Army Package Power Reactor (APPR-1), the submarine reactors, and the commercial power reactor (SPWR) at Shippingport, Pennsylvania are examples of the PWR type. The core of the SPWR is cooled with water at a temperature of 450°F and a pressure of 2000 psi. The carbon steel pressure vessel surrounding the core stands 33 feet high with an internal diameter of 9 feet and a wall thickness of 8.5 inches, clad on the inside with stainless steel. The control rods enter from the top, and in the event of an emergency shut down, the rods are dropped into the core under gravity. Three feet of water plus five feet of concrete serve as shielding around the pressure vessel.

As protection against the release of radioactive materials into the atmosphere in the event of an accident, the critical parts of the plant are enclosed in vapor-tight steel containers. The reactor is enclosed by a 38-foot diameter spherical shell that has an 18-foot cylindrical dome to house the control rod drive mechanism. Two 50-foot diameter cylinders 90 feet long house two primary coolant loops; a 50-foot diameter cylinder 144 feet long contains the pressurizer and auxiliary equipment. These secondary containers are inter-connected by a system of 8-foot and 12-foot diameter pipes and the design pressure for the system was 53 psi. A water-spray system is available to reduce the pressure in the shells in the event of a failure in a primary coolant loop.

The Boiling Water Reactor produces steam by boiling water in the core and the steam is then used to generate electric power. The water in the core serves as moderator, coolant, and steam source. The Commonwealth-Edison Dresden power generator (DBWR) and the Argonne National Laboratory reactor (EBWR-1) are examples of this type of reactor.

In the EBWR-1 water is boiled at a temperature of 488°F and pressure of 600 psi is developed in a core that is 4 feet in diameter and 4 feet high. The core is enclosed by a carbon-steel pressure vessel having an internal diameter of 7 feet and standing 27 feet high, with a 2.25 inch thick wall.

The reactor, turbine, generator, condenser, and all necessary equipment and piping are enclosed in a large secondary pressure vessel. For the EBWR-1 this cylindrical vessel is 80 feet in diameter and stands

119 feet high. It was designed for an internal pressure of 15 psi. A 15,000 gallon tank of water is suspended in the top of the shell to provide an emergency supply of water in the event of an accidental release of hot vapor. The shell has a hemispherical top and an ellipsoidal bottom. One-half of the shell is below the ground surface and this bottom half contains a concrete structure having four floors on which the reactor and other pieces of equipment are located.

The control rods of the reactor enter the core from above. In the event of an emergency shutdown the rods are dropped into place under gravity aided by an initial spring force. Blast shields surround the reactor to absorb energy in the event of an explosion from a potential metal-water reaction.

The Sodium Graphite Reactor (SGR) under experimental development by Atomics International Division of North American Aviation, Inc., (SGRE) uses sodium in the primary coolant loop and uses sodium also in an intermediate coolant loop from which heat is transferred to a secondary steam generating water coolant loop. The primary sodium coolant operates at a temperature of 960°F at atmospheric pressure.

The fuel rods are six feet long stainless steel tubes filled with six inch long, 3/4 inch diameter metallic uranium slugs, and the moderator is graphite. Control rods and safety rods enter from above. The reactor is contained in a stainless steel tank 11 feet in diameter, 19 feet high, with 1.5 inch thick walls. This tank is surrounded by another tank that serves to catch the sodium should the first tank lead. The entire assembly, with the primary coolant loop; is located in an underground concrete chamber.

The Gas-Cooled Reactor (GCR) uses an inert gas to control the temperature of the core. The moderator is graphite and a large stack of graphite blocks is required. This stack of blocks poses a serious earthquake problem in highly seismic locations. The blocks must be kept in sufficiently good alignment so that the fuel rods and control rods can easily be moved in and out and the proper clearances and tolerances must be maintained. The chief difficulty arises from the fact that at first exposure to radioactivity the graphite blocks undergo a marked expansion (the so-called Wigner expansion) and then, with prolonged operation, they undergo an even greater shrinkage. The Oak Ridge National Laboratory Gas-Cooled Reactor (ORNL GCR-2) is an example of this type. This design calls for slightly enriched uranium oxide fuel in stainless steel tubes with graphite as a moderator and helium as a coolant. The heat is transferred from the gas to water to form steam for electrical power generation.

