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EVALUATION OF METHODS FOR SEISMIC ANALYSIS OF MIXED-OXIDE FUEL FABRICATION PLANTS

F. J. Tokarz, D. F. Arthur, and R. C. Murray

October 8, 1975

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Contents

Abstract	1
Summary and Recommendations	1
Critical Structures and Equipment	4
Manufacturing Building	7
Receiving and Drum Storage	8
Unloading Station and Scrap Recovery System	8
Bulk Storage and Mixed-Oxide Storage	8
Blending Column and Pressing Column	10
Transfer System	10
Ventilation System	11
Diesel Generators	11
Instrumentation	11
Methods of Structural Analysis	12
Manufacturing Building	12
Equipment	14
Definition of Terms	15
Available Methods	22
Comparison of Methods	28
Conclusions	34
Generation of Floor Spectra	36
Floor-Spectra Calculations	37
Ground Motion Used	37
Building Models	37
Time-History Method	41
Approximate Methods	42
Comparison of Methods	52
Floor Spectra	52
Intangibles	53
Conclusions	57
Acknowledgments	57
References	58
Appendix. Description of the Kapur and Biggs Approximate Methods . . .	60

EVALUATION OF METHODS FOR SEISMIC ANALYSIS OF MIXED-OXIDE FUEL FABRICATION PLANTS

Abstract

Guidelines are needed for selecting appropriate methods of structural analyses to evaluate the seismic hazard of mixed-oxide fuel fabrication plants. This study examines the different available methods and their applicability to fabrication plants. Our results should provide a basis for establishing guidelines recommending methods of analysis to ensure safe design against seismic hazards.

Using the Westinghouse Recycle Fuels Plant as representative of future mixed-oxide fuel fabrication plants, we identified critical structures and equipment (systems, components, and piping/ducting). These included the manufacturing building and 11 different pieces of

equipment. After examination of the dynamic response characteristics of the building and the different methods available to analyze equipment, we recommend appropriate methods of analyses.

Because critical equipment analysis and test methods generally use floor-response spectra as their seismic input loading, we also examined several methods used to generate floor spectra. These include the time-history approach and the Kapur and Biggs approximate methods. Our examination included the effect of site characteristics and both horizontal and vertical structural response.

Summary and Recommendations

This is the final report of a Lawrence Livermore Laboratory study requested and funded by the U.S. Nuclear Regulatory Commission, Office of Standards Development. The report is submitted to NRC in fulfillment of that request and funding.

Guidelines are needed to specify methods of structural analysis that ensure safe earthquake design of nuclear fuel fabrication facilities. The objective of this study is to compare the methods of structural analysis available for seismic design

of nuclear fuel fabrication plants. The results may be used as the basis of a Regulatory Guide that recommends the method or methods of analysis to ensure safe structural design. The study is restricted to fuel fabrication structures and equipment defined to be critical, that is, structures and equipment whose failure could cause substantial radioactive hazard to the public.

To reach this objective we identified critical fuel fabrication plant structures and equipment. The Westinghouse Recycle Fuels Plant was selected to be representative of future fuel fabrication plants. Our review of this plant pointed to 11 items (listed in Table 2) as critical. We include a description of each critical item, its function, and its location within the manufacturing building.

The next step was to determine the method of seismic analysis appropriate for each item. Our recommendation for the manufacturing building is based on the results of a study recently completed for NRC and is shown in Table 1. In selecting methods of analysis for equipment, we evaluated 11 different approaches. We found that the choice of method depended heavily on the response

characteristics of both the equipment and its support structure (in this case, the manufacturing building). Table 3 summarizes the different methods of equipment analysis and Table 1 summarizes our recommendations for critical equipment analysis.

In the section *Generation of Floor Spectra*, we evaluate methods of calculating floor spectra for fuel fabrication plants. The choice of methods is important, because floor spectra will normally be required during the design of future mixed-oxide fuel fabrication plants (MOFFP's). A dynamic time-history analysis of the building is the most common approach used to calculate floor spectra. However, alternate approximate methods have been suggested by both Kapur and Biggs. We generated and compared horizontal and vertical MOFFF floor spectra by all three methods. Our comparison indicates that although the approximate methods could be made acceptable from a safety standpoint, they would be overly conservative. The time-history method will yield floor spectra that are less uncertain and less conservative for a relatively modest additional effort. We recommend the time-history approach for developing MOFFP floor spectra.

Table 1. Recommended methods of analysis for manufacturing building and critical equipment.

	Recommended method of analysis	Recommended model	Input loading
<u>Manufacturing building</u>			
Founded near or at grade	Dynamic (response spectra) ^a	Lumped mass or finite element ^b	Ground-response spectrum or acceleration time-history ^a
Deeply embedded (embedded depth >15% of least foundation dimension)	Dynamic (response spectra) ^a	Finite element	Ground-response spectrum or acceleration time-history ^a
<u>Critical equipment</u>			
Rigid (f > 33 Hz)	Static ^c	----- ^d	Maximum floor acceleration
Flexible (f < 33 Hz)	Dynamic (response spectra or time-history) ^c	Lumped mass or finite element	Floor-response spectrum or acceleration time-history
Heavy ^e	Dynamic (response spectra or time-history) ^c	Lumped mass or finite element (coupled building-equipment model)	Ground-response spectrum or acceleration time-history

^a If time-history-response quantities and their phase relationship are required, a time-history analysis by either modal or direct integration must be performed. If nonlinear effects are considered important, a time-history analysis by direct integration must be performed.

^b For layered and shallow sites, use of a lumped-mass model with soil springs may not be accurate.

^c If differential support motion need be considered for equipment, a dynamic analysis, either coupled (building-equipment) or uncoupled, must be performed.

^d Distribute loads per mass distribution. Model should reflect stiffness of actual structure.

^e A coupled model includes both the equipment and the supporting structure. Criteria for decoupling equipment from supporting structure are

$$\text{if } \begin{cases} R_m < 0.01, \\ 0.01 \leq R_m \leq 0.1, \\ R_m > 0.1, \end{cases} \quad \begin{cases} \text{decouple for any } R_f \\ \text{decouple if } \begin{cases} R_f < 0.8 \\ \text{or} \\ R_f > 1.25 \end{cases} \\ \text{do not decouple,} \end{cases}$$

$$\text{where } R_m = \frac{\text{mass of equipment}}{\text{mass of supporting structure}} \text{ and}$$

$$R_f = \frac{\text{natural frequency of equipment}}{\text{frequency of dominant support motion}}.$$

Critical Structures and Equipment

We chose to study the Westinghouse Recycle Fuels Plant, to be located in Anderson, South Carolina. The capacity of the Westinghouse plant is typical of those expected for future mixed-oxide fuel fabrication plants, that is, an ultimate production of about 1 metric ton/d of fuel in fuel rod form. We consider the planned process flow equipment, piping, and structures to be representative and inclusive of equipment and structures anticipated in future commercial-scale fuel fabrication plants.

The fuel received at MOFFP's is expected to be in the form of plutonium and uranium oxide powders. Fuel elements produced from these oxides will be used in light-water-cooled reactors.

The future MOFFP is assumed to be composed of a manufacturing building and structures housing auxiliary functions. The manufacturing building will house powder process operations and safety-related items that must remain functional during

the standard maximum credible accidents, such as tornadoes and earthquakes.

It is further assumed that the plutonium and plutonium-uranium mixtures will not be directly handled. A remote, automatic process and appropriate shields and confinement will be necessary. Thus, it is assumed that processing will be performed in a "canyon" capable of withstanding the design earthquake. Equipment critical to safe operation must also withstand the design earthquake.

Table 2 lists those structures and equipment we consider critical. For purposes of analysis, we have assumed that the failure of any of these structures or components could lead to a substantial radioactive hazard to the general public. It should be noted that these critical items are associated with the fabrication process when the plutonium and uranium oxides are in powder form. Systems and components for subsequently processing fuel pellets are not considered to be critical.

Table 2. MOFFP critical structures and equipment.

Outer confinement structure	Process equipment	Auxiliary systems
Manufacturing building	PuO ₂ receiving and drum storage	Powder transfer system
	PuO ₂ unloading station	Scrap recovery system
	PuO ₂ bulk storage tanks	Ventilation system exhaust (piping and final HEPA bank)
	Blending column	Diesel generators
	Mixed-oxide storage tanks	Instrumentation system
	Pressing column	

The following sources of information were used to develop this list: (1) the License Application for the Westinghouse Recycle Fuels Plant¹; (2) discussions with Ralph M. Parsons Company engineers, designers of the plant; (3) discussions with Battelle Pacific Northwest Laboratories personnel regarding airborne release of plutonium from generic mixed-oxide plants²; and (4) discussions with Regulatory staff. These discussions permitted us to study alternative building designs, systems, and components for future plants.

Figure 1 shows the manufacturing building plan of the Westinghouse plant. The plutonium and uranium oxide powders are received at the plant in drum containers (1). After initial storage the containers are moved to unloading stations (2) where

the oxide powders are transferred to the bulk storage bins (3). The powders are then taken from the bins in weighed amounts, mixed in a blending column (4), and sent to the mixed-oxide storage area (5). The properly blended mixed oxide is then compacted, granulated, and pressed into pellets in the pressing column (6). The final operation involves sintering, grinding, cleaning of rod hardware, and loading the pellets into fuel rods. (See Refs. 1 and 2 for more detailed information.)

