TESTIMONY OF JAMES P. KNIGHT

CONCERNING CONSERVATISMS IN SEISMIC DESIGN

SKAGIT NUCLEAR GENERATING STATION

Introduction

In this testimony I will briefly describe the seismic design process for nuclear power plants, with emphasis on uncertainties and compensating conservatisms employed in the design of structures, systems and components important to safety.

General

Seismic design of nuclear power plants requires interaction between two principal endeavors: (1) definition of seismic hazard, in terms of intensity and characteristics of shaking, and (2) design of structures, systems and components to resist the defined seismic shaking.

The definition of seismic hazard involves consideration of the geologic features of the plant site, observed and recorded ground motions related to these geologic features, and observed and recorded structural response to earthquakes. The information available from historic earthquake records, measurements recorded in more recent years, insights that can be gained from various types of analyses and damage assessment following earthquakes must be synthesized to arrive at the engineering methodology that will yield optimum design parameters for the plant in question. The optimum parameters are those that yield adequate seismic resistance while not adding unnecessary restraint to systems that must remain free to accommodate the thermal and other movements inherent in normal operation, or unnecessary structural supports that impede normal operation and inspection.

Much of the discussion that has taken place on this record seems to stem from the conviction of some parties that the adequacy of the seismic resistance finally achieved for the Skagit plant hinges on the absolutely certain definition of the geology of the area, presumably so that seismic input can be defined in equally absolute terms. Such absolutes are neither realistically obtainable nor necessary. Clearly, different experts have different opinions about a number of the geologic features at the Skagit site. Whether or not these differences exist, or whether there are means to dispel existing doubts, the importance of the fundamental question remains: Is there sufficient knowledge at hand to determine a seismic design basis for use in the normal design process for a nuclear power plant? As discussed in the Staff Safety Evaluation Report, the weight of evidence has compelled the Staff and their expert advisors to agree that a seismic design basis that is described by Regulatory Guide 1.60 spectra scaled to a reference acceleration of 0.35 g at 33 Hz is in fact conservative for design purposes. Beyond that finding, that encompasses the geologic and seismologic uncertainties, is a design process that brings to bear another set of uncertainties and compensating conservatisms with the balance set heavily to the conservative side.

The entire seismic design process for nuclear power plants is developed on the basis that the definition of seismic input be a reasonable one to be used in conjunction with conservatively developed seismic capacity of structures, systems and components. This same philosophy is the cornerstone of seismic design for all critical structures, e.g., hospitals, schools and dams, albeit the conservatisms employed in both definition of seismic hazard and structural design and the overall definition of seismic risks for nuclear power plants would be considered excessive in most other applications.

As discussed below the margins between design capacity and actual capacity of structures, systems and components, that accrue from use of standard design procedures, are very substantial. In the future (a decade or more) more sophisticated procedures that take into account the actual energy absorbing capability of engineered structures will become standard engineering practice. At that time I believe that these margins can and will be reduced as definitions of seismic and other loading become more precise.

Analysis

The seismic input, once defined, is used in a mathematical process to determine how the structure would vibrate in response to the seismic shaking. In order to perform these analyses, structures[1/] are characterized in a mathematical model by means of the mass of the major parts (floors, walls, domes, etc.) and the stiffness of the connections between these parts. The stiffness is usually characterized as a spring, and we therefore commonly speak of a spring-mass model.

Through the use of proven and common principles of applied mechanics and mathematics, the design earthquake motion is applied to the mathematical model and the response of each of the major portions of the structure to that motion as well as the response of the structure at the mounting location of safety-related systems and components, is defined for design purposes.

Throughout this process, as noted above, complex structures are characterized by fundamental characteristics, such as mass and stiffness; idealization

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1/ For purposes of this discussion buildings, frames, piping, equipment etc. are all considered structures since the same analytical approaches and methods apply to all these items.

of the various structural parts allows the analysis to be performed using standard analytical techniques thus reducing design time. In compensation for these idealizations, a principal part of the engineering practices involved is the use of techniques which consistently yield a conservative estimation of the various physical quantities being represented. In the analytical process these physical quantities interact in complex ways. In order to achieve overall conservatism, it is standard engineering practice to establish a conservative quantity at each stage in the analytical process so that the contribution of these conservatisms are multiplicative.

