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Review of the Technical Basis and Verification of Current Analysis Methods Used to Predict Seismic Response of Spent Fuel Storage Racks

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ABSTRACT

This report presents the results of a literature review on spent fuel rack seismic analysis methods and modeling procedures. The analysis of the current generation of free standing high density spent fuel racks requires careful consideration of complex phenomena such as rigid body sliding and tilting motions; impacts between adjacent racks, between fuel assemblies and racks, and between racks and pool walls and floor; fluid coupling and frictional effects. The complexity of the potential seismic response of these systems raises questions regarding the levels of uncertainty and ranges of validity of the analytical results.

BNL has undertaken a program to investigate and assess the strengths and weaknesses of current fuel rack seismic analysis methods. The first phase of this program involved a review of technical literature to identify the extent of experimental and analytical verification of the analysis methods and assumptions. Numerous papers describing analysis methods for free standing fuel racks were reviewed. However, the extent of experimental verification of these methods was found to be limited. Based on the information obtained from the literature review, the report provides an assessment of the significance of the issues of concern and makes recommendations for additional studies.

CONTENTS

Figures

EXECUTIVE SUMMARY

This report presents a summary of a BNL literature review on current analysis methods used to predict the seismic response of high density spent fuel racks. Based on the findings, it provides an assessment of the strengths and weaknesses of the analytical methods, modeling procedures and assumptions, and makes recommendations for additional studies.

Spent fuel storage pools were originally designed to provide temporary storage of spent fuel until it could be shipped to a reprocessing plant. The fuel was stored in steel racks with large center-to-center spacing to ensure subcriticality. The racks were typically anchored to pool floor embedments and braced to the pool walls. However, with the suspension of reprocessing and delays in the availability of a permanent storage repository, plant owners have been storing all of their spent fuel on site. In order to accommodate the increasing inventory of spent fuel, the original spent fuel racks have been replaced with high density fuel racks. In the high density rack design, fuel storage cells are arranged in a tight array and neutron absorbing materials are used to maintain subcriticality. For ease of installation and radiological safety considerations, high density racks have been designed as free standing modular structures which are not anchored to the pool floor or walls.

The reracking of a spent fuel pool requires a seismic evaluation of the new racks as well as a reevaluation of the existing pool to accommodate the increased loads. Due to the free standing nature of the racks, their seismic analysis requires careful consideration of complex phenomena such as rigid body rack sliding and tilting motions, impacts between adjacent racks, fluid coupling effects and frictional effects. The complexity of the analysis raises questions regarding the level of uncertainty and range of validity of the results. These uncertainties coupled with the higher loads, have been a source of concern to the NRC staff members responsible for reviewing the structural adequacy of a spent fuel pool reracking license amendment. Fuel rack vendors have developed their own nonlinear time history analysis methods to predict fuel rack seismic response. However, the analysis procedures, modeling methods and simplifying assumptions have varied significantly between the different vendors. The current NRC Standard Review Plan does not provide uniform acceptance criteria or guidelines for assessing the adequacy of these methods.

In order to provide the NRC staff with better guidance in this area, BNL has undertaken a program to investigate the strengths and potential weaknesses of current fuel rack seismic analysis methods. The first phase of the program involved a search and review of the technical literature to identify the extent of experimental and analytical verification of the analysis methods and assumptions. The primary goal of this phase was to identify potentially weak areas where further analytical and experimental studies are needed.

The literature search identified numerous technical papers on the subject of free-standing spent fuel rack seismic analysis. Several investigators presented detailed descriptions of analytical models and methods to simulate the nonlinear dynamic behavior of the racks. Highlights of the methodologies are presented in Section 6 of this report. The analysis methods were based on fundamental principles of structural mechanics and dynamics. In most cases, experimental verification of the results was not provided. Some dynamic tests on scale model fuel racks and their supports had been performed in France and Japan. However, the tests were limited in scope and primarily geared toward the development of seismic base isolation fuel rack support designs.

Recent BNL technical evaluations of vendor analyses supporting reracking license amendment applications had identified a number of areas of concern. These concerns are related to the adequacy of current analytical methods in properly considering multiple rack interactions, fluid effects, friction, impact stiffness, three dimensional effects, damping, load cases, and fuel assembly representation. The literature review revealed that some of these concerns had been investigated by others through analytical studies. A significant concern that was investigated by several authors was the adequacy of current analytical methods to simulate fluid effects. Potential theory is used to develop hydrodynamic mass terms in a mathematical model of a fuel rack system. The theory is based on incompressible, inviscid flow with small deflections relative to size of the flow paths (gaps between adjacent racks). However, in the case of fuel racks, the deflections are often large with gaps between adjacent racks opening and closing under seismic excitation. The literature review identified various studies which analytically demonstrated that potential theory provides conservative estimates of hydrodynamic mass and coupling force. In addition, some of the French experimental work indicated that the theory provides reasonably good agreement with test measurements. Therefore, further analytical studies in this area do not appear necessary.

The literature review found that analytical studies into the significance of multiple rack interaction effects suggest that current single rack analytical models may underpredict seismic response. Analytical studies into the treatment of friction have indicated that the current practice of performing analysis for only upper and lower bound values of friction coefficient may not provide bounding responses. BNL recommends that further analytical studies be carried out to investigate the safety significance of these modeling methods and determine whether revised methods are needed. BNL also recommends that parametric studies be performed to test the sensitivity of response to variations in other modeling parameters and assumptions (e.g., impact stiffness, damping, fuel assembly representation, etc.). These studies will provide additional information to define appropriate modeling practices and will identify sensitive areas for which additional testing is needed. It is anticipated that these studies will help identify and quantify conservatisms as well as potential weaknesses in current analysis methods.

1. INTRODUCTION

Spent Fuel Storage Pools were originally designed to provide temporary storage for fuel until it could be sent to a reprocessing plant. Most pools were built 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 typically anchored to embedments in the pool floor and often braced to the pool walls.

In the late 1970's the U.S. government announced the indefinite suspension of spent fuel reprocessing. Utilities were required to provide for interim storage of their spent fuel until facilities to permanently store nuclear waste material became available. One of the most cost effective ways to provide for additional fuel storage was by increasing the capacity of existing fuel pools. This could be accomplished by replacing the original storage racks with high density fuel racks. These racks were designed to provide maximum storage capacity by minimizing the spacing between storage cells. In order to maintain subcriticality, neutron absorbing materials were built into the storage cell walls. Since high density fuel racks were designed as replacements to existing racks, ease of installation was 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 led to the development and use of the modular free standing fuel rack design.

The use of high density fuel racks placed additional demands on the structural capacity of the existing fuel pools. Both the pool and the storage racks are seismic Category I structures which are required to remain functional during operating basis and safe shutdown earthquake conditions. This means that the fuel racks and the fuel pool shall maintain structural integrity so that fuel separation and leak tight integrity of the pool is ensured. The seismic analysis of free standing fuel rack modules requires careful consideration of several complex phenomena. A free standing rack module is a highly nonlinear structure. During an earthquake, the fuel assemblies can "rattle" inside their storage locations. The modules can slide on the pool floor and potentially impact adjacent modules or pool walls. The racks can tilt and lift off at one or more support pads with resulting pool floor impacts. The rack submergence in water further complicates its motion and requires consideration of hydrodynamic mass and coupling effects.

As utility needs for additional spent fuel pool storage have increased with projected delays in the availability of permanent storage repositories, some plants have already undergone a second generation of reracking. Spent fuel pools which were originally designed to store a few hundred fuel assemblies are being reracked to store several thousand fuel assemblies. Some utilities are planning to consolidate their fuel by using special containers which can store twice the fuel in the same volume as that of a single fuel assembly. The increased loads on the fuel pools can be expected to reduce the original design margins.

The uncertainties associated with the complex nonlinear seismic fuel rack analysis has been a source of concern to NRC reviewers for some time. In 1987, intervenor groups challenged the adequacy of the seismic analysis of the Diablo Canyon high density fuel racks. To address the concerns, the licensee had to perform additional studies to confirm the original analysis. In recent years, NRC staff reviewers have been evaluating high density fuel reracking license amendments in more detail to ensure ample safety margins. In many cases, licensees were asked to perform additional analyses to verify the design calculations.