The transfer and scrap recovery systems associated with the mixed-oxide powder operation are also considered critical. The transfer systems are assumed to be pneumatic. The scrap recovery system will gather mixed-oxide scrap and recycle it.

Fig. 1. Manufacturing building of Westinghouse Recycle Fuels Plant.

Parts of the ventilation system are also considered critical. This system will filter the air entering and leaving the process area to minimize the release of airborne oxide particles from the building.

MANUFACTURING BUILDING

Our selection of appropriate methods of seismic analysis of the manufacturing building is based on Refs. 3 and 4. Justification for our recommendations is contained in Ref. 4 and will not be repeated here.

Figure 2 shows the key structural elements of a representative manufacturing building. The building is approximately 210 ft square with 18-in.-thick reinforced concrete roof, floors, and exterior walls. The ground floor is at grade, the second floor 20 ft above grade, and the roof 50 ft above grade.

The vertical load-carrying system consists of slabs spanning supporting edge beams that bear on 2- x 2-ft columns on 30-ft centers each way. At end bays, the exterior walls act as bearing walls.

The lateral force-resisting system consists of floor and roof slabs and exterior shear walls. The slabs act as rigid concrete diaphragms spanning the shear walls, which

Fig. 2. Manufacturing building.

transmit the loads to the foundation. End walls perpendicular to the direction of lateral load and interior columns were assumed to provide negligible lateral resistance.

In our model the interior canyon walls are treated as partition walls and are not considered part of either the vertical or lateral force-resisting systems.

External structural design of this manufacturing building was governed primarily by tornado considerations.³ Many future recycle plants will be located east of the continental divide near fuel reprocessing plants and nuclear power reactors, and these buildings will have their external structural designs governed by Region I tornado criteria.^{5,6} The design of floors and columns will be governed by seismic criteria. Similarly, the 1.5-ft-thick floor slab was governed by seismic loading to equipment. External structure design of future fuel recycle plants located west of the continental divide may or may not be governed by tornado loading.

RECEIVING AND DRUM STORAGE

Plutonium oxide is received and stored in specially designed⁷ double shipping containers in the receiving and drum storage area. The outer container is similar to a 55-gal drum. The inner container is a thick-walled tube closed on one end and sealed on the other with a heavy, bolted lid. The inner container is centered in the outer container and is surrounded by packing material. The oxide powder is located in two sealed cans inside a thin-walled vessel within the inner container.

Design of the complete container is controlled by handling and transportation loading, which far exceeds seismic loading.

UNLOADING STATION AND SCRAP RECOVERY SYSTEM

The shipping containers are mechanically transferred to the unloading station. After the lid and packing material are removed the open shipping container is placed in a glove box enclosure and the powder is unloaded. Glove boxes are also used to enclose all waste reprocessing.

Figure 3 shows a representative glove-box design. The glove box is constructed of 12-gauge stainless steel with a 3/8-in. shatterproof glass window. It is 2-1/2 x 3-1/2 x 8 ft and weighs 5000 lb. The glove boxes are assumed fastened to a structural steel support frame anchored to the main building structure.

BULK STORAGE AND MIXED-OXIDE STORAGE

Prior to the blending operations the plutonium oxide powder is temporarily stored in bulk storage bins. These bins are designed to receive powder from the transfer system, are geometrically safe, and permit powder weighing. After blend-

Fig. 3. Glove box (5000 lb).

ing, the mixed-oxide powder is stored in similar bins until transfer to the pressing column.

Figure 4 shows a representative storage bin design. The bin is approximately 8 ft high, 8 ft wide, and 4 in. thick and is constructed of 1/4-in. stainless steel plate. We supported the bin by two seats and provided four braces for lateral support. The weight of the bin and powder is estimated at 1500 lb.

Fig. 4. Storage bin.

BLENDING COLUMN AND PRESSING COLUMN

The blending and pressing columns are an assembly of equipment arranged to perform a common operation. It is likely that arrangement and selection of equipment in future designs will vary considerably. For this reason we will not conduct structural response calculations to evaluate and recommend the most appropriate method of analysis for the columns. We consider, however, that both the *blending and pressing columns* are subsystems and require a dynamic analysis. This approach follows the same guidelines used for critical subsystems in power plants.⁸

Both the blending and pressing columns are enclosed by gloved barriers (α barriers), shown in Fig. 5. They are constructed of 10-in.-thick reinforced concrete and extend from the first-floor level to the second-floor level. They are $5\frac{1}{2} \times 8\frac{1}{2}$ ft in plan, and they are attached to the main building structure at both floor levels.

TRANSFER SYSTEM

The Westinghouse plant will use a pneumatic (vacuum) system to transfer the oxide powders. Future designs could use mechanical systems for transfer, but we consider the

Fig. 5. Gloved barrier.

pneumatic transfer system as representative for this study.

The pneumatic lines are assumed to be schedule-40 stainless steel pipe* with a maximum 6-in. diameter and 0.28-in. wall thickness. The pneumatic system will be used to transfer the

*The schedule number is not a structural term but refers to the pressure-stress ratio of pipe. For further information see American Standard ASA B36.10-1959.

powder oxides from the unloading station to the bulk storage bins and also to transfer the blended powder from the blending column to the mixed-oxide storage bins. Storage is assumed to be on an upper level to take advantage of gravity feed for blending and pressing operations.

VENTILATION SYSTEM

The ventilation system will employ high-efficiency particulate air (HEPA) filters to minimize the release of airborne oxides from the building. The system will always direct the air flow towards zones of greater radioactive contamination potential.

Separate HEPA filters are provided for glove boxes, gloved barriers, and work rooms. Air is filtered when it enters the building, when it enters glove boxes and gloved barriers, when it leaves the glove boxes and gloved barriers, when it leaves work areas, and when it leaves the building through a final HEPA filter bank.

For seismic considerations three parts of the ventilation system are important: the exhaust ducting, the box HEPA filters, and the final HEPA filter bank. The ducting will con-

sist of approximately 18-in.-diameter, relatively lightweight (16-gauge) pipe. The ducting will be anchored to the main building structure. The box HEPA filters are lightweight and are approximately a 1-ft cube. The final HEPA filter bank consists of a filter frame that houses the box HEPA filters.

Figure 6 shows a HEPA filter frame designed in accordance with ORNL-NSIC-65 guidelines.⁹ The frame is of welded stainless steel construction with dimensions of 1- x 10- x 20-ft and a total weight of 2000 lb.

DIESEL GENERATORS

Diesel-driven electrical generators are required as a backup electrical system. They are located on the second floor of the Westinghouse plant.

INSTRUMENTATION

The critical instrumentation consists of devices that measure and record earthquake ground motion and those that monitor the integrity of the systems confining the oxide powders.

Fig. 6. Final HEPA filters, frame, and enclosure.

Methods of Structural Analysis

MANUFACTURING BUILDING

We recommend that the manufacturing building for fuel fabrication plants be evaluated against potential seismic hazard using the guidelines shown in Table 3. These recommendations are based on the recently completed study "Evaluation of Methods

for Seismic Analysis of Nuclear Fuel Reprocessing Plants."⁴ The objective of that study was to examine available methods of structural analysis to evaluate the earthquake hazard of nuclear fuel reprocessing plants. The conclusions may be used as the basis for a Regulatory Guide that recommends methods of analysis necessary to insure safe design.

Table 3. Recommended models and method of analysis.

Foundation location	Model	Method of analysis
Near or at grade	Lumped mass or finite element	Response spectra ^a
Deeply embedded	Finite element	Response spectra ^a

^aIf time-history response quantities are required, time-history analysis by either modal or direct integration must be performed. If non-linear effects are important, a time-history analysis by direct integration must be performed.

In Ref. 4 we considered the Barnwell Nuclear Fuel Plant (BNFP) to be representative of future commercial reprocessing plants and identified critical structures requiring seismic analysis. We then placed these critical structures into four categories of different response characteristics: (1) structures founded near or at grade; (2) structures deeply embedded; (3) structures fully buried; and (4) equipment. After selecting one representative structure in each of the first three categories, we performed extensive response calculations using the different methods of analysis. The calculations included static and dynamic methods using lumped-mass and finite-element models. Response-spectrum, modal, and direct-integration analysis procedures were

used. The effects of site characteristics (such as hard, intermediate, and soft) on the response were considered. Regulatory Guide 1.60 was used as the basis for ground-motion input. We compared the calculational results and the required manpower and computer effort to form the basis for our recommendations. Also included in Ref. 4 were discussions of the available methods of analysis for both site response and structural response.

We chose the process building at the BNFP as representative of the structures founded near or at grade. The dynamic characteristics of the MOFPP manufacturing building in this study are sufficiently similar to those of the process building in the earlier study to base our recommendations on the calculations and evaluation in Ref. 4. For example, the horizontal fundamental frequencies are compared in Table 4 for hard, intermediate, and soft sites.