The core is 30 feet in diameter and stands 20 feet high. The unit operates at 300 psi pressure and the helium enters at a temperature of 460°F and leaves at 1000°F. The reactor is contained in a spherical shell of 50 feet diameter and 3.25 inches wall thickness. The core is made up of vertical graphite blocks 8 x 8 x 40 inches with longitudinal fuel channel holes in the center. Sixty-one control rods, 2 inches in diameter and 18 feet long, enter from above. The total weight of the graphite is 1,127 tons. The gross weight of the core and pressure vessel exceeds 2,000 tons.

The Fast Breeder Reactor (FBR) utilizes high energy neutrons for the fission process rather than the slow, or thermal, energy neutrons used in the preceding reactors. Sodium is used as a coolant and moderators are not used. The Experimental Breeder Reactor -II (EBR-II) is an example of this type. Sodium is used in the primary and intermediate coolant loops from which heat is transferred to a secondary water coolant loop that delivers steam to turbine generators. The core is very small, being approximately 20 x 20 x 14 inches. The unit operates at a temperature of approximately 900°F. The reactor is housed in a containment vessel 30 feet in diameter and 147 feet high with 1-inch thick wall, designed for 24 psi.

The Aqueous Homogeneous Reactor (AHR) is another type being investigated in the United States. The Homogeneous Reactor Test (HRT) is an example of this type. The fuel is an uranyl sulphate – D_2O solution contained in a spherical zirconium core that is surrounded by a breeding blanket of thorium oxide – D_2O slurry. The system operates at 2000 psi pressure. No control rods are required. The fission heat is transferred, by circulation of the fuel solution through a heat exchanger.

The reactor is contained in a steel sphere 5 feet in diameter and 4.4 inches thick. The unit and equipment is enclosed in a steel tank 25 x 54 x 30 feet that is designed for an internal pressure of 30 psi.

Design of Rigid Structures. For the strongest probable ground motion (El Centro 1940) the maximum ground acceleration to be expected is 0.33g. As can be seen from the spectrum curves of Fig. 2, if a mode of vibration of a structure has a natural period less than about 0.1 seconds it can be treated as if it were a rigid structure subjected to a horizontal acceleration of 0.33g. The vertical component of ground motion is observed to have somewhat smaller accelerations than the horizontal component and to exhibit somewhat higher frequency components. It is customary to take the vertical component as having a maximum acceleration and a spectrum intensity two-thirds as large as the horizontal components. It seems reasonable that Class 1 structures having periods less than about 0.1 seconds should be designed to resist 0.33g acceleration without exceeding normal working stresses.

A Class 2 structure may be designed less conservatively than a Class 1 structure with the justification that if it is overstressed, plastic yielding, etc., will occur but the structure will not collapse. In terms of usual earthquake-resistant design this might be equivalent to designing for 20%g.

Care should be taken to ensure that the structures are ductile and will not fail in a brittle manner. If other considerations necessitate a brittle structure, the design should be more conservative than outlined above. In this case it seems reasonable that for Class 1 structures the design should be made on the basis of 0.33g with a factor of safety of at least five. Correspondingly, for Class 2 structures the design could be made for 0.33g with a factor of safety of at least three.

Design of Flexible Structures. It seems reasonable that flexible Class 1 structures should be designed on the basis of a dynamic analysis using the average spectrum curves of Fig. 1 (El Centro 1940), and using normal allowable stresses.

For Class 2 structures the design may be based on a dynamic analysis, or its equivalent, taking into account absorption by overstress[5] and allowing a factor of safety of at least three against failure. Correspondingly, Class 1 structures should have at least a factor of safety of five against failure.

Care should be taken that all of the structures are ductile and will not fail in a brittle manner.

Design of Special Structures. In the following, some brief remarks will be made on the design of some of the special structures encountered in nuclear power generator design. It should be noted that in many instances the structures of a nuclear generator are well suited to resist earthquake forces and can withstand horizontal accelerations of 0.5g or even 1.0g without requiring any appreciable strengthening over ordinary operating design. Thus the relatively large design accelerations mentioned above are, in general, not difficult to meet and do not usually require any appreciable additional cost to meet the earthquake requirements. This can be expected, however, only if earthquake considerations are kept in mind from the beginning of the design. If careful thought is not given from the beginning of the design, the cost of earthqi ake protection may be appreciably increased.