In order to assist the NRC staff in evaluating future high density fuel rack license amendments, BNL has undertaken a review and evaluation of seismic analysis methods to assess the technical basis, ranges of validity and sensitivity of the analytical methods used to predict the behavior of spent fuel racks under seismic loads. The first phase of this effort has involved a literature review on fuel rack analysis methods with emphasis on identifying the extent of experimental and analytical verification of methods and assumptions. The goal of this review is to identify potentially weak areas that need further investigation and to propose analytical studies to assess the uncertainties in current methods and the need for additional experimental work. The outcome of this program is expected to provide better guidelines for future staff review of fuel rack license amendments and a higher level of confidence in the safety of spent fuel storage systems.

This report presents the results of the literature review and proposes analytical sensitivity studies. The following three sections describe current fuel rack designs, regulatory requirements and analysis methods. Section 5.0 discusses the current issues of concern regarding seismic analysis of the racks. Section 6.0 evaluates the technical basis and verification of analytical methods based on the findings of the literature review. Section 7.0 recommends specific analytical sensitivity studies for the next phase of this program.

2. SPENT FUEL RACK DESIGN FEATURES

A typical high density spent fuel rack module consists of stainless steel storage cells arranged into a welded honeycomb structure as shown in Figure 1. Each cell is designed to store a single fuel assembly. Rack modules can be made in different sizes to fill the space available in an existing storage pool. A typical module may have a storage capacity of a hundred or more fuel assemblies. The modules are arranged in close proximity to each other and to the pool walls as shown in Figure 2. With the installation of high density fuel racks, the total storage capacity of a spent fuel pool can be increased from a few hundred to several thousand fuel assemblies.

Fuel rack design and fabrication details vary between different vendors. Storage cells may be welded directly to adjacent cells at their corners or walls or through intermediate spacer elements. Fuel assembly vertical support may be provided by a single baseplate welded to the honeycomb structure or by individual plates welded to the bottom of each storage cell. Lateral fuel assembly restraint is provided by the cell walls but relatively large gaps exist between the fuel and cell walls (1/4" to 1/2"). A fuel rack module is typically supported on four or more adjustable support feet which rest on the pool floor. Differences in design and fabrication details can result in significant differences in rack module stiffness and natural frequency.

In order to maximize the storage capacity of the spent fuel pool, the rack modules are installed as close as possible to each other and to the pool walls. Gaps between adjacent rack modules in the pool typically range between zero and two inches (See Figure 2). The clearances between the peripheral rack modules and the pool walls are generally larger, typically ranging from two inches to twelve inches or more as shown in Figure 2. The sizes of the gaps are important design parameters because they affect both hydrodynamic coupling forces and impact forces between rack modules and adjacent structures.

3. REGULATORY REQUIREMENTS

Federal regulations covering design requirements for spent fuel storage systems are given in Appendix A of 10CFR50, General Design Criteria 61 and 62. 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. In 1979, the NRC staff issued the "OT Position for Review and Acceptance of Spent Fuel Storage and Handling Applications." This document provided guidance for the type and extent of information needed by the NRC staff to perform the review of licensee proposed modifications of an operating reactor spent fuel storage pool and the acceptance criteria to be used by the NRC staff in authorizing such modifications. The "OT Position" covered the nuclear and thermal-hydraulic aspects of the review; the mechanical, material, and structural aspects of the review; and the environmental aspects of the review. In 1981, a similar version of the mechanical, material, and structural requirements was incorporated into the NRC Standard Review Plan (SRP) as "Appendix D to SRP Section 3.8.4, Technical Position on Spent Fuel Pool Racks." This is the most recent NRC document which provides the minimum requirements and criteria for review of spent fuel racks and associated structures. A summary of the "Appendix D" requirements is given below.

Licensees are required to provide descriptive information of the spent fuel pool and rack. This includes the general arrangements and principal features of the horizontal and vertical rack supports. Methods of transferring loads between the racks and pool walls and floor should be identified. Gaps and sliding contacts should be indicated. Interface loads should be provided. Sketches of the fuel handling system should be provided.

Construction materials should conform to Section III, Subsection NF of the ASME Boiler and Pressure Vessel Code and should be compatible with the fuel pool environment to minimize corrosion and galvanic effects. Design, fabrication and installation of stainless steel fuel racks may be performed based upon Subsection NF requirements for Class 3 component supports.

For plants in which seismic response spectra are not available, the necessary dynamic analyses may be performed using the criteria of SRP Section 3.7 with ground spectra and damping values based on Regulatory Guides 1.60 and 1.61. For plants in which the seismic response spectra are available, the new rack system may be designed using either the existing spectra and damping values or new spectra and damping based on Regulatory Guides 1.60 and 1.61 respectively. The use of existing spectra with Regulatory Guide 1.61 damping is not acceptable.

Seismic excitation should be imposed simultaneously along three orthogonal directions. Peak responses from each direction may be combined by the SRSS method in accordance with Regulatory Guide 1.92. If only one horizontal spectrum is available, the same horizontal spectrum may be applied along each horizontal direction.

The effects of rack submergence in water may be taken into account and will be considered on a case-by-case basis.

Loads generated by the impact of fuel assemblies against the storage cell walls should be considered for local as well as overall effects on the rack walls and supports as well as for potential damage to the fuel assemblies. These loads may be determined from an estimate of the kinetic energy of the fuel assembly at maximum velocity. For loads generated by other postulated impact events, the licensee should provide the significant parameters including mass, velocity, and ductility ratio.

Loads resulting from changes in temperature distributions on the pool and rack structures must be considered. Maximum crane uplift forces must be considered. Accident load combinations must include drops of the heaviest postulated load including a spent fuel cask and fuel assembly. Functional capability and structural integrity must be maintained. Specific load combinations including deadweight, live weight, normal and accident temperature, OBE and SSE and other accident loads are provided.

The licensee is required to provide a detailed description of the mathematical model including the methods to incorporate the effects of gaps, submergence, and sloshing. When pool walls are flexible, a response spectrum analysis is permissible if the highest elevation spectrum is used and relative motion between pool floor and walls is considered.

Structural acceptance criteria for each specified load combination are given in "Appendix D." Acceptance limits for elastic analysis and limit analyses are based on the ASME Code Section III. For impact loading, the ductility ratios to absorb kinetic energy should be provided by the licensee. Minimum factors of safety against sliding and overturning of racks must be 1.5 for the OBE load combination and 1.1 for the SSE load combination. However, the safety factors need not be met if either: (a) sliding is shown to be minimal and impacts between adjacent racks and between racks and walls are prevented and minimum safety factors against tilting are met, or (b) any sliding and tilting motion is contained within suitable geometric constraints and impacts are incorporated.

The fuel pool structures must be reevaluated for the increased loads due to the new or expanded fuel racks. The pool liner leak tight integrity should be maintained or the functional capability of the fuel pool should be demonstrated.

The materials, quality control procedures, and special construction techniques should be described. The sequence of installation of the new racks should be provided including a description of precautions taken to prevent damage to stored fuel during construction. If any welded connections are made between racks and pool liner, the welder and welding procedure must be qualified in accordance with the applicable code.

4. CURRENT ANALYSIS METHODS

In recent years, all spent fuel rack vendors have been demonstrating seismic adequacy of spent fuel racks by performing nonlinear dynamic time history analysis. Detailed methods and modeling practices vary between different vendors, but the general approach is similar and can be described as follows:

A simplified mathematical model of a single fuel rack module is developed using either a special purpose or general purpose finite element computer program. The simplified dynamic model would typically represent the rack and fuel assemblies as two beams with appropriate stiffnesses and mass distributions. Nonlinear compression-only spring elements with gaps are used to represent the gaps and impact stiffnesses at the interfaces of fuel to rack cell, support feet to pool floor and, if necessary, rack to adjacent rack or pool wall. Friction elements are used at the support foot to pool floor interface if rack sliding is anticipated. Hydrodynamic effects are included through the use of either generalized mass or fluid coupling elements which account for added mass and inertial coupling between the fuel and rack cells and between the rack and adjacent structures.