To cover the possibility that future manufacturing buildings may be designed with a subgrade floor level, we also include recommendations for the "deeply embedded" category studies. For this category, the fuel receiving and storage station at BNFP was selected as representative.

The recommended models and methods of analysis given in Table 3 should

Table 4. Comparison of fundamental frequencies.

Building	Hard-site frequencies (Hz)	Intermediate- site frequencies (Hz)	Soft-site frequencies (Hz)
Manufacturing ³	10.4	8.6	2.9
Process ⁴	9.4	6.3	1.8

bracket all possibilities of future manufacturing building designs.

EQUIPMENT

The seismic integrity of equipment can be evaluated by either an equivalent-static method or one of several dynamic methods. Seismic loads can be determined by analyzing either a coupled building-equipment system or by conducting two separate analyses, one on the building structure and one on the equipment.

The coupled analysis would require only one set of dynamic response calculations. However, the mathematical model required would be more complex and require many more degrees of freedom in order to include both the equipment and the support structure. This more complex, larger model is necessary to capture accurately the response of the equipment. Such a model would not only require much more computer effort for its solution, but would also increase the likelihood of introducing errors (by way of ill-conditioned

mass and stiffness matrices) in its solution.

Performing separate analyses on the building structure and the equipment is generally more practical. Although two sets of response calculations are required, the models are much more manageable and result in the use of much less manpower and computer time. The building analysis provides the seismic loading to the equipment. This approach permits the flexibility of performing either an equivalent-static or dynamic analysis of the equipment, whichever is most appropriate.

If the mass and/or stiffness properties of the equipment could affect the overall building response, then a coupled dynamic analysis is necessary. If differential support motion must be considered (for example, because of a long pipeline extending several floor levels), then either a coupled analysis or two separate dynamic analyses with different support motions must be performed; a static analysis would not be appropriate.

Seismic input loading for the building analysis is generally in the form of a free-field-ground-response spectrum or a synthesized accelerogram. This input motion should be compatible with regional and local geology and seismicity. The Regulatory position for determining design-basis motion for nuclear power plants is described in Appendix A of Ref. 10. An acceptable ground-motion spectra for rock or soil sites for power plants is described in Regulatory Guide 1.60.¹¹

Seismic input loading for the equipment analysis is generally in the form of (1) a static coefficient, (2) a floor- or amplified-response spectrum, or (3) a floor- or amplified-acceleration record. The static coefficient is used as a multiplier in the equivalent-static analysis and usually reflects the peak floor acceleration or the peak of the acceleration-response spectrum at the location of the equipment within the building. The floor-response spectrum and acceleration time-histories are usually obtained from a dynamic analysis of the support structure and reflect the actual vibratory motion at the equipment support. Approximate methods are also available to develop floor spectra. The available methods to determine floor spectra are evaluated

in detail later in this report (see *Generation of Floor Spectra*).

Seismic analysis of structures and equipment must consider three components of motion: two perpendicular horizontal components and one vertical component. The probability is small that the maximum responses (displacements and stresses) caused by the three directional components would occur at the same time and therefore they are usually combined by the square-root-of-the-sum-of-the-squares (SRSS) method.

Definition of Terms

Single-Degree-of-Freedom System (SDOF)

The dynamic response of a system subjected to a specified base motion may be estimated by assuming that its mass, stiffness, and damping properties are concentrated into single physical elements. This model is called a single-degree-of-freedom system (Fig. 7). Once the system has been modeled the ground- or floor-response spectrum can be used directly as input motion to determine the maximum response.

Caution should be exercised in using single-degree-of-freedom representations of systems that physically have many possible displaced shapes. A single-degree-of-

Fig. 7. Single-degree-of-freedom system. Mass concentrated at single point M. Damping and stiffness characteristics concentrated in single elements D and S, respectively.

freedom representation will only approximate the true behavior.

Multiple-Degree-of-Freedom System (MDOF)

Often, dynamic response cannot be described with single-degree-of-freedom systems. True behavior can only be described in terms of more than one displacement coordinate, that is, a multiple-degree-of-freedom system is required to capture the motion.

Damping Factors

The response of a structure, system, or component usually has energy dissipation associated with it. These energy losses may be caused by internal energy dissipation within the material or support or joint slippage, and they are normally accounted for by means of a damping value.

Design damping values typically range from 0.5 to 10% of critical damping. Damping can have a significant effect on the dynamic response of the structure. Table 5 shows damping values used in the design of power-plant structures.¹² The lower value is for use with operating-basis earthquake motions, the larger with safe-shutdown earthquake motions.

Table 5. Damping values (percent of critical), from Regulatory Guide 1.61.

Structure or component	Damping value
Small-diameter piping (< 12 in.)	1-2
Equipment and large-diameter piping (> 12 in.)	2-3
Steel structures	
Welded	2-4
Bolted	4-7
Prestressed concrete structures	4-7
Reinforced concrete structures	4-7

In this study velocity-dependent damping was assumed, a standard modeling procedure in structural analysis.

Response Spectrum

A response spectrum is represented schematically in Fig. 8. A series of

single-degree-of-freedom systems (cantilever pendulums) with varying fundamental frequencies are fixed to a moveable base. As the length of the pendulums increases, the fundamental frequency decreases. If the base is moved with a time-varying motion and the motion of each pendulum is recorded, a curve can be developed that plots the maximum response against the frequency of each pendulum. This curve is called the response spectrum for that particular input motion, and is also shown in Fig. 8. The response motion can be displacement, velocity, or acceleration, because all are related to frequency. It is possible to generate spectra for both vertical and horizontal base motions.

Ground-Response Spectrum (Free-Field)

If the series of single-degree-of-freedom systems (pendulums) are assumed supported on the ground and are subjected to free-field ground motion resulting from an earthquake, then the response-spectrum curve developed is called a ground-motion spectrum. Figure 9a shows an example of the acceleration ground-motion spectrum for the 1940 El Centro earthquake. Figure 9b shows the measured horizontal accelerogram record used as input to develop this spectrum.

Fig. 8. Simulated cantilevered beams of varying response frequencies. (a) Pendulums of varying response frequency. (b) Plot of maximum response quantity for each single-degree-of-freedom system for particular input motion.

Fig. 9. 1940 El Centro earthquake. (a) Acceleration response spectrum. (b) Accelerogram.

Figure 10 shows the free-field-ground-motion spectrum currently used to define seismic input for nuclear power reactors.¹¹ This smooth spectrum is based on a statistical treatment of approximately 47 earthquake records and is plotted on tripartite log paper for the convenience of having maximum acceleration, velocity, and displacement values as a function of frequency on one plot. Both horizontal and vertical spectra are given for different values of damping. Both are normalized to a maximum horizontal ground acceleration of 1.0 g. Once the intensity of ground motion for a site is specified in terms of maximum horizontal ground acceleration, both horizontal and vertical spectra can be defined simply by scaling.

Floor- or Amplified-Response Spectrum

Floor-response spectra are similar to ground-response spectra except that the base of the series of cantilever beams is located at a particular floor level in the building rather than on the ground. Unless the building is rigid (that is, has a frequency greater than 33 Hz) the response motion at different elevations in the building will be different than the base ground motion. Usually the motion is amplified,

resulting in a floor spectrum with larger response values than ground-motion-spectrum values for a given frequency. Several methods available to generate floor spectra are discussed in the section *Generation of Floor Spectra*.

Rigid and Flexible System

In general, rigid systems are defined as those with fundamental frequencies in excess of 33 Hz. This is consistent with Regulatory's position for power reactors. In Fig. 10, for example, there is no amplification over the 1-g ground motion for frequencies greater than 33 Hz. Rigid systems exhibit no response amplification above the support or base motion. The response spectrum developed for a base motion from the 1940 El Centro earthquake (Fig. 9) shows the spectral acceleration equal to the peak ground acceleration for frequencies greater than 20 Hz.

Flexible systems are defined as those with fundamental frequencies less than 33 Hz.

Static Analysis

Static analysis refers to the application of static horizontal or vertical design load to a structural system. These loads are usually expressed as a coefficient or

Fig. 10. Design response spectra, scaled to 1-g horizontal ground acceleration (from Regulatory Guide 1.60). (a) Horizontal. (b) Vertical. Example: for 5% damping and $f = 0.25$ cps, $D = 73.8$ in., $v = 115.93$ in./s, $a = 0.47$ g.

multiplier of the acceleration of gravity. The loads are distributed consistent with the mass or weight distribution of the system.

Generally, the coefficient is based on the seismicity and soil characteristics at the site as well as the dynamic response characteristics, type, and function of the structural system under analysis. Another common way to determine the coefficient is to use the response spectrum defined for the structural system's base motion and an assumed damping value. Often the peak of the acceleration spectrum is chosen to develop an equivalent static load to apply at the center of gravity of the system. This, in effect, assumes that the structure behaves as a single-degree-of-freedom system in resonance with the support or base motion. No natural-frequency calculation is performed on the structural system.

Dynamic Analysis

In dynamic analysis the dynamic properties of the system (frequencies and mode shapes) are used to develop the seismic loads for design. One of two methods is used: the response-spectrum method or the time-history method.