For example, typical engineering analyses performed for nuclear power plants assure that all elements of the structure or equipment remain elastic or nearly so, i.e., allowable stresses are held near the minimum specified yield point of the material so that permanent deformations are very small and can be neglected. One of the principal reasons for this is that the maintenance of elasticity negates the need for complex inelastic analyses albeit the inelastic analyses would demonstrate that the structure or item of equipment had far greater seismic capacity than the elastic analyses would show. From the standpoint of function, major structures and components in nuclear plants, as well as in other commercial applications, can tolerate much inelastic deformation and typically the loss of numerous structural members. This deformation and loss of structural members can be sustained because of load sharing or redistribution, i.e., as the structure moves in response to the shaking from an earthquake, the loads assigned to various members in the analyses are actually redistributed among other members as small deformations take place and redundancy, i.e., more than one structural member is actually available to carry a given load (even though for design purposes only the primary member is considered to act).

Design

The design of the various structural parts is then based upon the results of the analyses characterized above. There is a common misconception that the design of the structural elements is such that the capacity of those elements just meets the requirements called for by the analyses. In fact, much of the structural design is controlled by the size of standard structural members such as reinforcing rods and beams, and construction requirements such as access to make large concrete pours. The end result is that each member is usually the next larger standard size above the member size calculated as necessary by the analyses.

Further, when the designer calculates required structural member sizes it is assumed that the material strength available in the members are those given in the appropriate design code. Engineering design codes specify "code minimum strength" for materials. These code minimum strengths are in turn specified by the applicant when the materials are ordered; any material found to be under that strength when delivered is rejected. The result is that the material supplier, in order to assure that he stands no risk of having costly material returned, provides material of considerably higher strength. The fact that these higher strengths almost inevitably occur are born out by the mill test reports for steel and concrete cylinder tests that have been taken by the thousands at various nuclear power plants (as well as at other commercial projects). There is normally no motivation to go back and assess the true strength of various structures, systems and components, because the costs of reanalysis and construction time lost while waiting for reanalyses and redesign usually swamps any reduction in costs or equipment capabilities that may be gained.

Testing

The testimony above cites the numerous conservatisms resulting from standard analytical techniques and use of standard structures, shapes, sizes and materials. A very analogous phenomena occurs in the testing of the equipment and components. The seismic energy that reaches an item of equipment or component is filtered through the building in which that equipment or component is mounted. That is to say the building is shaken at its foundation by the movement of the earth but does not transmit the shaking directly to equipment or components; much of the energy available at some frequencies is absorbed by the building and amplification occurs at other frequencies. An integral part of the structural analysis is the determination of the building response at the mounting location of essential equipment and components. The motion thus determined then becomes the "ground" motion for the analysis of that item of equipment or component. However, the conservative assumptions noted above that over predict the forces and loads acting on the structure and underpredict the strength of the structure lead to over prediction of structural response; i.e. the movement, of the structure at equipment and component mounting locations. The basic test requirements that are specified for each item of equipment or component start from this conservative basis and then build up additional conservatisms throughout the process as discussed below.

In order to assure fully representative testing with respect to both direction and characterization of vibratory input, a given piece of equipment is subjected to a large number of individual tests each one in excess of the most likely vibration to be seen by the equipment in any single actual earthquake (by virtue of the conservatisms embodied in the development of the test requirements as discussed above). The number of tests typically range from 10 to 50 before a program for an individual piece of equipment is completed. In addition, as a practical matter, there is inevitably margin between the maximum test level survived by the equipment and the actual capacity of the equipment. It is the Staffs' practice to require that equipment considered qualified for seismic service must perform in its completely normal mode during the height of the test shaking. For instance, electrical or electronic equipment must be energized and must exhibit no anomalous behavior or signs of degradation during the test sequences. The tests are typically run only up to the required level of shaking for a particular application so that the actual capacity is somewhere above even the conservatively defined test levels.

The end result of the conservatisms employed in the analyses compounded by the conservatisms resulting from standard design and testing practices is structures, systems, components and equipment, with seismic capability well in excess of the established design goal. The accumulation of the conservatisms cited above will vary with the actual location in various structures, systems and components. Various studies have placed these accumulations at a minimum of 2 to over 20 times the calculated seismic capacity of individual members, structures and components. The most recent and perhaps most definitive of these studies, Newmark and A. Cornell, 1978[2/] estimates that a median factor of safety in the range of 4 to 8 results as a consequence of current seismic design practices for nuclear power plants.

As a result of these conservatisms the record is replete with cases where well-engineered structures, even those for which no specific seismic design standard was invoked, have withstood major earthquakes that far exceeded the design estimated capacity while remaining fully functional.