The linear properties of the simplified dynamic model are often determined from a more detailed linear finite element model of the fuel rack. The detailed model may include a finite element representation of the storage cells, base plate and support feet. Effective structural properties for the dynamic model can be determined from the natural frequencies and mode shapes of the detailed model. The same detailed model is often used to calculate component stresses based on loads determined from the dynamic analysis of the simplified model.

Hydrodynamic effects are based on flow models which assume incompressible, inviscid flow (potential theory) and small deflections. The mass matrix of the dynamic model is modified by the addition of added mass (diagonal) terms and inertial coupling (off-diagonal) terms. This accounts for the inertial effects of water on vibrating structures. Fluid damping effects are usually neglected. Since the water couples the motion of adjacent structures, a single rack analysis must make assumptions regarding the motion of adjacent racks. They are generally assumed to move either in-phase or out-of-phase with the rack being analyzed.

Special nonlinear elements representing Coulomb friction interfaces are used to transfer horizontal loads from the rack feet to the pool floor. These elements behave like stiff springs until the spring force reaches a limiting value equal to the friction coefficient times the normal force. Upper and lower limits of friction coefficient are usually considered. Differences between static and dynamic friction coefficients are generally ignored.

Compression only gap spring elements are used at the fuel to storage cell and rack to pool floor interfaces. These elements are also used at rack to rack and rack to pool wall interfaces if significant deflections and impacts are anticipated. Methods for defining and incorporating impact stiffness into the simplified model vary. Testing or detailed analysis may be used. Arbitrary high stiffness values may be used if they can be shown to be conservative.

Synthetically generated acceleration time histories based on pool floor response spectra are generally applied to the dynamic model. One vertical and two horizontal statistically independent floor motions are usually generated and applied simultaneously to the three dimensional dynamic model. In the past, however, most vendors used two dimensional planar models and applied the three directional seismic input loads in separate load cases. The resulting co-directional responses were combined by the SRSS method.

Several load cases are run to cover the variations in fuel rack geometry, fuel loading, location in pool and friction coefficient. Vendors make various judgements to define a limited number of bounding load cases.

The results of the nonlinear time history analyses provide fuel rack loads and deflections. Stresses in critical rack components are determined by applying the controlling loads to a detailed finite element model or by hand calculations when feasible. The seismic stresses are included in the appropriate load combinations and evaluated in accordance with the acceptance limits of SRP 3.8.4 Appendix D. Impact loads on the fuel assemblies are evaluated to ensure that fuel structural integrity is maintained. Potential sliding and overturning safety factors are determined if necessary. Maximum loads on the spent fuel pool are checked to reevaluate the pool structure integrity.

5. SEISMIC ANALYSIS ISSUES

Current NRC requirements documented in SRP 3.8.4 Appendix D provide no guidance to the NRC staff for assessing the acceptability of a nonlinear analysis of spent fuel racks. Guidelines on design and analysis procedures discuss response spectrum methods, simplified energy methods for determining impact loads, and factors of safety against rack sliding and overturning. This suggests that the authors of this document envisioned the use of simplified linear analysis procedures to evaluate the seismic adequacy of high density fuel racks. However, the complexities of the free standing high density rack systems and the higher loads associated with the storage of large numbers of fuel assemblies in existing pools have required the development and application of more sophisticated nonlinear analysis techniques.

A primary issue of concern to NRC staff members responsible for the technical review and approval of spent fuel pool expansion license amendments is the high level of uncertainty associated with current nonlinear seismic analysis methods. Real margins of safety are difficult to predict in any nonlinear system because the response is not directly proportional to the input. In a nonlinear system, a small change in seismic input level can result in a potentially large increase in seismic response. For example, a free standing fuel rack module may respond linearly to a low level of seismic excitation. However, at higher excitation levels, the rack displacement will increase dramatically when rigid body motions are induced. A free standing fuel rack can undergo a variety of rigid body motions in response to seismic excitation. A rack can slide along the pool floor when lateral forces are large enough to overcome frictional resistance at the pool floor interface. Overturning moments can cause a rack to tilt and momentarily lift off one or more supports and then fall back onto the pool floor. Significant seismic motion can force a rack module to tilt about two horizontal axes and pivot around one corner support (torsional motion). Combined sliding, tilting and torsion may occur simultaneously. During an earthquake the spent fuel pool assemblies will rattle within their storage cells. Since the fuel mass is significant, the fuel to cell impacts will affect the overall response of the rack. Since the rack modules are in close proximity, they may impact adjacent racks or pool walls as they undergo rigid body motion. These impact forces will further affect the seismic response.

The submersion of fuel racks in water further adds to the complexity of the seismic analysis. Whenever a body vibrates in water, the surrounding fluid is accelerated. This generates fluid pressures on the body and adjacent structures. These pressures develop forces which have a significant effect on the dynamic response of the vibrating body. In a fuel rack system, hydrodynamic forces will couple the motion of fuel assemblies with their storage cells as well as the motion of a fuel rack with adjacent fuel racks and pool walls.

The multiple nonlinearities of the fuel rack system combined with the significance of rack submersion require detailed mathematical models with accurate definitions of physical parameters to predict seismic response with a reasonable level of confidence. However, computer costs associated with nonlinear dynamic time history analysis of large finite element models are much higher than costs associated with linear analysis of similar size models. As a result, the analyst is forced to make simplifying assumptions to reduce the size of the model. In addition, the modeling parameters may be difficult to define accurately. Recent NRC and BNL technical evaluations of high density fuel reracking license applications identified a number of areas where analysis methods, simplifying assumptions or parameter variability contributed to the overall uncertainty in seismic analysis results. These areas of concern were documented by DeGrassi (1989) in an NRC-sponsored study of fuel rack analysis methods. They are summarized below:

<u>Multiple rack interaction:</u> Even though a spent fuel storage pool may contain ten to twenty free standing rack modules, single rack mathematical models have generally been used in seismic analysis (DeGrassi 1989). However, the seismic response of any single rack in the pool is not independent of surrounding racks. Fluid coupling and potential impact with adjacent racks and pool walls is an important consideration. Simplifying assumptions regarding the motion of adjacent racks must be made in a single rack mathematical model. The analyst generally assumes that adjacent fuel racks move either in-phase or out-of-phase with the rack being analyzed. To justify the assumption, the analyst may argue that in-phase motion is appropriate because fluid coupling will force all racks to move together or he may argue that out-of-phase motion is conservative because impact forces between adjacent racks would be maximized. The true seismic response probably lies somewhere between these extremes. In-phase rack motion may be more realistic when all racks in the pool are identical and equally loaded with fuel but this is rarely the case. Some limited multiple rack studies by Singh and Soler (1991) have suggested that single rack seismic analysis results may be unconservative.

<u>Fluid Effects:</u> Fuel rack seismic analyses will generally consider the inertial effects of water. Finite element models may include hydrodynamic mass coupling elements which provide added mass (diagonal) terms and inertial coupling (off-diagonal)

terms to the system mass matrix. The effect of these terms is to lower the frequency and couple the motion of the fuel assemblies, rack modules and pool walls. The hydrodynamic mass terms are generally calculated based on the assumption that the water is incompressible and inviscid and that deflections are small compared to the flow paths (gaps). In the case of fuel racks, the deflections are often large relative to the gaps. Fuel to rack cell gaps open and close as the fuel rattles. Rack to rack and rack to pool wall gaps often close under seismic excitation. Experiments on concentric cylinders with small vibration amplitudes have shown good agreement with theory. However, the application of the same theory to fuel rack systems with complex multibody geometries, small gaps and potentially large vibration amplitudes is questionable without experimental verification.

Friction: Finite element models employ Coulomb friction elements at the rack support foot to pool floor interface. These elements transfer the full horizontal inertial rack loads to the pool floor until a limiting value equal to the coefficient of friction times the normal vertical load is exceeded. The rack then slides against this frictional resistance force. The coefficient of friction is subject to significant variability depending upon local surface conditions. Static and dynamic coefficients of friction may differ. Normal pressure, temperature and speed of sliding may also affect the friction coefficient. The choice of friction coefficient can have a significant impact on the seismic response.