The response-spectrum method requires the base motion to be in the

form of a response spectrum. Mode shapes and frequencies of the mathematical model must be calculated.

Because of the way the modal quantities are combined to get the total response, this method yields only an approximation. The response is calculated (such as for displacement or loads) in each mode, and all the calculated responses are superposed by the SRSS procedure. This procedure is used because the maximum value in each mode may not occur at the same time. The procedure is modified when closely spaced modes occur. Enough modes must be included in the analysis to capture the complete structural response.

The time-history method determines the structural response to an arbitrary force-time history or acceleration-time history. The method solves the equations of motion developed for the system at each time step using one of two approaches: mode superposition or direct integration.

Using mode superposition the eigenvalue problem associated with the model is solved to determine the mode shapes and frequencies of vibration. The response of each mode is then determined and all modes are combined to get the total response. This approach is limited to the linear response of structures.

The direct integration approach is used to obtain a solution by step-by-step integration of the equations of motion. Solution of the eigenvalue problem is not required, and non-linear effects may be included if required.

Either approach gives an "exact" time-history of response. A direct integration analysis is equivalent to an analysis by the mode-superposition approach in which all mode shapes and frequencies are included and the same time step, Δt , is used. Both approaches involve larger amounts of computer time than the response-spectrum method to solve for the dynamic response of a structure because small time steps are required to achieve meaningful results.

For more detailed discussion of the static and dynamic methods, particularly the advantages and disadvantages of each, see Ref. 4.

Available Methods

We have categorized the different seismic analysis methods for equipment according to the dynamic response characteristics of both the building (or support structure) and the equipment. The response characteristics of the building will influence the choice of seismic loading suitable for equipment analysis. The response characteristics

of the equipment will dictate the suitable method of analysis.

Figure 11 illustrates the standard^{*} approach used to develop seismic loading to equipment located at different levels in the building. The input seismic loading to the building is usually expressed in the form of an accelerogram considered representative of the free-field ground motion at the site (A_G). The free-field accelerogram is usually (1) based on a single recorded earthquake accelerogram considered representative of the site or (2) developed from a free-field response spectrum (S_G) based on a statistical treatment of many past earthquake records.

When an acceleration time-history is required, a synthesized accelerogram (A_G) is derived from the free-field response spectrum. An example of this approach is Regulatory Guide 1.60, which defines the seismic input for nuclear power reactors.

The free-field ground motion (S_G or A_G) is used as the exciting motion to a lumped-mass or finite-element model of the building. This model usually includes soil springs, which permit soil-structure interaction effects to be considered.

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^{*}Approximate approaches are discussed in the section *Generation of Floor Spectra*.

The dynamic response of the model is calculated using a computer program. Response quantities include member forces, displacements, velocities, and accelerations throughout the building. Figure 11 illustrates calculated acceleration time-histories at different floor levels (A_F). Depending on the location of the equipment, the accelerograms can be used directly as input to an equipment dynamic analysis. An alternative technique is to develop acceleration-response spectra corresponding to these floor accelerograms, designated as S_F in Fig. 11. These floor spectra are then used as input to the dynamic analysis of equipment.

An equivalent-static analysis of equipment uses a single value from either the acceleration time-history or acceleration-response spectrum to represent the seismic force. These include, for example, maximum ground or floor acceleration ($A_G^{\max}$ or $A_F^{\max}$) and ground- or floor-spectra values that correspond to the frequency of the building or equipment ($S_G^{f_e}$, $S_G^{f_B}$, $S_F^{f_e}$). Appropriate damping values must be used.

Figure 12 identifies 11 methods for evaluating the seismic integrity of equipment. To find the appropriate method we first determine the stiffness of the building that houses the

equipment. We then determine the stiffness of the equipment. Finally, after these two stiffnesses are known, the precision in the seismic input load indicates the appropriate analysis method.

The two classes of stiffness, in either buildings or equipment, are rigid and flexible. Rigid systems are those that exhibit no response amplification when subjected to input motion. Flexible systems exhibit response amplification. For example, for the design of power plants Regulatory Guide 1.60 suggests 33 Hz as the frequency cutoff for rigid structures. Those structures with fundamental frequencies greater than 33 Hz need not be designed for amplified acceleration levels. Flexible structures include those with frequencies less than 33 Hz. For our purposes the 33-Hz value appears reasonable as the dividing line between rigid and flexible buildings and equipment.

As shown in Fig. 12, methods 1 through 4 pertain to the rigid-building situation and methods 5 through 11 the flexible-building situation. Because no dynamic response characteristics or calculations are required for rigid buildings, methods 1 through 4 can determine seismic equipment loading directly from the free-field ground motion.

Input motion

Free-field seismic ground motions (vertical or horizontal) usually defined as acceleration spectrum.

Earthquake motion

Free-field acceleration time-history is developed from free-field ground motion spectrum (i.e. synthetic accelerogram).

Model

Model (LM or FE) of building structure that includes foundation effects (via soil springs).

Response

Acceleration time-history response of the model is calculated at different building levels by using dynamic analysis techniques.

Floor spectra

Floor or amplified acceleration response spectra are generated from calculated acceleration time-history results at each level.

Fig. 11. Standard approach used to develop seismic loading to equipment at different levels in building.
 Definition of symbols: A_G , A_F = acceleration time-history for ground, floor; $A_G^{\max}$, $A_F^{\max}$ = maximum acceleration for ground, floor; S_G , S_F = acceleration response spectrum for free-field ground, floor; S_G^{peak} , S_F^{peak} = peak value from acceleration response spectrum for ground, floor.

^aIf differential support motion need be considered for equipment then a dynamic analysis, either coupled (building-equipment) or separate, using appropriate support motions must be performed.

^bIf mass and/or stiffness of equipment influences overall building response then a coupled (building-equipment) dynamic analysis must be performed.

^cMust demonstrate that rigid building or rigid equipment response characteristics will not amplify input ground or floor motions. Generally this implies that both have fundamental frequencies greater than 33 Hz.

^dMust demonstrate that flexible building responds as single degree-of-freedom system.

^eUse a damping value consistent with equipment.

^fUse a damping value consistent with structure.

Fig. 12. Decision tree showing analysis method to evaluate seismic integrity of equipment. Double under-scores indicate recommended methods. Definition of symbols: A_G , A_F = acceleration time-history for ground, floor; $A_G^{\max}$, $A_F^{\max}$ = maximum acceleration for ground, floor; S_G , S_F = acceleration response spectrum for free-field ground, floor; S_G^{peak} , S_F^{peak} = value from acceleration response spectrum for ground, floor; $S_G^{f_B}$, $S_G^{f_e}$, $S_F^{f_e}$ = acceleration response spectrum value corresponding to frequency of building, equipment for ground, floor.

Method 1 (rigid building, rigid equipment) recognizes that no load amplification over the free-field values is possible and therefore uses the maximum ground acceleration ($A_G^{\max}$) as the static coefficient or multiplier for an equivalent-static equipment analysis.

Method 2 (rigid building, flexible equipment) accounts for the situation where the maximum seismic equipment loading must include amplification of the maximum ground-motion acceleration. It conservatively selects the peak-ground-motion-spectrum value (S_G^{peak}) using a damping value consistent with the equipment. The equipment must respond as a single-degree-of-freedom system.

Method 3 (rigid building, flexible equipment) accounts for the same situation as method 2, but with the conservatism removed. Method 3 selects a ground-motion-spectrum value consistent with both the fundamental frequency and damping of the equipment. It also requires the additional effort of calculating the fundamental frequency. The equipment here, too, must respond as a single-degree-of-freedom system.

Method 4 (rigid building, flexible equipment) is used when the equipment does not respond as a single-degree-of-freedom system. Here, either the free-field ground accelerogram (A_G)

or response spectrum (S_G) are used as input to a dynamic equipment analysis. Either response-spectrum or time-history methods of analysis are appropriate.

Method 5 (flexible building, rigid equipment) is a special case. Although it falls into the flexible-building class, because the equipment is considered rigid the seismic forces can, as in methods 1 through 4, be related directly to the free-field ground motion. As long as the building responds primarily as a single-degree-of-freedom system the maximum possible seismic loading to the equipment can be expressed as a function of the peak-ground-response-spectrum value.

Methods 6 through 11 are in the flexible-building class and therefore require dynamic characteristics and/or response calculations of the building to determine the input seismic loading to the equipment.

Method 6 (flexible building, rigid equipment) uses the free-field ground motion directly. Here, as in method 5, the building must respond as a single-degree-of-freedom system. Because the equipment is considered rigid, no dynamic response calculations are required. However, the fundamental frequency and damping of the building must be determined so that a spectral acceleration value

corresponding to the building frequency (S_G^{1D}) can be obtained. This corresponding acceleration value often results in a substantial load reduction over method 5.

Method 7 (flexible building, rigid equipment) is for rigid-equipment cases where the building does not respond as a single-degree-of-freedom system. It uses the maximum floor acceleration ($A_F^{\max}$) as the static coefficient. To get this maximum floor acceleration a dynamic response analysis is required of the building using a multiple-degree-of-freedom model. Either a modal analysis or the direct method of solution can be used.