A sample of actual case histories follows. Only electric generating stations and a refinery are cited here but the results are typical of the performance of all types of well engineered commercial structures.

LONG BEACH STEAM STATION

This station was located on Terminal Island in Long Beach, California, about four miles from the fault that caused the Long Beach earthquake on March 10, 1933. This earthquake was of magnitude 6.3 and caused accelerations at the site of the steam plant estimated to be about 0.25 g. Damage in Long Beach itself was very extensive.

Part of the station was built in 1922, and the remainder was built in 1928. A total of five units were in operation at the time of the earthquake. The plant structures were designed for lateral static forces of 0.2 g. (Current nuclear plants are designed for simultaneous vertical and horizontal forces by full

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[2/] "On the Seismic Reliability of Nuclear Power Plants," C. A. Cornell and N. M. Newmark, May 1978.

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dynamic analyses). Foundations of both plants were heavily reinforced concrete mats supported by wooden piles 50 to 60 feet long driven to hard sands. No information is available on seismic design of the piping and equipment, but considering the state of the art it is possible that the 0.2 g static design was used, but very likely that seismic design was not considered.

None of the five units suffered any significant damage. Some minor damage such as to lighting fixtures was reported; however, the steam plants either operated through the earthquake or were shut down due to loss of load and were back in operation the same day. The important point is that five steam units designed with at most static methods to a 0.2 g level (probably nothing for systems and components) experienced 0.25 g and were undamaged and fully operational, i.e. all systems and instruments required for operation were functional. Design by todays dynamic methods would yield capacities often from 2 to 20 times those obtained by simple static methods.

KERN COUNTY STEAM STATION

This oil fired 60 Mw steam plant was designed and built in 1947-8. It is located on the Kern River near Bakersfield, California, about 25 miles from the epicenter of the July 21, 1952 Kern County earthquake.

This earthquake, sometimes referred to as the Taft, the Tehachapi, or the Arvin-Tehachapi, was of magnitude 7.7. It was the most severe earthquake recorded in the continental United States since that of 1906 in San Francisco.

The structures of the plant were designed for 0.2 lateral load on a simple static basis. This is one of the first electric power plants to have some piping (steam and feedwater lines) designed by dynamic analysis, however, the amplification factors were well below what would be required for nuclear plants by todays NRC practices.

An acceleration record obtained at Taft, California was further from the epicenter than the Kern County Plant. Maximum acceleration recorded at Taft was 0.17 g and it was estimated that ground acceleration at the plant site was over 0.25 g. The plant operated through the earthquake with no significant damage. It was shut down after the earthquake due to loss of load but was returned to service in a few hours. There was some minor damage to oil tank seals and a small house turbine thrust bearing, but no damage at all to piping systems.

THE CHUGACH ELECTRIC COMPANY PLANT

The Alaska Earthquake of 1964 was of 8.4 magnitude and was the largest recorded earthquake of modern times. It was centered east of the city of Anchorage, near the town of Valdez. There was widespread destruction through the area, not only from earth vibration, but from tsunami, the failure of poor soils and fire.

The Chugach Electric Company Plant in Anchorage, a fossil fueled plant of about 50 Mw, was built between 1949 and 1957. The plant was designed to 0.1 g by the Uniform Building Code (static method). (For comparison, a reference acceleration of .75 g was required for a magnitude 7.5 earthquake at the Diablo Canyon Plant). There was no damage in the turbine room nor to piping and critical equipment. There was minor damage in the boiler room consisting of bending of some bracing members and appreciable damage to framing supporting the coal bunders. Many piping hangers on the main steam lines were broken, but the piping itself (fluid systems analogous to those important to safety in a nuclear power plant) was undamaged.

ESSO REFINERY

An earthquake of magnitude 7.5 struck Managua, Nicaragua on December 23, 1972. There was much damage and great loss of life. The loss of life was largely unrelated to damage of industrial buildings and facilities since the earthquake occurred near midnight.

A complete accelerograph record was obtained at the ESSO refinery in Managua. The peak measured acceleration was 0.39 g E-W and 0.34 g N-S. The design of the refinery met provisions of the Uniform Building Code for 0.2 g (static method) including tall fractionating towers, some of which exceed several hundred feet. There was almost no damage at the refinery and none to the piping systems. Some piping jumped out of saddle supports and was pushed back into place. The facility was shut down for an inspection but was operating at full capacity within 24 hours even though there was a loss of offsite power. The similarity of the systems, components, instrumentation and equipment at a refinery and a nuclear power plant and the fact that a refinery, because of the much higher pressures and extreme flammability of the fluids and gases being handled is far more sensitive to small leaks and systems abnormalities than is a nuclear power plant make this a particularly good case in point.