Impact Stiffness: Nonlinear compression-only springs are used at finite element model gap interfaces. These areas may include fuel to storage cell, support foot to pool floor, rack to rack, and rack to pool wall interface locations. Accurate representation of the impact stiffnesses of these spring elements in a simplified fuel rack model is difficult. The level of effort that goes into defining these properties may vary significantly between different fuel rack analysts. Seismic response may be very sensitive to variations in impact stiffnesses.

Three Dimensional Effects: In the past, most fuel rack systems have been analyzed using two dimensional planar finite element models. To satisfy NRC guidelines, three directional seismic input loads would be applied as separate load cases and the resulting co-directional responses would be combined by the square root of the sum of the squares (SRSS) method. The adequacy of this method for predicting three dimensional response in a nonlinear system is questionable. Rack sliding and tilting may be underpredicted unless all directional loads are applied simultaneously. Torsional response of a fuel rack about its vertical axis would not be simulated in a two dimensional planar model.

Damping: The damping values used in seismic analysis are generally based on FSAR or NRC Regulatory Guide 1.61 values for welded steel structures. Fluid damping is usually neglected as recommended by NRC guidelines. In recent years, fuel rack analysts have been claiming that fluid drag effects may add significant amounts of damping to the system. However, further experimental studies are needed to better quantify this effect.

Load Cases: There are various possible rack configurations that must be considered in a seismic evaluation. They include size of rack, location in pool, and number and location of fuel assemblies within a rack. The analyst must select a limited number of bounding load cases for analysis. However, the system nonlinearities make the selection of bounding load cases difficult and subject to uncertainty.

Fuel Assembly Representation: In a fuel rack mathematical model, the fuel assemblies are usually represented as a single beam connected to the rack model by gap elements. The model incorporates the composite structural properties of all stored fuel assemblies which are assumed to move in unison. However, some analysts have argued that since the fuel assemblies cannot move exactly in phase with each other, the model should include only a fraction of the total fuel mass. While the assumption that the full fuel mass moves in unison is clearly conservative, variations from this assumption are difficult to justify.

6. ASSESSMENT OF THE TECHNICAL BASIS AND VERIFICATION OF ANALYSIS METHODS

The seismic analysis issues described in Section 5.0 were identified as concerns during technical reviews of spent fuel pool expansion license amendment submittals conducted by NRC and BNL in recent years. In order to compensate for the uncertainties in the analyses, the reviewers in most cases asked licensees to perform additional studies to provide a higher level of confidence in the results or demonstrate substantial design margins. These studies included both single rack model and simplified multiple rack model analyses to investigate the effects of variations in modeling assumptions and input parameters on the results. However, since this process increased both the time and expense required to license the new racks for both licensees and NRC staff, the need to establish clearer NRC guidelines and acceptance criteria in this area was identified. In order to establish these guidelines, a thorough and systematic investigation into the validity and strengths and weaknesses of current analytical methods is needed. The effort must identify the extent to which the methods are supported by analytical and experimental data. Areas found to be potentially weak can be studied further by performing analytical studies to assess their sensitivity. Finally, experimental work can be performed to verify the more sensitive parameters as well as the analytical methods.

In order to assess the technical basis and verification of current analysis methods, an extensive literature review was performed. The review concentrated on papers published in technical journals and conference proceedings in the last fifteen years. The papers were identified through a computer database search. Databases queried included the NTIS, Compendex Plus (Engineering Index), and DOE Energy Dialog Systems. The papers were collected and compiled and reviewed with specific emphasis on identifying the extent of experimental and analytical verification of the methodologies. The majority of papers presented seismic analysis methods and modeling procedures for free-standing fuel racks. Some papers discussed alternate fuel rack designs and their seismic analysis. A few presented experimental data and compared analysis results to test results. Some of the references to the papers were also obtained and reviewed. The references included analytical and experimental studies on hydrodynamic effects and an experimental study on friction. A list of all papers included in the review is provided in Section 8. Highlights of the more significant papers are given below.

6.1 Summary of Literature Review

One of the earliest papers on the subject of nonlinear dynamic analysis of spent fuel racks was published by Habedank et al in 1979. It provides a qualitative description of the seismic analysis of a free-standing fuel rack which is not anchored to the pool floor or walls. This rack is prevented from sliding by guide pins at the pool floor but is free to tilt and lift up vertically off the floor. Nonlinear dynamic analysis of simplified 2-D and 3-D mathematical models was performed using the ANSYS finite element program. The authors considered only single rack models because they assumed that if racks of a given type are equally filled with fuel assemblies, their dynamic response will be comparable and the influence of neighboring structures will be the same for all. They stated that model tests with several racks vibrating in water in close proximity to each other and in the vicinity of solid boundaries had shown this assumption to be approximately valid. A number of different models were developed. The racks were represented either by beam elements or by ANSYS "super-elements." In some models fuel assemblies were modeled as a separate structure but fuel to rack impact was apparently not considered. The supports were treated as frictionless gap elements with spring constants representing the local flexibility of the rack feet. The effect of water submersion was considered by increasing the structural mass by the amount of added mass due to water. With the added mass, the fundamental frequency was shown to be just above that of the peak of the response spectrum. The authors presented sample results in terms of displacement, uplift, support bending moments and axial force transmitted to the pool floor. It was noted that maximum forces transmitted to the racks and floor occur during the impact and rebound phase following support foot uplift.

In 1979, Reed et al published a paper which discussed the relative merits of alternate fuel rack systems. They included a stiff system anchored and braced to the pool, two flexible systems, one of which utilized pendulum supports and the other, ball and disk supports, and a force limiting system which was free to slide and tilt. In the force limiting system, special materials were used at the rack support pads to ensure that the coefficient of friction did not exceed a pre-established value. The authors stated that laboratory tests were performed to establish friction coefficients. A simple nonlinear two dimensional model of a single rack was developed. The model utilized beam and truss elements to represent the rack, and friction and gap elements to represent the rack support pads. Fuel assemblies were not modeled separately. Horizontal time history floor motions were input to the model. Peak vertical accelerations were included as static forces and were both added and subtracted to the rack weight. Ranges of friction coefficients between 0.1 and 0.33 were considered. These values represent the mean plus or minus two standard deviations from the test results. Typical results were presented in terms of sliding and uplift displacements. For the lowest coefficient of friction, there was no uplift but the sliding displacement was highest. For the highest coefficient of friction, the sliding displacement was a minimum and the uplift was a maximum.

In 1980, Hossain published a paper which provided detailed qualitative discussions of special analytical problems that are encountered in performing dynamic analysis of high density spent fuel racks and presented some analytical results. He discussed both anchored and free-standing racks of the space frame type (storage tubes connected to a top and bottom grid) and the shear panel type (storage tubes welded together to form a honeycomb structure). For the shear panel type, he discussed the merits of equivalent stick models versus detailed finite element models with dynamic degrees of freedom reduced by condensation techniques. He concluded that both types of models provide similar results but the equivalent stick model may result in a savings in cost. Hossain recommended that nonlinear models should use the lowest values of friction coefficient to predict conservative values of sliding distance and velocity. The experimental work of Rabinowicz (1976) which provided upper and lower bound values of 0.8 and 0.2 was referenced. Hossain emphasized the importance of hydrodynamic mass effects by pointing out that inaccuracies or uncertainties in estimating the added mass can affect the predicted response significantly. However, he stated that rigorous computation of added mass is impractical because of complex multiple structure-water interaction. According to Dong (1978), the methods commonly used rely on engineering judgment derived from analytical and experimental work on single structures in an infinite medium. To avoid underestimating response, Hossain recommended that the added mass be varied within the limits of various approximate methods such as those discussed by Dong. Finally, Hossain discussed the importance of fuel assembly "rattling" within the storage cells. Using a simplified fixed base nonlinear model in which the fuel was modeled as a gapped mass element, rack response was determined for various rack stiffnesses, fuel to rack mass ratios, and maximum input accelerations. The results were compared to the response of comparable linear models in which the fuel assembly mass was lumped with the rack mass. In all cases, the ratio of nonlinear model to linear model response exceeded one. Preliminary results of a similar study on sliding racks indicated that the ratios are smaller. Further study in this area was recommended to reduce the conservatisms in the nonlinear model, especially the assumption that all fuel assemblies rattle in-phase.