(a) Secondary Pressure Container. These large, spherical or cylindrical, steel structures are very stiff and will normally have periods of vibration less than 0.1 seconds. The structures are well adapted to resist lateral forces and usually the only special earthquake design required is that of the connection of the tank to its foundation, so that it can transmit the lateral force from the structure to the ground.

(b) Primary Pressure Containers. The sizes and shapes of primary pressure containers are usually such that there is no difficulty in designing them to resist earthquakes. Again here, the most critical point is usually the connection of the vessel to its base.

(c) The Reactor Core. Of all the reactor cores, the only one that is likely to pose a serious earthquake design problem is the gas-cooled, graphite-moderated core. For this reactor, the core consists of a large pile of graphite blocks that may weigh a thousand tons or more. These blocks have holes through them that must be lined up so as to permit rods to be inserted and withdrawn, which means that only a very limited relative motion of blocks is permissible. At first, the radioactive environment causes the blocks to undergo an expansion and later the blocks undergo a shrinkage which leaves them smaller than their original size. The earthquake problem is thus one of designing a stack of loose, unbonded blocks so that they will not be appreciably disarranged by strong ground motion. The design of these cores usually employes keying of the blocks, courses of keyed, flat platelets of graphite, and external containment rings. Minimizing the number of courses by using relatively long blocks of graphite appears to have advantages.

(d) Important Pieces of Equipment. As an example of a dynamic analysis consider a piece of equipment resting on a platform that is supported by a number of free standing columns that must resist in bending any lateral forces that are applied to the equipment. It is necessary first to assume a reasonable size of column and compute the elastic lateral displacement, δ , that would (ideally) be produced by a 1g lateral load. If m is the mass of the equipment, the stiffness of the columns is $k = mg/\delta$. The natural period of vibration of the structure is then:

$$T = \frac{1}{2\pi}\sqrt{\frac{m}{k}} = \frac{1}{2\pi}\sqrt{\frac{\delta}{g}}$$

Suppose that this formula gives T = 0.4 seconds, then reading from Fig. 1 for 1% damping we find S_v = 0.73 ft per sec. and multiplying by 2.7 gives for the probable strongest ground motion, S_v = 2.0 ft per sec., or

$$S_a = 2.0 \frac{2\pi}{0.4} = 31.4 \text{ ft per sec}^2.$$

The maximum horizontal acceleration of the structure would thus be 31.4 ft per sec^2 which is practically 1g. The columns must then be able to resist 1.0g without being overstressed (Class 1 structure). If this load requires larger columns than were originally assumed, the analysis must be repeated until column size, period, and load are in agreement. Although a load of 1.0g may appear relatively large, stresses corresponding to 1.0g loading have occurred in structures subjected to earthquakes[5].

If the steel columns are to be designed so as to have a factor of safety of n against failure, a limit-design[5] must be made. This is discussed in more detail elsewhere in this publication and only an indication of the approach will be given here. The maximum kinetic energy of the structure is taken to be

$$KE = \frac{1}{2} m S_v^2$$

and thus a kinetic energy of n times this value must be taken by the structure without failure. It is assumed that the total energy is absorbed in the formation of plastic hinges at the tops and bottoms of the columns and that the energy absorbed by each hinge is

$$E_{abs.} = M_o \phi$$

where M_o is the yield moment consistent with the applied axial load, and ϕ is the plastic angle of rotation of the columns. The total energy to be absorbed is the kinetic energy of vibration plus the loss of potential energy in lowering the weight of the equipment a distance

$$h(1 - \cos \phi) = \frac{h\phi^2}{2}$$

where h is the length of the column. Therefore, assuming that all of the energy is absorbed in plastic excursions in the same direction gives:

$$n\left(\frac{1}{2} m S_v^{\,2} + \frac{1}{2} mgh (\phi^2)\right) = 2N_c M_o \phi$$

where N_c is the number of columns withstanding this component of motion. The column size is then specified by the requirement that the yield moment be

$$M_o = \frac{n\,m}{4N_c}\left(\frac{S_v^{\,2}}{\phi} + gh\,\phi\right)$$

The value of ϕ that makes M_o a minimum is the value for which the column will just collapse and this is:

$$\phi = \frac{S_v}{\sqrt{gh}}$$

which in turn gives for the required yield moment

$$M_o = \frac{nS_v}{2N_c}\sqrt{\frac{h}{g}}\; W$$

where W is the total weight supported by the columns. The plastic collapse of a structure is a complex phenomenon* of which the foregoing analysis is merely indicative. It is advisable to be conservative when making such plastic designs.