Method 8 (flexible building, flexible equipment) uses either the floor response spectrum (S_F) or floor acceleration (A_F) for the seismic motion. Here, the equipment must respond as a single-degree-of-freedom system, and the peak spectral value (S_F^{peak}) is conservatively selected as the static coefficient.

Method 9 (flexible building, flexible equipment) is the same as method 8 except that the spectral value selected (S_F^{fe}) is less conservative and consistent with the calculated fundamental equipment frequency.

Method 10 (flexible building, flexible equipment) also uses either

the floor-response spectrum (S_F) or floor acceleration (A_F) for the seismic motion. But here the equipment can be a multiple-degree-of-freedom system. Either response-spectrum or time-history methods of solution can be used.

Method 11 (flexible building, heavy equipment) is the special case where the equipment is of sufficient mass and/or stiffness to affect the overall dynamic response of the building. Here, dynamic response calculations must be made on a coupled building-equipment model. Free-field ground motion (S_G or A_G) can be used for analysis. Either response-spectrum or time-history methods of solution are appropriate.

Several general comments can be made regarding the selection process described in Fig. 12.

1. If a frequency value of approximately 33 Hz is used to delineate between rigid and flexible systems, very few building structures used at nuclear facilities (particularly if soil-structure interaction effects are important) will fall into the rigid class. As stated earlier, the 33-Hz value is consistent with Regulatory Guide 1.60 for power plant buildings.

2. When choosing between methods 2 and 3, methods 5 and 6, and methods 8 and 9 for most buildings and equipment combinations, the latter method in each pair will be the most practical because of the undesirable conservatism associated with using the peak-response-spectrum value. The additional effort required to determine the fundamental frequency will be justified.
3. When choosing between methods 2, 3, and 4; methods 5, 6, and 7; and methods 9 and 10 because of the single-degree-of-freedom requirement, it will generally be more practical to use methods 4, 7, and 10. Most of the equipment and buildings are sufficiently complex that they cannot be modeled as a single-degree-of-freedom system. Further, once the response characteristics necessary to determine whether or not the system responds as a single-degree-of-freedom system are calculated, very little additional effort is required for the dynamic response solution.
4. Given only a single piece of equipment to evaluate in a

building, the methods most frequently applied will be methods 1, 4, 7, or 10. The usual situation is to calculate the response of many pieces of equipment located in one building. Method 10 is probably the best compromise since floor spectra only need to be computed once.

5. If differential support motion need be considered for the equipment (e.g., a pipe that extends over several floor levels), then a dynamic analysis is required. The single analysis using a coupled building-equipment model may be performed, or two separate analyses using appropriate support motion may be conducted.

Comparison of Methods

The dynamic response characteristics of the manufacturing building we consider representative of future fuel fabrication buildings is discussed in detail in the section *Generation of Floor Spectra*. The basis for the building design is discussed in the section *Critical Structures and Equipment*.

The fundamental frequencies of the building were calculated for two site conditions for both horizontal

and vertical ground motions. The first site reflects an average site shear velocity of 3500 ft/s, and the second, a softer site, reflects a shear velocity of 1500 ft/s. The calculational model included soil springs to account for soil-structure interaction effects. The calculated fundamental frequencies for horizontal motion were 7.7 and 9.7 Hz for the soft and hard sites, respectively. The calculated frequency for vertical motion is 7.7 Hz for both site characterizations.

Using the 33-Hz frequency value for the division between rigid and flexible structure classes, the manufacturing building must be considered a flexible structural system. The fundamental frequency of building horizontal motion is dominated by the end shear walls; for vertical motion the floor and roof slabs dominate the response characteristics. Even with substantial variations in wall and slab design (e.g., decrease or increase of thickness by as much as 50%) the building would still fall within the flexible rather than rigid class.

Figures 13 and 14 show the acceleration floor spectra calculated for different levels of the manufacturing building for both horizontal and vertical motions. The floor spectra are for 0.5% damping. Also

given are 0.5 and 4% free-field-ground-motion spectra. These spectra were developed from the synthesized free-field accelerogram that was used for the time-history response analysis of the building model. The 4% spectrum is consistent with that used for the building response analysis. The 0.5% spectra are included to permit a comparison of free-field motion with calculated building response motion for the same damping. The free-field ground motion reflects a 1-g maximum ground motion for both horizontal and vertical directions. For other maximum horizontal free-field motion the floor- and ground-response spectra can simply be scaled.

These figures clearly show building influence on the seismic loads to equipment. The response characteristics of the building clearly amplify the ground motion. For example, Fig. 13 (horizontal motions, soft site) shows roof, second-floor, and ground-floor peak spectral values of 114, 80, and 45 g, respectively, for 0.5% damping. The effect of the building fundamental frequency can also be observed to force the largest amplification near that frequency. The ground-motion spectrum shows a lesser peak amplification of 10 to 12 g at 0.5% over the 1-g maximum horizontal ground

Fig. 13. Free-field ground motion and calculated floor response spectra, horizontal motions, soft site.

Fig. 14. Free-field ground motion and calculated floor response spectra, vertical motions, soft site.

acceleration but over a wider frequency range. Similar amplifications are shown in Fig. 14.

Soil-structure interaction effects influence the seismic loading to the equipment. Figure 13 shows a free-field-spectra amplification factor of approximately 4 (45/12) over the ground floor at a frequency near the building fundamental frequency. This amplification is directly attributed to the soil springs.

Table 6 shows estimated fundamental frequencies of each of the critical pieces of equipment. Variations in equipment design could substantially modify these frequency estimates. For example, the location of support points plays a significant role in the response characteristics of the equipment. For this reason and also because future equipment designs may be substantially different we have decided not to use the estimated equipment frequencies when comparing seismic equipment loads. Instead, we will assume that the critical equipment could have any fundamental frequency less than 20 Hz.

A comparison of seismic equipment loads determined using the different methods discussed previously is given in Table 7. The acceleration values shown reflect horizontal building motion for a soft site (Fig. 13). The input free-field

ground motion is based on a 1-g maximum horizontal ground motion.

Table 6. Estimated fundamental frequency of critical equipment.

Critical equipment	Estimated frequency (Hz)
Unloading station (glove box)	10-20
Bulk storage	25-50
Mixed-oxide storage	25-50
Transfer system (piping)	5-20
Scrap recovery system (glove box)	10-20
Ventilation system (ducting)	5-20
Final HEPA frame	5-10

Table 7. Comparison of seismic equipment^a loads determined using different methods, horizontal motion, soft site.

Method	Equipment frequency (Hz)	Acceleration ^b (g)
1	> 32	1
2	3-8	12
3	0.25-33	1-12
5	3-8	4
6	7.7	4
7	> 33	4
8	7.7	80
9	0.25-33	4-80

^aEquipment assumed to be located on second floor of manufacturing building.

^bSee Fig. 13.

The equipment is assumed to be located on the second floor of the manufacturing building. The building is assumed to have 4% damping and the equipment 0.5% damping.

As previously indicated, we assume that future manufacturing buildings will fall within the flexible-building class (methods 5 to 11). However, for comparison we include seismic equipment loads that reflect the rigid-building class (methods 1 to 4). Methods 4, 10, and 11 are not included in the comparison because it would be necessary to completely define the equipment design.

To facilitate comparison, we can briefly describe the methods listed in Table 7 as follows:

Method 1 (rigid building, rigid equipment). Because the free-field ground motion is not amplified, the maximum seismic loading on the equipment is the maximum ground acceleration, 1 g.

Method 2 (rigid building, flexible equipment). This method selects the peak free-field spectral acceleration for the seismic equipment loading. Rather than requiring a frequency calculation for the equipment, it conservatively uses the peak free-field spectral value of 12 g that

assumes the equipment frequency to coincide with the dominant free-field frequency on the 0.5% damping curve.

Method 3 (rigid building, flexible equipment). This method assumes that the equipment frequency is determined and that the result is a seismic equipment loading that ranges from 1 to 12 g, depending on the actual equipment frequency.

Method 5 (flexible building, rigid equipment). Because the rigid equipment will not further amplify the free-field motion above that of the flexible building, this method uses the peak-ground motion-spectrum value of 4 g (4% building damping). It does not require a frequency calculation; it assumes that the building fundamental frequency matches the dominate frequency of the free-field motion. It also assumes that the building responds as a single-degree-of-freedom system.

Method 6 (flexible building, rigid equipment). This method uses the calculated frequency of the building (7.7 Hz), which results in a corresponding ground-motion spectrum value of 4 g. It assumes that the building responds as a single-degree-of-freedom system.

Method 7 (flexible building, rigid equipment). This method assumes the building has multiple-degree-of-freedom characteristics and yields a seismic equipment load of 4 g. This value is based on the maximum second-floor acceleration, which is the same as the second-floor spectral acceleration corresponding to a frequency of 33 Hz or greater at 0.5% damping.