Durlofsky and Sun (1981) further examined the effects of impacts between fuel bundles and storage tubes in high density fuel racks for both fixed and sliding base systems. They developed two simplified mathematical models of a single fuel assembly and storage tube. One model considered the stiffness of the rack and fuel, the hydrodynamic and impact effects between the fuel and rack, and potential base sliding. The other model neglected the impact and hydrodynamic effects and lumped the mass of the fuel to the storage tube which was current industry practice at that time. Two sets of analyses were performed on the models. In the first analysis, three friction coefficients were considered: 0.132, 0.2, and infinite (fixed base). The two models were subjected to the same base accelerations and the maximum loads on the fuel rack were determined and compared. In the second analysis, the ratio of fuel mass to rack mass was varied for a fixed base rack and the maximum rack loads were compared. The results of the first set of analyses indicated that for the sliding rack cases, the maximum load in the impacting fuel model is less than the load predicted by the lumped model. However, for the fixed base case the impacting fuel model predicted higher loads. For the second set of analyses, the impacting fuel model predicted higher loads in all cases. The ratio of maximum loads predicted by the two models increased with the fuel to rack mass ratio.

Gilmore (1982) presented a comprehensive description of a nonlinear seismic analysis of free-standing fuel racks. A time history analysis of a detailed two dimensional single rack model was performed using the modal superposition methods of the WECAN finite element analysis program. The fuel rack model consisted of three-dimensional beams, two-dimensional rotary springs, general matrix elements, gap elements and friction elements.

It included 99 linear elements and 20 nonlinear elements with 60 unique nodes. Gap elements, consisting of springs and dampers in parallel connected to a gap in series, were used to model the fuel to cell impact behavior. Friction elements were used to model the friction interface between the rack support pads and pool floor. Fluid effects were considered by assuming incompressible potential flow. The finite element method discussed by Yu (1980) was used to determine the fuel assembly hydrodynamic mass. This method considered flow through the 15x15 array of fuel rods. A general mass matrix element was used to incorporate the hydrodynamic mass into the fuel rack system model. The technique modeled the hydrodynamic mass effect on both frequency and force response of fluid coupled bodies as discussed by Fritz (1972) and Stokey and Scavuzzo (1977). Hydrodynamic mass coupling of the fuel rack with the pool wall followed the same methodology. The fuel rack system model was analyzed for different fuel assembly loading configurations including full, half-full, and empty. Since the model was a two cell representation of a fully loaded rack, the half-full and empty configurations were represented by removing one and two fuel assemblies, respectively. The analysis also considered variations in friction coefficient between minimum and maximum values of 0.2 and 0.8. Typical dynamic responses were presented in terms of pool floor loads, fuel to cell impact loads, and rack displacements. The maximum floor loads and pool impact loads resulted from the full fuel assembly loading configuration with maximum friction coefficient. The maximum sliding displacement resulted from the same configuration with minimum coefficient of friction. Sample plots of the results demonstrated that the fuel rack system response is significantly influenced by the structural interaction between fuel assembly and cell.

In 1983, Soler and Singh published a detailed description of a nonlinear time history analysis method for determining seismic response of a free-standing spent fuel rack module. The authors developed a simplified fourteen degrees-of-freedom model of a rack system. Instead of using finite element analysis, the governing equations of motion were developed and solved using the "component element method" of Levy and Wilkinson (1976). The model represented the rack structure as an elastic beam. A single lumped mass connected to the top of the rack beam through gap elements represented the "rattling" fuel mass. Half of the total fuel mass was assumed to rattle and the other half was assumed to move with the rack base. Four gap elements were used to simulate the vertical behavior of the support legs at the base plate corners. Friction elements and rotational elements represented the sliding potential and resisting moments of the support legs. Fluid added mass and coupling effects were determined in accordance with the methodology described by Fritz (1972). Three orthogonal seismic time history excitations were applied simultaneously. Six load cases were analyzed with variations in seismic input level, friction coefficient (0.2 and 0.8), and fuel load (fully loaded and half loaded rack). Structural damping of 2% was used in all cases. Results for two typical rack designs (honeycomb vs. end connected tube construction) were presented in terms of stresses, displacements and floor loads. In discussing the results, the authors stressed the importance of performing a 3-D analysis. They pointed out that large horizontal displacements can occur during the instant when the rack is supported by only one foot and the seismic loads cause the rack to pivot about that contact point. This was particularly significant for the half full rack. Maximum fuel rack displacements were seen when the high friction coefficient was used. This was explained by the rack's greater tendency to stick and pivot about one foot.

Soler and Singh (1982) also studied the effects of large displacements on the hydrodynamic forces which develop during seismic excitation of fuel rack systems. The methods described by Fritz (1972) and Dong (1978) which are generally applied in fuel rack analysis are based on the assumption that the vibrations are infinitesimal relative to the gaps. This is often not the case in fuel rack applications. The authors developed a simple two dimensional model of a channeled BWR fuel assembly in a fuel storage cell. Lagranges equations of motion were used to characterize the fluid forces for inviscid flow under large amplitude motion. Expressions for equivalent damping due to drag were also developed. Using typical fuel rack parameters and sinusoidal input, the model was analyzed for five conditions: (1) no fluid mass or damping, (2) small deflection model and damping, (3) large deflection model, no fluid damping, (4) large deflection model with fluid damping, and (5) large deflection model with reduced fluid damping. Results were presented in terms of rack spring force, local impact force and fluid damping force. The authors concluded that large displacement effects coupled with fluid damping decrease rack forces and may eliminate fuel to cell impacts. They also stated that experimental work was planned to verify the analysis. However, no further information on experimental verification or further development of the methodology has been found in the literature.

Harstead et al (1983) described a simplified fuel rack analysis procedure using a special purpose computer program, FRAK. The structural model had three degrees of freedom. The hydrodynamic effects were computed according to the methods described by Fritz. A seismic time history analysis was performed for a proposed system of twelve racks which were tied together at their bases. The racks were free to slide but the ties ensured uniform translational motion. The system was analyzed with coefficients of friction of 0.1, 0.2, 0.4, and 0.6. Sliding occurred for all cases. The resulting maximum base moments and displacements showed no clear pattern, however. The authors attribute the lack of a predictable pattern of response to the dominance of fuel to rack impact effects. They point out that it is customarily assumed that if a system works for a very high and very low coefficient of friction, the design is satisfactory. However, impacts do not allow one to make this assumption. They recommend that analyses be carried out for several coefficients of friction.

Bouche-Pillon et al (1983) presented a study on the seismic behavior of fuel racks with three different support configurations: rigidly supported, free-standing (sliding and rocking), and supported by an aseismic device consisting of horizontal roller bearings. A two dimensional nonlinear time history analysis of a finite element model was performed for each design. The models considered fuel-to-cell impact and fluid damping, Coulomb friction between bottom of fuel assembly and cell, and hydrodynamic coupling effects in accordance with Fritz. The free-standing rack model considered friction and gaps at the support pad to pool floor interface. Typical forces and displacements were presented for each rack support design. The results indicated that softening of the connection between racks and pool reduces the loads on structures. The roller bearing aseismic support design had a horizontal reaction force of nearly zero. The vertical reaction force was significantly lower than the free-standing rack which experienced liftoff and vertical impact forces. Fuel assembly impact loads and hydrodynamic loads were also lowest for the aseismic support design. Two series of tests to verify the aseismic design were described. The first was a 1/4 scale rack model tested in air on a triaxial shaker table. The tests demonstrated the dynamic characteristics of the design and their capability to attenuate horizontal vibrations. They were also used to verify the finite element model. The second series of tests were on a 1/10 scale pool model. The results confirmed the possibility of applying the Fritz theory to this kind of structure. Pool sloshing was shown to have no major effect on the response. Asymmetric rack loading induced a yawing motion onto the translational motion, but generated only small additional translations in the direction perpendicular to the excitation. Finally, viscous fluid effects were found to be important and added approximately 15% damping to the system.