(e) Elevated Water Tanks. Elevated water tanks are important to the operation of a nuclear reactor power plant (Class 2). The heavy mass together with the low damping capacity makes it difficult to design such a structure to remain elastic during strong ground motion. A plastic analysis and design shows that the elevated water tank can absorb an appreciable amount of energy without collapsing[5].

(f) Non-Elevated Water Tanks. In some nuclear installations large quantities of water are stored in reservoirs or in tanks resting on the ground. In the design of these structures, attention must be given to the dynamic fluid pressures and to the waves that are generated during earthquakes.

(g) Piping. Pipes connecting two pieces of equipment must be designed so as not to be pulled apart when the equipment begins vibrating. In fact, all piping, whether for steam or water, must be designed and supported so as to resist seismic forces. More careful attention must be given to details of piping than is the usual practice when designing industrial

*See paper Plastic Collapse of Frames During Earthquakes which appears elsewhere in this publication.

installations, and this problem is particularly severe in the case of nuclear reactors because of their very extensive piping systems.

Foundation Conditions. Prudence would dictate the avoidance of sites whose geology is suspect. For example, soils that might consolidate during earthquake ground motion and cause uneven settlement of the reactor structures should be avoided. On the other hand, it does not seem advisable to make large expenditures in order to utilize a site whose geology might indicate somewhat less intense ground motion than other sites in the general locality. In the present state of knowledge, the design of the nuclear reactor must be made for the worst possible conditions and it would not seem advisable to reduce the design criteria on the basis of assessed geological merits of the site.

There would appear to be little economic advantage in seeking out sites where the accelerations produced by the passage of seismic waves might be reduced. There wodld be a marked advantage in safety, however, in avoiding those sites where consolidation, soil slip, etc., might occur.

Conclusions. The earthquake-resistant design of nuclear reactor power generators calls for more thorough and detailed analysis and design than is customary when designing ordinary structures. A more precise knowledge of the ultimate strengths of structures is required and a better understanding of the plastic behavior of structures is desirable. Certain portions of the nuclear reactor and its appurtenances should be designed for significantly large seismic forces than are used for ordinary structures. The earthquake problems of nuclear power generators are different in degree, but not in kind, from the problems of ordinary structures, and with proper engineering there should be no difficulty in protecting a nuclear power generator against earthquake hazards.

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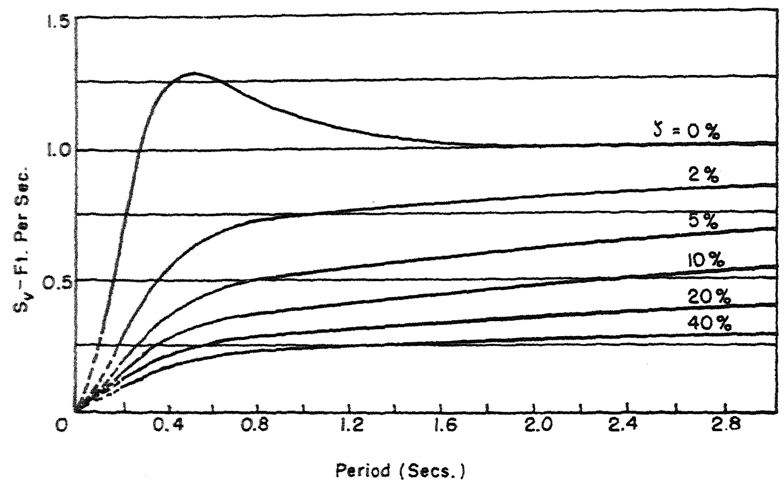
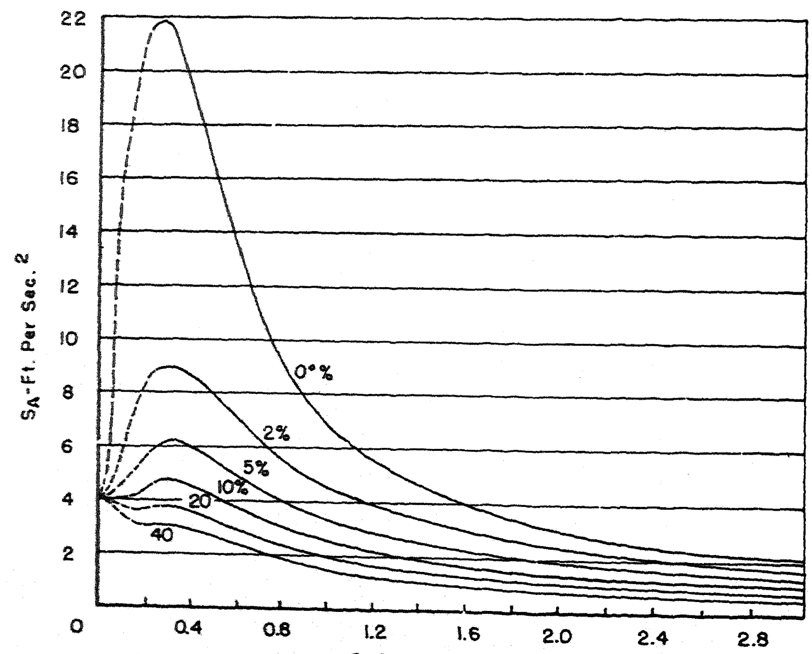