Method 8 (flexible building, flexible equipment). This method requires a floor-response spectrum, the result of a dynamic building analysis appropriately accounting for the flexibility of the building, as the input seismic motion to the equipment analysis. It selects the peak spectral floor acceleration of 80 g (0.5% damping) to arrive at the seismic load for the equipment. It will produce extremely conservative loads unless the equipment fundamental frequency matches very closely that corresponding to the peak floor spectrum. It assumes that the equipment responds as a single-degree-of-freedom system.

Method 9 (flexible building, flexible equipment). This method requires a floor-response spectrum as the input seismic motion to the

equipment analysis. It also requires the determination of the fundamental frequency of the equipment, resulting in equipment loads that could vary from 4 to 80 g depending on the actual equipment frequency.

Future fuel fabrication manufacturing buildings and most critical equipment will fall into the flexible building, flexible equipment class of methods 8 and 9.

Conclusions

The conclusions that follow are based on the dynamic response characteristics of future manufacturing buildings and the pros and cons of the different methods of analysis.

Future fuel fabrication manufacturing buildings should be considered flexible structures. Therefore, we are concerned only with methods 5 through 11. These choices provide for the possibilities of rigid, flexible, or heavy (rigid or flexible) equipment.

For rigid equipment we recommend method 7 over methods 5 and 6. Methods 5 and 6 require that the manufacturing building respond as a single-degree-of-freedom system. The dynamic analysis we performed (in the section *Generation of Floor Spectra*) clearly demonstrates that

the building must be modeled as a multiple-degree-of-freedom system.

For flexible equipment we recommend method 10 over methods 8 and 9. In most cases method 8 will yield loads that are too conservative. Method 9 not only requires that the fundamental frequency be calculated, but also that the equipment responds as a single-degree-of-freedom system. With the exception of the simpler equipment configurations, most

equipment will require a multiple-degree-of-freedom analysis. Furthermore, the additional analysis effort for the frequency determination in method 10 is small beyond that already required by method 9.

For heavy equipment, which could affect the overall response of the building, method 11 is necessary.

These recommendations are summarized in Table 8.

Table 8. Recommended methods for seismic analysis of equipment located in flexible buildings.

Equipment stiffness	Recommended method	Description
Rigid equipment	Method 7	Use maximum floor acceleration and conduct static analysis of equipment
Flexible equipment	Method 10	Use floor-response spectra or floor-acceleration time-history and conduct dynamic analysis of equipment
Exceptionally heavy equipment	Method 11	Use ground-response spectra or ground-acceleration time-history and conduct coupled dynamic analysis of building-equipment system

Generation of Floor Spectra

Almost all seismic analyses of equipment involve the use of floor-response spectra. In most instances a complete set of response spectra are calculated for the building prior to equipment design. The floor spectra will encompass motion in three orthogonal directions at all possible equipment locations and damping.

The time-history method is normally used to calculate the floor-response spectra. This can be accomplished by enveloping the floor spectra generated from the response of the structure to several recorded earthquake ground motions. The approach currently favored by designers is to use a synthesized ground motion whose spectrum envelopes the probable site spectrum at all frequencies of interest.

Additionally, approximate methods have become available for generating floor spectra. Although developed by different authors, these methods share certain characteristics: the response spectra of the ground motion and a modal analysis of the building are required as input; no time-history calculations are required; the methods are generally more conservative than the time-history approach.

There are three main reasons for using one of the approximate methods in lieu of the time-history approach:

1. A synthetic accelerogram need not be generated
2. An approximate method is less complex
3. Less analyst and computer time is required.

Two approximate methods were developed by Kapur¹³ and Biggs.^{14,15} Kapur's method was published in 1973. Biggs' method was first published in 1970 and in 1971 revised to be more conservative.

We assessed the suitability of the Kapur and Biggs methods for use on MOFFP's. (We used the more recent method presented by Biggs in Ref. 14.) Both authors have demonstrated the conservatism that results when their methods are used on power reactor buildings. Because MOFFP buildings have different response characteristics (such as higher natural frequencies) than power reactors, we felt it appropriate to re-examine the issue.

To accomplish this, we developed a free-field synthetic accelerogram whose response spectrum envelopes those of many past earthquakes. Four

structural models of our MOFFP building were developed that encompass the range of dynamic characteristics expected in the future. The four consist of vertical and horizontal response models founded on soft and hard soil. Floor-response spectra were generated with the time-history, Kapur, and Biggs methods for all four models and the results compared.

FLOOR-SPECTRA CALCULATIONS

Ground Motion Used

As noted previously, the time-history method for calculating floor spectra requires a free-field-ground-motion accelerogram. The approximate methods require response spectra of the ground motion. We generated an earthquake-like accelerogram whose response spectrum is very similar to that in Regulatory Guide 1.60.¹¹ This similarity ensures that our accelerogram has the characteristics of many past earthquakes and therefore provides a sound basis for comparing resultant floor spectra. The accelerogram was developed with the code SIMEAR.¹⁶ It has a 30-s duration, has approximately 12 s of strong motion, has a maximum ground acceleration of 1 g, and consists of 5000 points spaced 0.006 s apart.

Figure 15 shows the 4% damped response spectrum of our synthetic

free-field ground motion and the 4% horizontal spectrum from Regulatory Guide 1.60. The figure illustrates that, while the agreement is not precise, the spectral content of the synthetic earthquake is adequate for our purposes. The response spectra of the artificial ground motion was used as input to the approximate methods.

Figure 15 shows that the Regulatory Guide 1.60 vertical and horizontal spectra are very similar. They are identical, in fact, over the range of MOFFP natural frequencies. Therefore, we elected to use the same synthetic ground motion for the vertical and horizontal floor-spectra calculations.

Building Models

Table 9 lists the material properties used in formulating the calculational models for both horizontal and vertical response. Four percent of critical damping is appropriate for the reinforced concrete MOFFP structure and was used for all calculations of building response. Our soft-soil material properties correspond to the lower limit of shear-wave speed for the range that is normally considered intermediate. Our hard-soil-shear-wave speed is at the lower limit of the hard range. The purpose of

Fig. 15. Response spectrum of synthetic acceleration compared to Regulatory Guide 1.60.

Table 9. Material properties for MOFFP analytical models.

Material	Weight density, γ (lb/ft ³)	Shear-wave speed, V_s (ft/s)	Young's modulus, E (kips/in. ²)	Shear modulus, G (kips/in. ²)	Poisson's ratio, ν	Damping ratio (%)
Concrete	150	----	3000	1200	0.25	4
Soft soil	125	1500	164	60.6	0.35	4
Hard soil	125	3500	891	330	0.35	4

varying the soil properties was to make the floor-spectra comparisons extend over a range of site conditions considered representative of future MOFFP plants.

Figure 16 shows the MOFFP analytical model used for horizontal response calculations. Note that the

only difference between the soft- and hard-soil models is the value of the soil springs at the base. The MOFFP is symmetric in plan, and the floors are relatively rigid in their plane. Therefore, a simple beam model is adequate. The masses, m_1 through m_3 , and inertias, I_1 through

Soil springs

	k_x (kips/in.)	k_ϕ (in. · kip/rad)
Soft soil	3.97×10^5	7.46×10^{11}
Hard soil	21.6×10^5	40.6×10^{11}

Fig. 16. Analytical model for MOFFP horizontal response.

I_3 , represent the mass and rotational inertia of the building roof, floors, and tributary wall areas. The lateral stiffening effect of the interior columns and partitions is negligible. The beam-element shear area represents that of the sidewalls. The bending inertia is that of the entire perimeter wall. The soil springs were calculated by the procedures recommended by Whitman and Richart.¹⁷

Figure 17 shows the analytical model used for vertical MOFFP response calculations. Here again, the only difference between the soft-

and hard-soil models is the value of the soil springs. In formulating this model it was important to include the vertical bending action of the upper-floor and roof slabs. Our model allows for this effect and yet provides a measure of economy in computing and modeling time. The model shown in Fig. 17 represents a 30-ft-wide strip of the MOFFP.

Figure 18 shows the origin of the strip model. Because the building is symmetric, it was necessary to model only one-half the length of the strip (105 ft) with the addition of

Fig. 17. Analytical model for MOFFP vertical response, elevation view. Soil springs: soft soil, $k_z = 1.00 \times 10^4$ kip/in.; hard soil, $k_z = 5.42 \times 10^4$ kip/in.

Fig. 18. Basis for the vertical MOFFP model, plan view.

symmetric boundary conditions at the centerline as shown. The interior vertical elements are the 24- × 24-in. columns. The horizontal elements and exterior vertical elements (at the left) are beams 18 in. thick by 30 ft wide. The base mat has been made artificially stiff to account for the supporting effect of the underlying soil.

The soil springs, k_z , represent the appropriate fraction of the

overall soil spring for the building. They were calculated as follows. The vertical soil spring for the entire 210- × 210-ft foundation was computed by the method in Ref. 17. The k_z shown in Fig. 17 represents the fractional value of the overall spring for a 30- × 30-ft section of the slab (that is, k_z overall^{1/49}).

Time-History Method

All the time-history analyses

were performed in the same manner. We used the SAPIV finite-element code¹⁸ to make the calculations on a CDC-7600 computer. We used the direct-integration scheme with the free-field-ground-motion accelerogram described above as input and 4% of critical viscous damping.