Conclusion

The Staff has completed an extensive review of the geologic and seismologic factors that determine the selection of a seismic design basis for the Skagit site. Although there are, as there inevitably will be, some aspects of those factors that cannot be defined with absolute certainty, the Staff and their expert advisors believe that all the information necessary to make a finding has been developed. This finding goes beyond the myriad details that would constitute an absolute categorization of every geologic and seismologic factor to a deep understanding of the very nature of the region developed by studies conducted over the last five years or so.

The end product of the Staff review is the finding that a seismic design basis described by the Regulatory Guide 1.60 spectral shape anchored at a reference acceleration of 0.35 g at 33 Hz is a conservative design basis encompassing the geologic and seismologic uncertainties. This seismic design basis is the input to a design process that is itself replete with conservatisms. The source of these conservatisms are well recognized and present at each stage of the design process. Numerous studies of the performance of well engineered structures, systems and components under seismic load, even those for which no seismic design basis or woefully inadequate bases by present standards were specified, offer bountiful proof that the conservatisms cited do in fact exist. These same studies have shown that the cited conservatisms are particulary effective in reducing the seismic response of structures, systems and components analogous to those important to safety at a nuclear power plant.

Professional Qualifications

James P. Knight

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Division of Systems Safety

I am Assistant Director for Engineering responsible for the review and evaluation of design criteria to ensure the integrity of structures, systems and mechanical components, criteria for materials selection and use, the dynamic analyses and testing of safety related structures, systems and components, the geological and seismological review of reactor sites and review of seismic design bases, criteria for protection against the dynamic effects associated with natural environmental loads and postulated failures of fluid systems for nuclear facilities. In this capacity I am responsible for the activities of the Structural Engineering Branch, Materials Engineering Branch, Mechanical Engineering Branch and the Geosciences Branch (geology, seismology and geotechnical engineering).

I received a B.S. Degree in Mechanical Engineering from Northeastern University in 1957. Since that time, I have completed the equivalent of approximately 35 semester hours at the graduate level in structural dynamics, nuclear engineering and fracture mechanics at the Massachusetts Institute of Technology, Lehigh University and the George Washington University.

From June 1957 to September 1959 I served as a commissioned officer with the U. S. Army Corps of Engineers.

From September 1959 to October 1963 I was employed by the Special Products Division of the American Machine & Foundry Company, Alexandria, Virginia.

In the latter period of this experience, I had full responsibility for design concept, material selection and analytical review for critical components of high speed spin test equipment, re-entry simulation systems and spin stabilization test systems for manned and un-manned spacecraft.

In October 1963, I joined the Reactor Radiations Division at the National Bureau of Standards. During this period, I was responsible for the mechanical and structural design, testing and certification of the NBSR core elements, control rod drive mechanisms, high level radiation handling equipment and structures to support reactor components and major experimental facilities. I was also fully responsible for the analytical review and experimental certification of the NBSR reactor vessel and a variety of experimental equipment to the requirements of the ASME Boiler and Pressure Vessel Code. In early 1967, I was appointed Chief of the Engineering Services Section responsible for all structural, mechanical and electrical engineering design services for both the NBSR facility and experimental equipment development. Following receipt of the NBSR operating license, I was appointed Vice-Chairman of the NBSR Hazards Committee responsible for review of the mechanical and structural hazards for all experiments proposed for insertion in the NBSR.

In September 1968, I joined the U. S. Atomic Energy Commission and have remained with this organization through the transition to the U. S. Nuclear Regulatory Commission. In 1973 I was appointed Chief of the Mechanical Engineering Branch. In 1976 I was appointed to my present position. During this time, I have participated in the review and evaluation of over fifty

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construction permit and operating license applications and participated in the review and planning activities for Government and industry sponsored programs such as the Heavy-Section Steel Technology Program, development of the B31.7 Nuclear Power Piping Code and the ASME Nuclear Component Code.

I have served as a member of numerous industry code and standards writing bodies including: the ASME Section III Subgroup on Pressure Relief, the ASME Section III Working Group for Design of Valves, the ASME Section III Working Group for Design of Pumps, ANSI B16 Subcommittee N - Steel Valves, ANSI B16 Subcommittee H - Valve Operability and ASME Subcommittee on Qualification of Nuclear Plant Equipment.