AVERAGE VELOCITY SPECTRUM CURVES

FIG. 1



AVERAGE ACCELERATION SPECTRUM CURVES

FIG. 2

TABLE I

SPECTRUM INTENSITIES FOR TWO HORIZONTAL COMPONENTS OF GROUND MOTION

		SI_o	SI_o Aver.	$SI_{0.2}$ Aver.	Maximum Ground Acceleration
El Centro, Calif.	NS	8.94	8.35	2.7	0.33g
18 May 1940	EW	7.77			0.23g
El Centro, Calif.	NS	5.93	5.88	2.1	0.26g
30 December 1934	EW	5.83			0.20g
Olympia, Wash.	S80W	6.05	5.82	2.2	0.31g
13 April 1949	S10E	5.59			0.18g
Taft, Calif.	S69E	4.84	4.69	1.9	0.18g
21 July 1952	N21E	4.53			0.17g
San Francisco, Cal.	N81E	0.5	0.48	0.28	0.05g
22 March 1957	N9W	0.45			0.05g
Alexander Bldg.					

TABLE II

PROPERTIES OF NUCLEAR REACTORS

	PWR SPWR	BWR EBWR-1	SGB SGRE	GCR ORNL-GCR-2	FBR EBR-2	AHR HRT
1. Thermal Power (MW)	260	20	20	687	63	5
2. Design Core Pressure (psi)	2500	800	18	300	120	2000
3. Coolant Exit Temperature (°F)	540	488	960	1000	900	570
4. Emergency shutdown time (sec.)	1.35	0.35	0.6	--	0.38	--
5. Moderator Material	H_2O	H_2O	Graphite	Graphite	None	D_2O
6. Primary Coolant	H_2O	H_2O	Na	He	Na	Fuel
7. Secondary Coolant	H_2O	None	Na	H_2O	Na	None
8. Fuel Material	U-Zr	U-Zr-Nb	U	UO_2	U	UO_2SO_4-D_2O
9. Fuel Element	flat plate	flat plate	rod	rod	pin	liquid sphere
10. Primary Container Shape	cylinder	cylinder	cylinder	sphere	cylinder	sphere
11. Primary Container Diameter (ft.)	9	7	11	50	26	5
12. Primary Container Height (ft.)	33	23	19	50	25	5
13. Primary Container Thickness (in.)	3.5	2.25	1.5	3.3	0.5	4.4
14. Primary Container Material	carbon steel	carbon steel	304SS	steel	SS	steel
15. Secondary Container Shape	cylinder sphere	cylinder	RC chamber	RC building	cylinder	rectangular

TABLE II (Continued)

	PWR SPWR	BWR EBWR-1	SGB SGRE	GCR ORNL-GCR-2	FBR EBR-2	AHR HRT
16. Secondary Container Diameter (ft.)	various	80	--	--	80	--
17. Secondary Container Height (ft.)	various	119	--	--	139	25x32x54
18. Secondary Container Material	steel	steel	--	--	steel	steel
19. Secondary Container Pressure (psi)	+53, -3	+15, -0.5	--	--	+25, -1	+32, -1