Wright (1985) presented a nonlinear seismic analysis of a fuel rack system using the ANSYS finite element program. The paper concentrated on the use of substructuring as an efficient method for modeling the fuel rack structure. The model was comprised of two rack substructures and two fuel substructures. It included gap and friction interfaces and hydrodynamic elements so that fuel impact, rack-to-rack impact, uplift, sliding, and fluid interaction could be assessed. Since substructuring was used, a relatively small number of degrees of freedom were needed to characterize the response. Each rack substructure contained substructures along with other ANSYS elements. The primary building block was a 2x5 storage cavity model of plate elements. The fuel element substructures were formed from beam elements with all fuel bundles assumed to vibrate in phase. By using substructuring, the equivalent of 10000 plate elements and 40000 degrees of freedom went into each rack model. Stresses in the model could be recovered by performing two levels of stress pass runs.

Alliot (1986) presented additional experimental and analytical qualification of the Framatome aseismic bearing devices (Bouche-Pillon et al). The device consists of two orthogonal layers of rollers and three support plates. The rollers consist of cylindrical portions with offset centers of curvature. Because of the offset, a horizontal displacement forces the rack module to rise producing a gravity-induced restoring force. A 1/4 scale model of 4 bearing devices supporting a lead block was tested on a shaker table. Both sine sweep tests and scaled down earthquake records were applied. Two sets of rollers were tested: one with a small value of offset and one with a larger offset. Tests indicated natural frequencies of 0.56 Hz for the small offset rollers and 1.18 Hz for the large offset rollers. The tests showed the devices highly effective in reducing accelerations, especially with the small offset. Biaxial tests showed that vertical seismic acceleration had little effect on horizontal response. Slight tilting of the system did not alter the system response. A test of a full size 5x9 spent fuel module in a test pool was also performed. A sine displacement was imposed on the upper end of the rack at various frequencies. This test provided information on damping and hydrodynamic coupling. Damping was found to be 4% for a fully loaded rack and 7% for an empty rack. Hydrodynamic coupling masses were calculated based on potential flow theory and from test results. A comparison showed that the two values differed by less than 10%.

Kabir et al (1987) described the seismic analysis of existing fuel racks at Millstone 1 to accommodate a 2:1 fuel consolidation. The fuel pool contains 32 racks arranged into six "super modules." Each super module contains 6 or 4 racks welded together by tie plates. The super modules are free-standing on the pool floor but braced 9 inches above the base against the pool walls. They are only 1 inch apart at the top and may impact against each other. The ADINA finite element program was used to develop two mathematical models. A nonlinear 3-D model was developed to obtain global responses. A detailed 3-D model was developed to determine stresses and forces for structural evaluation. The global model included four super modules. The heaviest super module was a corner module and was modeled as three dimensional. Two adjacent supermodules were modeled in 2-D for interaction in the east-west direction. One adjacent module was also represented in 2-D for north-south interaction. The fuel racks and fuel canisters were represented by beams. Coupled mass matrices between adjacent modules and between modules and pool walls represented hydrodynamic coupling. Nonlinear gap elements were used between super modules and between fuel and storage cells. Hydrodynamic coupling between fuel and cell was determined by the method of Soler and Singh (1982). Contact friction elements were used to model possible sliding and uplift at the support leg to pool floor interfaces. The model was subjected to three components of seismic displacement time history at the pool floor. Maximum forces from the 3-D super module were applied to the detailed model to obtain stress results in various components for evaluation. The results indicated super module uplift and impact on the pool floor, pressing and disengagement against lateral restraints, and impact of fuel canisters on the cell walls.

Champomier et al (1989) performed studies to investigate the possible out-of-phase motion of adjacent rack modules during an earthquake. A simplified two dimensional linear model of a row of five modules was developed. Three models were fully loaded and two were half full. Each module was assumed to be connected to the pool floor by rotational springs. Hydrodynamic coupling between modules based on potential theory was included. A modal analysis showed that the frequencies and displacements of each module are very similar because of the hydrodynamic coupling. The authors concluded that the modules can be expected to vibrate in phase with very limited amplitude and that the possibility of impact between adjacent racks can be ruled out. The simplified study, however, neglected various nonlinear effects including rack sliding and tilting and fuel assembly to rack impacts. The effects on global response have been shown significant by others. A nonlinear analysis would probably have indicated that impacts between racks can occur.

Fujita et al (1989) presented the results of seismic testing and nonlinear seismic analysis of a Japanese base isolated spent fuel storage rack. The base isolation system consists of sliding support pads which rest on the pool floor liner. The support pads utilize graphite pellets to minimize the friction at the interface. A scale model (1/2.92 scale) aluminum rack was fabricated for the test. The scaling ratio was based on the ratio of elastic modulus of stainless steel and aluminum. Lead weights were installed in the rack cells to simulate the added mass of the fuel. The test model was placed in a water tank fabricated on a 6m x 6m three dimensional shaker table. The tank was 3 meters long and 1.8 meters high. The dynamic characteristics of the rack model were investigated by a detailed finite element analysis. Based on these characteristics, a simpler beam model was developed for performing nonlinear seismic response analysis. Equations of motion for the analytical model were developed for translational and rotational motion. The equations considered hydrodynamic effects and friction. Both static and dynamic friction coefficients were considered. Dynamic friction coefficient was specified as a function of sliding velocity. The seismic response time history was calculated by the Runge-Kutta-Gill method. Tests included sine sweep tests to determine frequencies and mode shapes of the rack. Test results compared reasonably well with analytical results. A series of simulated earthquake tests were also performed. Both single direction and three directional tests were performed. Friction coefficients were measured and typical values were 0.14 for dynamic friction and 0.15 for static friction. Fluid added mass and damping effects were also measured and incorporated into the analytical model. A comparison of calculated to measured response time histories showed reasonably good agreement. The authors concluded that the adequacy of the analytical method was verified by the test. For the sliding base rack design, they concluded that the acceleration ratio of rack response to input decreases as excitation level increases, and that the combination of horizontal and vertical excitation and fuel eccentricity does not have a significant effect on the seismic response.

Ellingson et al (1989) investigated the effects of fuel rack wall flexibility on hydrodynamic mass and coupling. They performed experiments with two full-scale welded box sections submerged in a water tank. The test apparatus consisted of a plexiglass water test tank with two short sections of thin-walled, three-cell, fuel rack assemblies mounted in a horizontal position. One assembly was connected to a Tinnius Test Machine through a water seal at the bottom of the tank. The other assembly was supported from above by a mechanical spring. A sinusoidal input motion was applied. Frequency, amplitude, and surface-to-surface gap were varied. Measurements taken included force, gap size, acceleration and water gap pressure. The authors concluded that preliminary results indicated (a) a reduction in hydrodynamic mass due to box wall flexibility (compared to predicted values based on the methods described by Fritz and Dong), (b) a lack of impacting of box wall to box wall over the entire frequency range, and (c) large hydrodynamic coupling forces under all test conditions. They also hypothesized that the coupling forces are sufficiently strong to prevent rotational motion of one rack when surrounded by adjacent racks.

Pop et al (1990) presented another description of a three-dimensional nonlinear dynamic analysis of a single free-standing fuel rack for three orthogonal components at earthquake motion. The authors state that a rigorous analysis should involve the simultaneous solution of the coupled motions of a group of neighboring racks and fuel assemblies vibrating as individual components. Since this is tedious and computationally impractical, they recommend that several separate analyses be performed. These may include a 3-D single rack analysis to evaluate 3-D effects and a 2-D multirack analysis to evaluate multirack effects such a sliding of two or more racks towards the pool wall and momentarily piling up against the wall. Their paper describes the 3-D model but notes that a 2-D model would be similar. Using the ADINA finite element analysis program, they develop a simplified stick model with the rack and fuel assemblies represented by linear stiffness elements. Gap elements are used to model impact between fuel and rack, between adjacent racks, and between racks and pool wall. Three dimensional contact elements are used at the support legs to model uplift, sticking and sliding using Coulomb friction. All fuel assemblies are assumed to vibrate in phase. Hydrodynamic coupling effects between fuel assemblies and rack cells are modeled in accordance with the method described by Fritz (1972). Rack to rack and rack to pool fluid coupling is calculated on the assumption that the rack being analyzed oscillates while adjacent racks remain stationary. The hydrodynamic mass matrix was calculated by potential theory using an ADINA finite element model. Potential-based fluid finite elements were used to model the fluid in the gaps. The hydrodynamic masses were calculated based on initial gaps and the effects of gap reduction were neglected. Structural damping of 4% was used. Fluid damping was neglected. The rack model was subjected to the simultaneous action of dead load and three statistically independent orthogonal components of seismic acceleration time histories. The solution was obtained by direct integration using the Newmark method. Typical results were presented for a corner fuel rack which was judged to have maximum impact loads because of its location. The large gaps adjacent to the pool walls will provide the least resistance from hydrodynamic effects. A half loaded rack and fully loaded rack were analyzed. Coefficients of friction of 0.2 and 0.8 were considered. Results for the half loaded rack with friction coefficient of 0.2 were presented. They indicated that the rack supports uplifted and impacted the floor many times during the seismic motion. High impact forces were produced after each uplift and fallback. Sliding of the rack was also observed. The fuel assemblies oscillated back and forth between the opposite walls of the cell. A comparison of maximum horizontal displacements between the full rack and the half full rack showed that the full rack experienced larger displacements. The authors concluded that this indicates that the rack horizontal motion results primarily from fuel to rack impact.