Because the equations of motion are formulated in terms of relative displacements, the accelerations output by SAPIV are relative to free-field. The absolute acceleration time-history was obtained by a post-processing operation that added the ground acceleration to the structure acceleration at each time step. The final step was to calculate the pseudo-acceleration response spectrum of the motion at each degree of freedom of interest. This was done for 0.5% of critical (equipment) damping.

The time-history-derived floor response spectra are shown in Figs. 19 and 20. Figure 19 shows the horizontal floor spectra associated with soft- and hard-soil models. For the most part, the horizontal spectra are dominated by the fundamental frequency of the building. The one exception is the ground-floor spectrum of the hard-soil model. In this case, the 15-g peak occurs at 5.3 Hz and results from a "spike" in the response

spectrum of the free-field ground motion at this frequency. The 5.3-hz peak can be seen in the other floor spectra, but does not dominate when the modal response is more evident. The uneven character of the spectrum of the input motion also accounts for the split resonance peak occurring in the soft-soil horizontal spectra. Note in Fig. 19a that there appears to be two closely spaced resonances. In actuality there is a "valley" in the spectrum of the input motion near the fundamental frequency of the building.

Figure 20 shows the vertical MOFFP floor spectra calculated by the time-history method. We chose nodes 2, 8, and 16 of our vertical model for floor-spectra calculations. They are representative of the ground floor, second floor, and roof, respectively. The split resonance phenomenon observed in the horizontal soft-soil spectra is also evident in the vertical soft-soil calculations.

Approximate Methods

The Kapur and Biggs approximate methods for generating floor spectra are well documented in Refs. 13 and 14. However, for completeness the two methods are outlined in the appendix to this report.

There are two essential differences between the two methods. The

Fig. 19. Time-history-derived horizontal floor spectra, 1/2% damping.
 (a) Soft soil. (b) Hard soil.

Fig. 20. Time-history-derived vertical floor spectra, 1/2% damping.
(a) Soft soil. (b) Hard soil.

first is that Kapur's method is based on a hypothetical upper limit to the amplification of the building and/or ground motion; Biggs' amplification factors are based on the envelope of several time-history analyses of a two-degree-of-freedom system. Kapur used a time-history analysis to estimate amplification factors only at equipment-building resonance.

The second difference is that Kapur's method involves artificially broadening the resonance peaks in the floor spectra by $\pm 10\%$; Biggs' method does not broaden the peaks.

To our knowledge Biggs' method is published for only one set of structure-equipment damping values: 4.0 and 0.5%. Kapur's method is published for a range of structure-equipment damping values that does not include the two that Biggs reports. We therefore extrapolated Kapur's resonance amplification factor to 4.0 and 0.5% structure-equipment damping to facilitate the comparison. The extrapolated amplification value only affects Kapur's floor spectra near building-equipment resonance.

As noted previously, both methods require a modal analysis of the building and the response spectra of the free-field ground motion. The modal analyses required by the approximate methods were accomplished

with the SAPIV code. The analytical models used were identical to those used in the time-history calculations.

Figure 21 shows the results of the modal analysis of the two horizontal models. In both the soft- and hard-soil cases, the four lowest natural frequencies were input to the approximate methods. None of the modes were closely spaced.

Table 10 gives the modal-analysis data for the two vertical response models. Here, the model was more complex, and therefore the resulting mode shapes were more complex. Of the 15 frequencies obtained for the soft- and hard-soil models, 10 were chosen for input to the approximate methods. The frequencies were chosen for maximum response, based on the participation factor, Γ , the eigenvector, ϕ , and preliminary calculations of approximate floor spectra.

It is of interest to note that many of the modes of the vertical model are closely spaced under the criteria in Regulatory Guide 1.92.¹⁹ This fact affects the approximate floor spectra because, as we point out in the appendix, the criteria and summing procedure in the Guide are used in the Biggs and Kapur methods.

In performing the analysis we discovered that in some instances the approximate vertical spectra could

Soft soil					Hard soil				
f_{ln} (Hz)	Γ_{ln}	ϕ_{sn}			f_{ln} (Hz)	Γ_{ln}	ϕ_{sn}		
		s = 1	2	3			s = 1	2	3
7.30	9.94	0.128	0.0925	0.0526	9.69	8.71	0.147	0.0834	0.0150
14.8	2.59	0.0364	0.0395	0.0563	22.8	3.43	0.0797	0.122	0.0326
20.0	2.21	0.104	0.0549	0.0878	26.4	0.741	0.0475	0.0495	0.0094
28.9	1.29	0.0418	0.112	0.107	41.5	4.89	0.0055	0.0369	0.154

Fig. 21. MOFFP horizontal response model, normal mode data input to approximate floor spectra methods, lowest four normal modes. Γ , modal participation factor; ϕ , eigenvector. (See Appendix for additional definitions.)

actually be increased by leaving out one of the normal modes of the building. This resulted because: (1) the discarded mode was of minor importance to the building response and (2) the closely spaced modes were grouped in a different fashion by the algorithm in Regulatory Guide 1.92. We note this anomaly here as a matter of general interest.

Figures 22 through 25 show the MOFFP floor spectra derived by the

Kapur and Biggs approximate methods. Each figure shows the three floor spectra for a particular soil stiffness, method, and direction.

The overall appearance of the Biggs spectra is much the same as the time-history spectra. The Kapur spectra, on the other hand, are characterized by very broad, flat resonance peaks. This feature results from the $\pm 10\%$ peak broadening that is part of the Kapur method.

Table 10. Normal-mode data for MOFFP vertical response model.

Mode No. "n"	Soft soil					Hard soil				
	f_{1n} (Hz)	Γ_{1n}	ϕ_{sn}			f_{1n} (Hz)	Γ_{1n}	ϕ_{sn}		
			S=2	8	16			S=2	8	16
1 ^{a,b}	7.70	.987	.084	.081	1.16	7.72	.039	.0056	.192	.924
2 ^{a,b}	7.74	2.07	.124	.566	.333	8.29	.031	.0035	.556	.507
3 ^{a,b,c}	7.98	.088	.102	.471	.744	8.42	.303	.020	.934	1.16
4 ^{a,b,c}	8.19	.328	.072	.453	.503	8.82	1.35	.0049	.270	.495
5 ^{a,b,c}	8.44	.484	.059	.803	.532	9.15	1.17	.035	.374	.235
6 ^{a,b,c}	9.63	.234	.029	.866	.315	9.89	.502	.018	.908	.385
7 ^{a,b}	11.43	.362	.080	.873	.577	11.77	.253	.022	.805	.440
8 ^{a,b,c}	12.67	.669	.062	.471	.349	13.08	.509	.015	.848	.468
9 ^a	13.23	.256	-0-	.583	.418	16.88	.089	.047	.059	.105
10 ^{b,c}	16.04	.059	.151	.083	.150	19.67	.229	.057	.291	.517
11 ^c	18.48	.106	.315	.382	.509	21.31	.974	.058	.037	.026
12 ^{a,b,c}	19.49	.787	.251	.400	.399	22.26	.752	.052	.258	.447
13	25.74	.482	.220	.019	.256	34.79	.047	.156	.018	.011
14 ^c	27.04	.158	.680	.055	.174	35.47	.159	.248	.123	.074
15 ^c	29.07	.051	.552	.009	.006	36.09	.709	.138	.124	.080

^aSoft-soil modes used.^bHard-soil modes used, nodes 8 and 16.^cHard-soil modes used, node 2.

Fig. 22. MOFPP horizontal floor spectra by Kapur's method, 1/2% equipment damping. (a) Soft-soil model. (b) Hard-soil model.

Fig. 23. MOFPP horizontal floor spectra by Biggs' method, 1/2% equipment damping. (a) Soft-soil model. (b) Hard-soil model.

Fig. 24. MOFPP vertical floor spectra by Kapur's method, 1/2% equipment damping. (a) Soft-soil model. (b) Hard-soil model.

Fig. 25. MOFFP vertical floor spectra by Biggs' method, 1/2% equipment damping. (a) Soft-soil model. (b) Hard-soil model.

COMPARISON OF METHODS

Floor Spectra

Normally, the designer will draw smooth response spectra that envelope the calculated spectra. These smoothed curves are a much more convenient and reasonable tool for design purposes. Also, the primary resonance peaks of the floor spectra are artificially broadened for design purposes to allow for uncertainty in building frequencies. We felt these measures would blur our comparison, particularly so since the spectrum of the input motion was not smooth. Therefore, we did not make these modifications on our floor spectra. Kapur's method already had a $\pm 10\%$ -peak-broadening feature built into it, but rather than tamper with the method, we left it in.

All floor spectra were calculated at the same set of frequencies. The set contained 198 points between 0.10 and 33 Hz. Numerical comparison of the floor spectra was somewhat complicated by the jagged nature of the input spectrum. This problem was overcome by plotting the *ratio* of each approximate floor spectrum to the corresponding time-history-spectrum vs. frequency.

