lower bound friction cases are usually analyzed. Analyzing every possible combination is usually prohibitively expensive, so engineering judgment must be applied to limit the number of load cases. However, due to the system complexities and nonlinearities, bounding cases may be difficult to identify.

RECOMMENDATIONS FOR FURTHER RESEARCH

Our review of the various analysis methods suggests that additional research could provide greater confidence in the analysis methods by reducing the levels of uncertainty. Such research could provide valuable information which could be used to allow the use of more reasonable acceptance criteria and define clearer regulatory guidance to expedite the licensing process. Suggested areas of research include the following;

- o Experimental verification of hydrodynamic mass coupling parameters in a multibody environment
- o Experimental verification of nonlinear modeling parameters
- o Experimental studies to define increased damping due to fluid immersion and component impacts
- o Parametric studies to assess the sensitivity of response to variations in model parameters
- o Analytical studies to define guidelines for requiring multiple rack model analysis
- o Analytical studies to develop guidelines for defining bounding load cases
- o Analytical studies to define acceptance conditions for simplified analysis including linear and two dimensional analysis
- o Analytical studies to define guidelines for multiple fuel assembly modeling
- o Scale model testing of multiple free standing fuel racks in a pool of water

CONCLUSIONS

As the storage capacities of spent fuel pools are expanded to accommodate the growing inventories of spent fuel, it becomes increasingly important to assure adequate design safety margins. Additional research into the seismic behavior of free standing fuel racks could contribute significantly toward the verification of existing analysis methods, the development of more realistic approaches, and the development of more reasonable regulatory guidelines and acceptance criteria.

REFERENCES

Code of Federal Regulations, Title 10, Part 50 Appendix A, "General Design Criteria for Nuclear Power Plants."

U.S. Nuclear Regulatory Commission, Letter to All Power Reactor Licensees B.K. Grimes, April 14, 1978, "OT Position for Review and Acceptance of Spent Fuel Storage and Handling Applications," as amended by NRC letter dated January 18, 1979.

U.S. Nuclear Regulatory Commission Standard Review Plan, Section 3.8.4 Appendix D, "Technical Position on Spent Fuel Pool Racks," NUREG-0800, July 1981.

NOTICE

on simplifying assumptions. There is no experimental data known to the authors to verify the accuracy of the methods used.

Gaps: Compression-only springs are used to model the gap interfaces at the fuel to storage cell and support leg to pool floor locations. These elements are also used between adjacent racks and between racks and pool walls when large displacements are anticipated. Methods used to calculate the impact spring stiffness vary significantly. Some vendors have performed sensitivity studies and found that under certain conditions, the results could be quite sensitive to stiffness variations.

Friction: Coulomb friction elements are used at the rack support leg to pool floor interface. These elements behave like stiff springs until the force reaches a limiting value equal to the specified friction coefficient times the normal force. Most vendors assume a constant friction coefficient and ignore differences between static and dynamic values. Separate analyses are usually performed to consider upper and lower limits on the friction coefficient. Thus a maximum "sliding" case and maximum "rocking" case are considered. Average friction values are generally not used.

Multiple Rack Interactions: Most fuel racks have been analyzed using single rack models. However, since the motion of a rack affects adjacent racks through hydrodynamic coupling, a single rack model analysis must make assumptions regarding adjacent rack motion. Adjacent racks have been assumed to move either in-phase or out-of-phase with the rack being analyzed. Different vendors have presented different arguments including: 1) In-phase motion assumption is appropriate because of the strong fluid coupling between racks 2) Out-of-phase motion assumption is conservative because it maximizes impact forces between adjacent racks, and 3) the case which gives a rack frequency closest to the seismic response spectrum peak is most conservative. For strong seismic motion, the problem is further complicated when racks impact each other and the pool walls and additional interaction forces are introduced into the system.

Fuel Assembly Representation: The composite structural properties of all the fuel assemblies in a rack are represented by a single stick model as shown in Figure 3. It is usually assumed that all fuel assemblies in a rack module will move in phase. However, some vendors have argued that since the fuel will not move exactly in unison, only a fraction of the total fuel mass should be included in the model. Although this argument has some merit, further study is needed to verify this approach.