S. Singh et al (1990) provided a description of the same analytical methodology presented by Pop et al (1990) and presented results of additional studies which investigated the effects of gap variation on hydrodynamic mass. Using the ADINA fluid finite element model of Pop et al, hydrodynamic mass of a fuel rack was determined and plotted as a function of normalized eccentricity. The normalized eccentricity was defined as the rack offset from the initial equal gap position divided by the sum of the gaps. The plot showed that hydrodynamic mass increases with increasing eccentricity but the increase is not large until the gap on one side becomes very small. For a normalized eccentricity of 0.8, the increase is about 50%. To determine the effect on seismic response, a nonlinear seismic analysis was performed in which hydrodynamic mass was increased by 50%. A comparison of impact forces between fuel and rack and in the support legs showed an average difference of about 15% between the two cases. The authors concluded that this shows that the practice of using a constant hydrodynamic mass based on initial gaps is reasonable. They also pointed out that in the analysis, damping due to fluid interaction was conservatively neglected although studies by Chen et al (1976) showed that damping for a system with small gaps could be 5% or more.

Singh and Soler (1991) performed analyses to investigate the adequacy of single rack analysis versus multiple rack analysis. They discussed the intrinsic inadequacy of a dynamic simulation of only one rack to predict the motion of an entire pool of rack modules with any quantifiable level of accuracy because of hydrodynamic coupling effects between all racks in a pool. In order to quantify these effects, they performed a whole pool multi-rack (WPMR) analysis of the Chin Shan spent fuel pool in Taiwan. These racks had initially been analyzed by a 2-D seismic model. The DYNARACK computer program which uses the component element method discussed by Soler and Singh (1983) was used to perform a nonlinear seismic analysis of the entire assemblage of racks (14 modules) in the pool with due consideration of fluid coupling effects. The authors stated that the analysis results indicated that the presence of water injected a certain symmetry into the motion of adjacent racks, although a certain amount of out-of-phase motion occurs. Comparison with single rack 3-D analysis, however, showed that the single rack results did not bound the results of the whole pool simulations. In the Chin Shan analysis which used a friction coefficient of 0.2, the whole pool model displacements were 8.5 times those predicted by the single rack model. Impact loads between the rack support pedestals and pool floor decreased slightly from the values obtained from the single rack analysis. A similar analysis was performed for the Oyster Creek spent fuel pool using friction coefficients of 0.2 and 0.8. In that case, the WPMR analysis predicted maximum displacements of 1.4 times the single rack analysis prediction. The impact loads predicted by the WPMR analysis were slightly higher than the values predicted by the single rack analysis. The authors concluded that these studies suggest the potential unconservatism of single rack 3-D analyses and indicated the need for whole pool multiple fuel rack analysis despite its high cost.

6.2 Review of Hydrodynamic Mass References

In the seismic analysis of spent fuel racks, the work of Fritz (1972) is most frequently cited as the basis for computing hydrodynamic effects. The Fritz paper developed the fluid coupling equations for the classical case of two long concentric cylinders separated by a liquid annulus. The fluid was assumed incompressible, frictionless, and irrotational. Potential theory was applied to solve for fluid velocity and kinetic energy. Lagrange's equation was applied to determine the fluid reaction forces on the inner and outer cylinders. In applying Lagrange's equation, a simplification was introduced by assuming the motion of the solid bodies to be small with respect to the fluid channel thickness. The fluid forces were shown to be dependent on the acceleration of the solid bodies multiplied by hydrodynamic mass terms. A generalized procedure for determining hydrodynamic forces in systems with two or more bodies immersed in a liquid was presented. Tables of hydrodynamic mass relations for single body motions for different geometries and motions were given. Using the procedure, the data can be transformed into hydrodynamic mass relations for multiple body motions. Additional restrictions on the procedure require fluid velocities to be less than 10% of the speed of sound in fluid and the flow channel length to be less than 10% of the wave length for propagating vibratory disturbances in order to avoid the possibility of standing wave effects. Fritz also provided some additional guidance to judge when a fluid may be considered frictionless. Test data was presented for various concentric cylinder vibration tests. Comparisons indicated favorable agreement. Fritz noted that more confirmation is desirable but since the information of the paper was based on basic principles, the equations should be accurate for the specified conditions.

Dong (1978) is another frequently cited reference for hydrodynamic effects in spent fuel rack seismic analysis. The author presented information based on the results of a survey of the literature and of design methods that were used by industrial firms at the time. Structures of concern were spent fuel storage racks, main steam relief valve lines, and reactor internals. The paper presented a summary of different methods and assumptions used to calculate added mass and damping due to fluid submersion. Dong found that the methods used were largely based on engineering judgment. The paper provides an extensive compilation of analytical and experimental data on added mass and added damping for single isolated members and for multiple members. For single isolated members, Dong concluded that potential theory is adequate for describing the added mass phenomenon. Added damping for single isolated structures decreases with increasing structural size and is generally small. For multiple members, he found that fluid dynamic effects are more complex. Experimental data was limited. Dong believed that the concept of added mass and added damping still applies although the formulation is more complicated. Theoretical added mass coefficients for arrays of tube bundles compared well with experimental data. Damping tends to be higher than for single isolated members and tight spaces between members can increase the damping measurably. Dong concluded that, in general, additional experimental validation is needed and the range of various analytical techniques needs to be established.

6.3 Review of Friction Coefficient Reference

The work of Rabinowicz (1976) has most frequently been cited as the basis for considering lower and upper bound friction coefficients of 0.2 and 0.8. The friction coefficients were determined from a series of experiments performed for Boston Edison Company to support their design of new spent fuel racks at the Pilgrim Nuclear Plant. A pin-on-disk friction tester was used in these experiments. In this apparatus, the top specimen, the pin, is held stationary in a dynamometer while it is pressed against the rotating disk by a dead weight load. The angular speed of the disk is adjusted to produce the desired sliding speed. The friction force is measured using a strain gage ring. In these tests, the pin was 304 stainless steel of 1/4" diameter and 1" in length. Two configurations were tested. In one case, the end of the pin was 1/4" diameter hemisphere to produce point contact. In the other case, the pin had a .09 inch diameter flat. When loaded by a dead load of 2 Kg, this configuration produced the same surface stress as that of a fuel rack pad of 6" diameter loaded by 22,000 lb. The flat specimen was a 304 stainless steel plate of dimensions 2" x 2" x 1/4". Two different surface finishes were tested. In these tests the flat specimen was mounted in a cup and immersed in 2 cm of distilled water. Two water temperatures were used, namely room temperature and an elevated temperature of 160°-180°F. In some of the tests fine iron oxide particles were introduced into the water to simulate the effect of corrosion products in the spent fuel pool. Two sliding speeds were used. A speed of 4 inches/second corresponded to the maximum sliding speed of a fuel rack. The other speed, .04 inches/second was chosen to be two orders of magnitude slower than the top speed. A total of ten sliding friction tests were carried out. Nearly all tests were of one hour duration. During each test, ten friction coefficient values were obtained at roughly uniform time intervals. In addition, a series of static friction tests were carried out on surfaces which had been stationary for times of 1, 10, 100, 1000, 10,000, and 50,000 seconds. For these tests, the speed applied to induce sliding was .0004 in/sec.