We feel that these ratio plots, shown in Figs. 26 through 29, have two important limitations. First,

The artificial peak broadening in Kapur's method can cause a great deal of conservatism in the regions on either side of the building natural frequencies. Second, as the ratio curves indicate, both the Kapur and Biggs methods tend to produce very unconservative horizontal and vertical spectra at the ground floor when the soil is hard. The base mat moves, for the most part, as the soil moves. To model this situation correctly, many more of the higher building frequencies need to be included. We did not include all the building frequencies in the approximate-floor-spectra calculations and the resulting spectra at the ground level were too low at some frequencies.

Excluding the cases above from consideration, the ratio plots indicate that the Kapur floor spectra range from 0.6 to 4.5 times the time-history floor spectra; Biggs' range from 0.8 to 3.7. In general, the methods tend to estimate the spectrum at the fundamental building frequency very closely and to overestimate it at higher frequencies.

As currently formulated, the approximate-floor-spectra methods of Kapur and Biggs do not provide a reasonably constant degree of conservatism. Additional study and modification of these methods could

Fig. 26. Ratio of approximate to time-history floor spectra, horizontal motions, soft soil.

eliminate, for the most part, the regions where the spectra are unconservative. However, the designer would still be faced with a degree of method-introduced uncertainty and at the same time a potential design-load increase of 300 to 400%.

Intangibles

We noted earlier that there are three reasons for using an approximate method instead of the time-history

method: (1) no synthetic accelerogram is needed; (2) an approximate method is less complex; and (3) less analyst and computer time is required. However, our experience indicates that these reasons may not be valid.

It is true that the approximate methods do not require generation of a synthetic accelerogram. However, computer programs that produce such tailored accelerograms have lately become more widespread and more satisfactory in performance.^{16,20,21}

Fig. 27. Ratio of approximate to time-history floor spectra, horizontal motions, hard soil.

The notion that the time-history procedure is more complex seems debatable. The most demanding task facing the analyst is to formulate a reasonable analytical model, and he must do this with any of the methods. The time-history calculation, although requiring more time, does not greatly increase complexity.

The time-history approach does require more analyst and computer time. We estimate that it costs twice as much to perform as either of the approximate methods. However, the total dollar cost for floor spectra would still be a very small fraction of the value of a NOFFP.

Fig. 28. Ratio of approximate to time-history floor spectra, vertical motions, soft soil.

Fig. 29. Ratio of approximate to time-history floor spectra, vertical motions, hard soil.

CONCLUSIONS

Our study indicates that the time-history method of generating floor spectra is the most suitable method for fuel fabrication facilities and other installations of similar value and importance. The basis of this conclusion can be summarized as follows:

1. The approximate methods may yield floor spectra that are

3-to-4 times the time-history spectra at some frequencies.

2. Methods for generating the synthetic ground motion required by the time-history method are becoming widely available.
3. The time-history method results in a minor increase in complexity and a cost increase that is minute compared to the project cost.

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Appendix

Description of the Kapur and Biggs Approximate Methods

Before describing each method, a definition of terms is necessary. It should be noted that for clarity and uniformity we have changed some of the terminology used by the two authors. However, the mathematical intent is preserved exactly. Quantities required as input to the two methods are:

f_{1n} = nth natural frequency (Hz) of the building. (All first subscripts "1" and "2" refer to the building and equipment, respectively).

f_2 = equipment frequency.

Γ_{1n} = modal participation factor for mode n.

ϕ_{sn} = mode-shape value for mode n at modal point where equipment is supported.

S_{1gn} = acceleration value from response spectrum of free-field ground motion at building frequency, f_{1n} , and damping, ξ_1 .

S_{2g} = acceleration value from response spectrum of free-field ground motion at equipment frequency, f_2 , and damping, ξ_2 .

S_g = maximum ground acceleration of the free-field ground motion.

Output quantities defined (that is, floor spectra for equipment analysis) are:

S_{2n} = contribution of the nth building frequency to the equipment response spectrum at equipment frequency, f_2 .

S_2 = acceleration value of the approximate floor spectrum obtained by summing the S_{2n} in an appropriate manner.

KAPUR'S APPROXIMATE METHOD

For each equipment frequency of interest, f_2 , perform the following:

1. For each significant building frequency, n:

a. If $\frac{f_{1n}}{f_2} \leq 0.9$, then S_{2n}

= $\phi_{sn} \Gamma_{1n} A_1 S_{1gn}$, where

$$A_1 = 1 / \left(1 - \frac{f_{1n}}{f_2} \right).$$

b. If $0.9 < \frac{f_{1n}}{f_2} < 1.10$, use the

equation for S_{2n} above where

A_1 is taken from the appendix in Ref. 3. The value of A_1 depends on the structure and equipment damping and is not listed in Ref. 3 for $\xi_1 = 0.04$ and $\xi_2 = 0.005$. Enough values are provided so that it may easily be extrapolated. We determined A_1 to be 23.0 for 4 and 0.5% structure and equipment damping.

$$\begin{aligned} \text{c. If } \frac{f_{1n}}{f_2} \geq 1.10, \text{ then } S_{2n} \\ = \phi_{sn} \Gamma_{ln} \left[A_2 (S_{1gn}^2 - S_g^2)^{1/2} \right. \\ \left. + S_{2g} \right], \text{ where } A_2 \\ = 1 / \left(\frac{f_{1n}}{f_2} - 1 \right). \end{aligned}$$

If, however, the lowest building frequency, f_{11} , is such that

$\frac{f_{11}}{f_2} \geq 1.1$, then S_{2n} is calculated in a different manner:

$$S_{2n} = \phi_{sn} \Gamma_{ln} A_2 (S_{1gn}^2 - S_g^2)^{1/2}.$$

2. When S_{2n} has been calculated for all the significant building frequencies, the contributions are summed as follows:

If, in step 1c above $\frac{f_{11}}{f_2} \geq 1.1$,

$$\text{then } S_2 = \left[\sum_n S_{2n}^2 \right]^{1/2} + S_{2g}.$$

If $\frac{f_{11}}{f_2} < 1.1$, then

$$S_2 = \left[\sum_n S_{2n}^2 \right]^{1/2}.$$

Kapur recommends that for closely spaced building modes, "the absolute sum of the closely spaced modes should be obtained before taking the square root of the sum of the squares with the other modal responses." In our study, we found closely spaced modes in the vertical floor-spectra calculations. We therefore took Kapur's recommendation and followed the guidelines set forth in Regulatory Guide 1.92 for combination of modes.¹⁹

BIGGS' APPROXIMATE METHOD*

For each equipment frequency of interest, f_2 , do the following:

1. For each significant building frequency, n :

a. If $\frac{f_{1n}}{f_2} < 0.90$, compute

$$S'_{2n} = \phi_{sn} \Gamma_{ln} S_{1gn} A_3, \text{ where}$$

*For the reader who decides to refer to Biggs' paper (Ref. 14) it is worthwhile to point out a typographical error in that document. In our copy of this paper, on page 333, the author's references to his Figs. 2 and 3 have been reversed [that is, step 2(A) should refer to Fig. 3 and step 2(B) should refer to Fig. 2].

A_3 is read from the author's Fig. 3 and our Fig. A-1. One enters the plot with the frequency ratio f_{1n}/f_2 and determines the corresponding amplification factor.

b. If $\frac{f_{1n}}{f_2} > 0.50$, compute

$$S_{2n}'' = \frac{\phi_{sn} \Gamma_{1n}}{C} A_2 S_{2g}, \text{ where}$$

the value of A_2 is read from the author's Fig. 2 and our Fig. A-1. The value of C is determined as follows:

$$\text{If } \frac{f_{1n}}{f_2} \leq 1.25, C = 1.0.$$

Fig. A-1. Biggs' amplification factors.

$$\text{If } 1.25 < \frac{f_{1n}}{f_2} < 2.25, C = 1.0$$

$$+ \left(\frac{f_{1n}}{f_2} - 1.25 \right) \times \left[\left(\sum_n (\Gamma_{1n} \phi_{sn})^2 \right)^{1/2} - 1.0 \right].$$

$$\text{If } \frac{f_{1n}}{f_2} \geq 2.25,$$

$$C = \left[\sum_n (\Gamma_{1n} \phi_{sn})^2 \right]^{1/2}.$$

$$c. \text{ If } \frac{f_{1n}}{f_2} \leq 0.50, S_{2n} = S_{2n}'.$$

$$\text{If } \frac{f_{1n}}{f_2} \geq 0.90, S_{2n} = S_{2n}''.$$

$$\text{If } 0.50 < \frac{f_{1n}}{f_2} < 0.90,$$

$$S_{2n} = S_{2n}' + (S_{2n}'' - S_{2n}') \times \frac{\frac{f_{1n}}{f_2} - 0.50}{0.40}.$$

$$\times \frac{\frac{f_{1n}}{f_2} - 0.50}{0.40}.$$

2. When S_{2n} has been calculated for all building frequencies of interest, Biggs recommends an SRSS sum to get the total spectral value, S_2 :

$$S_2 = \left(\sum_n S_{2n}^2 \right)^{1/2}.$$

However, we followed the recommendation in Regulatory Guide 1.92 for closely spaced modes, just as we did in using Kapur's method.