Three Dimensional Effects: Many fuel rack vendors have used two dimensional planar fuel rack models to perform seismic analysis. The three directional seismic input loads would be applied in separate load cases, and the resulting codirectional responses would be combined by the square root of the sum of the squares (SRSS) method. Although the regulatory documents may suggest that this approach is acceptable, the general applicability of this procedure for the analysis of free standing racks is questionable. A planar model cannot account for torsional response of a rack about the vertical axis. This response may be especially significant when a rack tilts and lifts off with only one corner support leg remaining in contact with the floor. Furthermore, unless the three directional seismic components are applied simultaneously, nonlinear phenomena such as sliding may not be accurately predicted. Two dimensional analysis may be adequate for low seismic levels but further study is needed to make this judgment.

Load Cases: Various possible fuel rack configurations must be considered in a seismic evaluation. A pool will generally contain rack modules of different sizes. The gaps between adjacent modules and pool walls vary. Any module can be filled with fuel, partially filled or empty. The fuel in partially filled racks may be uniformly or eccentrically distributed. In addition, upper and sometimes at the rack to rack or rack to pool wall interface nodes. Gap and friction elements are used at the support leg to pool floor interface nodes. Fluid effects are accounted for through the use of hydrodynamic mass coupling elements.

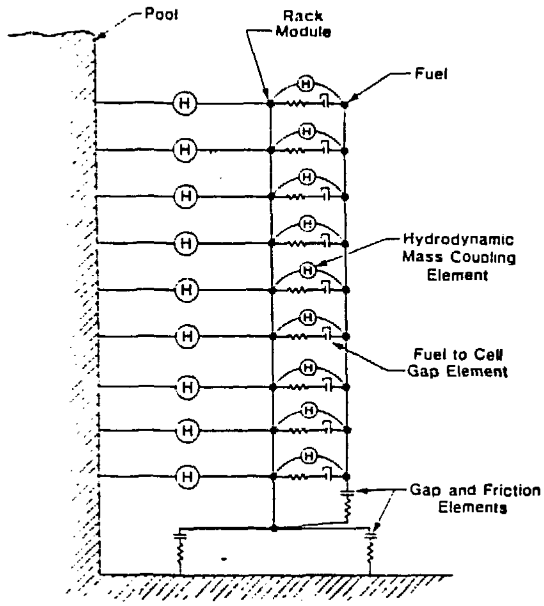

Figure 3. Typical Single Rack Dynamic Model

Rack vendors use various approaches in developing the dynamic model properties. Some vendors develop a separate detailed finite element static model which can be used for both the derivation of equivalent mass and stiffness properties and also for the detailed stress analysis. Regardless of the method used, simplifying assumptions must be made to develop a model with a reasonable number of degrees of freedom to predict the seismic response of the fuel rack system. The assumptions are discussed in greater detail in the next section.

The nonlinear seismic analysis is performed by applying the pool floor seismic time history motion to the model. Direct integration methods are generally used to perform the analysis. Some vendors use nonlinear modal superposition methods. The analysis results provide internal forces, impact loads, and displacements. These results are then used to calculate maximum stresses which are combined with stresses from other required loads to complete the structural evaluation.

DISCUSSION AND COMMENTS ON ANALYSIS METHODS AND ASSUMPTIONS

The methods currently used by fuel rack vendors to consider fluid immersion, nonlinearities, and other effects are discussed below.

Fluid Effects: The inertial effects of water on the vibrating structures are considered while fluid damping and sloshing effects are generally ignored. Hydrodynamic mass coupling elements are used in the finite element stick model (Figure 3) between fuel assembly and storage cell nodes, and between fuel rack and pool wall or adjacent rack nodes. These elements provide added mass (diagonal) terms and inertial coupling (off-diagonal) terms to the system mass matrix. This affects the frequency of the system and couples the motion of the fuel assemblies, rack modules, and pool walls. The methods used to determine the hydrodynamic mass element parameters are varied. They are generally based on flow models which assume incompressible, inviscid flow (potential theory). For simple systems, such as concentric cylinders with small vibration amplitude, experiments have shown good agreement with this theory. For the more complex multibody fuel rack system, the formulation is much more complex and must rely

LICENSING REQUIREMENTS AND ISSUES

When a utility decides to expand the storage capacity of its existing fuel pool, it must apply to the NRC for a license amendment. As part of the licensing process, the utility must demonstrate that the fuel pool modification meets the requirements specified in the General Design Criteria 61 and 62 of Title 10, Part 50 Appendix A of the Code of Federal Regulations. These regulations require fuel storage systems to be designed to assure adequate safety under normal and postulated accident conditions and to assure that criticality is prevented. NRC documents which provide guidance for implementing the basic regulations in terms of structural design requirements are the "OT Position for Review and Acceptance of Spent Fuel Storage and Handling Applications" published in 1979 and USNRC Standard Review Plan 3.8.4, Appendix D published in 1981. These documents provide overall design requirements such as loads, load combinations, applicable codes and structural acceptance criteria.

The free standing high density fuel rack design concept is not a new one and many plants have been licensed to use them. However in recent years, due to delays and the uncertainty in the schedule for a permanent storage repository, many plants have undergone a second generation of reracking, replacing high density racks with maximum density racks. Spent fuel pools which were originally designed to store a few hundred fuel assemblies are being reracked to store several thousand fuel assemblies. Utilities are also preparing to consolidate their spent fuel by using special containers which can store twice the fuel in the same volume as that of a single fuel assembly. Storage of consolidated fuel in high density racks will place even greater demands on the structural capacity of the racks and pool.

In recent years, the NRC staff has been reviewing high density spent fuel rack license applications in detail to assure that adequate safety margins are maintained. Increased public awareness and concern about the storage of larger quantities of radioactive material at plant sites has further highlighted the need to ensure conservative design practices. Because the current high density rack designs are free standing, particular attention has been focused on the adequacy of seismic analysis methods. Recent NRC licensing reviews have resulted in several rounds of requests for additional information usually involving additional analyses to verify the original design calculations. Due to the perceived high level of uncertainty in the analysis, NRC acceptance has generally been based on demonstration of ample safety margins.

DESCRIPTION OF CURRENT SEISMIC ANALYSIS METHODS

Evaluation of spent fuel racks for seismic loading is more complex than for most other nuclear plant structures. The analysis of free standing racks is complicated by their submersion in water and the presence of various nonlinearities. The presence of water affects the dynamic response of the racks and spent fuel assemblies. As the structures vibrate, the surrounding fluid is accelerated inducing added mass effects and fluid coupling forces between structures. Sources of nonlinearities in the fuel rack system include gaps and friction interfaces. Gaps exist between fuel assemblies and storage cell walls, between adjacent rack modules, and between rack modules and the pool walls. At the rack base to pool floor interface, both friction due to possible rack sliding and impact due to rack tilting and support leg liftoff must be considered.

Because of the inherent nonlinearities in the fuel rack system, a nonlinear dynamic time history analysis is normally performed to demonstrate seismic adequacy. A fuel rack is generally represented by a simplified finite element stick model of the rack structure and fuel assemblies as shown in Figure 3. The stick model is used to predict the maximum forces and displacements. The model includes a beam element representation of the honeycomb rack structure and fuel assemblies. Gap elements are used at the fuel to cell interface nodes and led to the development and use of the modular free standing fuel rack design concept.

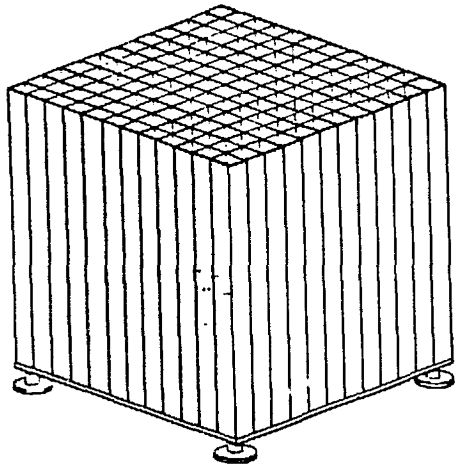

Figure 1. Typical Free Standing Spent Fuel Storage Rack Module

The honeycomb construction type of fuel rack module as shown in Figure 1 is a common design configuration. Design and fabrication details vary with different vendors but the overall design can be described as follows. The module is a welded honeycomb structure which consists of square cross-section stainless steel storage cells. Each cell is designed to accommodate a single spent fuel assembly. A typical module may contain a hundred or more cells. Thin sheets of neutron absorbing material are included in the cell walls. These are typically non-structural elements containing boron material which are either sandwiched between adjacent cell walls or held in place by stainless steel sheaths. The honeycomb structure is welded to a base support assembly which may consist of a base plate with four or more support legs. The legs usually include leveling screws which can be adjusted from the top.

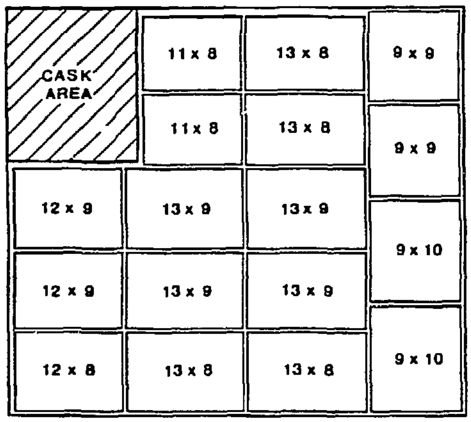

Figure 2. Typical High Density Spent Fuel Pool Module Layout

A high density spent fuel rack installation may include ten to twenty or more modules in a pool. The modules could vary in size and storage capacity. They are usually made as large as possible within the constraints of transportation and site handling capabilities. To maximize fuel storage, they are arranged in close proximity to each other and to the pool walls. Gaps of zero to two inches are common. A typical spent fuel storage module installation layout is shown in Figure 2. This pool can store over 1600 fuel assemblies in 17 free standing rack modules. The figure indicates the storage cell arrays. The smallest module in the pool (9 x 9) accommodates 81 fuel assemblies while the largest module (13 x 9) can store 117 fuel assemblies.

INTRODUCTION

In the early years of nuclear power plant construction in the United States, it was envisioned that after the fuel is used in the reactor, it would be temporarily stored in the spent fuel pool located in a safety-related structure and then shipped to a reprocessing plant where it would be processed to recover the reusable portion of spent fuel. Most spent fuel storage pools were originally designed to accommodate 1 1/3 core of spent fuel in steel storage racks. The racks were typically of open lattice construction with large center-to-center spacing between storage cells to ensure subcriticality of fuel. The racks were usually anchored to embedments in the pool floor and often braced to the pool walls.

With the prohibition on reprocessing of spent fuel in the late 1970's, the pools which were supposed to be short term storage spaces became quasi-permanent storage spaces for the spent fuel. Recognizing a need to provide permanent storage facilities for such nuclear wastes, the U.S. Congress enacted a law cited as the Nuclear Waste Policy Act of 1982. The Act, in essence, required the Department of Energy to find ways for long term storage of high level waste. However, it also required the owners of nuclear power plants to provide for interim storage of their spent fuel. The permanent government owned repositories are not scheduled to be operational until the year 2005.

In order to accommodate the increasing inventory of spent fuel, the U.S. utilities started looking for various means to store spent fuel at the reactor sites. One of the most economical ways to accommodate more spent fuel is to arrange storage locations as closely as possible at the same time making sure that the fuel remains subcritical and that there are adequate means to cope with the heat load. The free standing high density rack configuration is an outcome of efforts to accommodate more fuel in the limited space.

RACK DESIGN DESCRIPTION

High density fuel racks maximize the storage capacity of a spent fuel pool by minimizing the center-to-center spacing between fuel storage cells. In order to maintain subcriticality, neutron absorbing materials are built into the cell walls.

Since many high density fuel racks have been installed as replacements to existing fuel racks, ease of installation has been a critical design requirement. Radiological safety considerations, the need for rack installation in water, and the difficulties of matching rack supports with existing fuel pool embedments

CONF-890855--43

BNL-NUREG-42667

DESIGN AND ANALYSIS OF FREE-STANDING SPENT FUEL RACKS IN NUCLEAR POWER PLANTS (AN OVERVIEW)

H. Ashar
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555 U.S.A.

BNL-NUREG--42667

DE89 012667

G. DeGrassi
Brookhaven National Laboratory
Upton, N.Y. 11973 U.S.A.