A total of 199 values of friction coefficient were measured in these tests. Rabinowicz performed statistical analyses of the data. He first separated the results of friction runs which gave high values from those which gave low values. For the 139 high friction coefficient values, he determined a mean value of .563 and a standard deviation of .096. For the 65 low friction coefficient values, he determined a mean value of .380 and a standard deviation of .080. Lumping all values together, he determined a mean of .503 and a standard deviation of .125. Based on limits of plus and minus two standard deviations, the upper limit is .753 and the lower limit is .253. Rabinowicz noted that temperature and contact pressure had little effect as did the introduction of iron oxide particles. Surface roughness had some influence in that very rough surfaces gave somewhat lower friction. Sliding speed had a major effect, with distinctly higher friction at lower sliding speeds. Time of stick, however, had little effect. For fuel rack design, Rabinowicz recommended that the design be based on friction coefficient values between 0.20 and 0.80.

6.4 Assessment of Methodology

6.4.1 Analytical Studies

A review of the literature revealed that several papers have been written on the subject of free-standing spent fuel rack seismic analysis. A number of investigators have presented descriptions of analytical models and analysis methods used to simulate fuel rack dynamic behavior. The most detailed descriptions have been provided by Gilmore (1982), Soler and Singh (1983), Kabir et al (1987), and Pop et al (1990). While details of the analyses varied, the analytical models described by the different authors had many common features which are representative of the current analysis methods described in Section 4.0 of this report. The mathematical models include linear and nonlinear elements. Fuel rack and fuel assembly stiffnesses and mass distributions are generally represented by linear beam type elements. Nonlinear gap spring and Coulomb friction elements are used to represent interface locations such as fuel to rack cell, support pad to pool floor, and rack to adjacent rack or pool wall. Hydrodynamic mass and coupling effects are represented by incorporating added mass terms into the mass matrix of the system. Flow models used to determine the hydrodynamic mass terms assume incompressible, inviscid flow (potential theory) and small deflections. Finite element programs with nonlinear capability (ADINA, ANSYS, WECAN) have generally been used to develop and analyze the fuel rack models. The Soler and Singh paper describes an analytical method in which the governing equations of motion are developed and solved using a special purpose computer program. All methods required a seismic time history analysis with simultaneous application of gravity, vertical seismic, and one or two horizontal seismic input accelerations or displacements at the pool floor. Because of the nonlinearities, the direct integration method is generally used to determine the dynamic response. Gilmore, however, reported the use of the nonlinear modal superposition method of the WECAN program. Seismic analysis results presented by the authors also showed a similarity of response. Fuel assemblies were shown to rattle and impact the rack cell walls, the racks had a tendency to slide and uplift, and high impact loads were transmitted to the pool floor when a rack uplifted and fell back.

Differences between the analysis methods include the degree of detail in the model, methods for determining the linear and nonlinear properties, methods of calculating hydrodynamic mass terms, etc. Some of the more obvious differences reflect an evolution of the methodology. The Gilmore model was very detailed but was two-dimensional. The Soler and Singh model had less detail but was three-dimensional. The Kabir model was a detailed three-dimensional model of a single rack with adjacent 2-D models included to account for multiple rack interaction effects. Pop recommended development of both a single rack 3-D model to evaluate 3-D efforts and a 2-D multirack model to evaluate multirack effects.

The analysis methods are based on fundamental principles of structural mechanics and dynamics. The authors did not present experimental data to verify the analytical methods or their range of validity.

6.4.2 Experimental Verification

Some limited experimental work to verify the seismic response of fuel racks has been performed in France and Japan. In both cases, the tests were performed in conjunction with the development of seismic base isolation fuel rack supports. Framatome has developed a roller bearing aseismic support which significantly reduces the horizontal seismic forces. MHI has developed a sliding support pad design which utilizes graphite pellets to minimize the horizontal friction and thus reduce horizontal seismic forces.

Bouche-Pillon et al (1983) performed analytical studies of different rack support designs: rigidly supported, free-standing (sliding and rocking), and roller bearing. Planar finite element models were developed utilizing beam elements and gap spring elements. Hydrodynamic mass effects according to the method of Fritz were included. The equations of motion were solved by direct integration. The results showed that the roller bearing support design had horizontal reaction forces of nearly zero. Vertical reaction forces were significantly lower than those of the free standing rack since there was no liftoff and vertical impact. Two series of tests were performed to verify the roller bearing support design. The first was a 1/4 scale rack model tested in air on a triaxial shaker table. The authors claimed that this test qualified their finite element model and verified the capability of the seismic isolation design. The second series of tests were on a 1/10 scale pool model. The authors claimed that this test demonstrated the applicability of the Fritz theory but also showed that viscous effects are important and provide 15% damping in the system. Pool sloshing was insignificant. Asymmetric rack loading introduced a rotational motion into the system but was judged to be a secondary effect.

Alliot (1986) presented additional experimental and analytical results on seismic response of roller bearing supported fuel racks. The tests included a 1/4 scale model shaker table test of the aseismic bearing devices supporting a lead block in air and a full scale test of a 5x9 fuel rack in water subjected to sinusuidal displacement at its upper end. Alliot developed the equations of motion for the rack. Hydrodynamic mass effects were calculated based on potential flow theory. Viscous damping was also included. Based on comparisons with full scale vibration test results, the calculated hydrodynamic mass was found to be within 10% of the value determined from test. Damping was determined to be 4% for a fully loaded rack and 7% for an empty rack based on test measurements.

Fujita et al (1989) presented experimental data on seismic testing of a 1/2.92 scale model fuel rack with sliding graphite pellet support pads in a pool of water. Measured friction coefficients for the pads were approximately 0.15. Lead weights were installed in the rack cells to simulate the added mass of the fuel. The test model was placed in a water tank mounted on a three directional shaker table. The test model was subjected to sine sweep tests and to simulated earthquake excitation in one horizontal direction and also in three directions simultaneously. The authors determined vibration characteristics of the fuel rack by a detailed finite element analysis. This was reduced to a cantilever beam model to perform nonlinear seismic response time history analysis by direct integration. The equation of motion of the system included hydrodynamic mass and damping, and considered static and dynamic friction. The values of these parameters were measured in the test and incorporated into the analytical model. A comparison of calculated to measured response time histories showed reasonably good agreement. The authors concluded that the adequacy of the analytical method was verified by test and that the seismic reliability of the sliding rack design was proven.

Ellingson et al (1989) performed some testing to investigate the effects of fuel rack wall flexibility on hydrodynamic mass and coupling forces. They applied sinusuidal motion to one of two welded box sections of fuel racks in close proximity and submerged in a water tank. Based on their preliminary test measurements, they found a reduction in hydrodynamic mass (compared to Fritz and Dong methodology), a lack of impacting between walls, and large coupling forces under all test conditions.

6.4.3 Assessment of Seismic Analysis Issues

The literature review provided some additional information to assess the significance of the seismic analysis issues discussed in Section 5.0 of this report. A summary of the findings is provided below.

<u>Multiple rack interaction:</u> The importance of multiple rack interaction effects has been recognized in recent years. Kabir et al (1987) developed a multiple rack model with a combination of 3-D and 2-D rack models to more accurately account for hydrodynamic interaction between racks in a pool environment. Pop et al (1990) discussed the need for performing 2-D multirack analysis to evaluate multirack effects such as sliding of two or more racks towards the pool wall and momentarily piling up against the wall. The work of Singh and Soler (1991) provided direct comparisons between 3-D single rack and 3-D whole pool multirack analysis results. They demonstrated that a single rack

analysis may significantly underpredict rack displacements.

Fluid Effects: The limitation of the application of potential theory to develop hydrodynamic mass terms in a fuel rack system has been investigated by various authors. The theory assumes incompressible, inviscid flow with small deflections. Fritz (1972) presented test data for concentric cylinder vibration tests which showed good agreement with the theory. Dong (1978) compiled extensive analytical and experimental data and concluded that the theory is adequate for single isolated members. For multiple members, experimental data was limited, but Dong believed that the concept still applied. Soler and Singh (1982) investigated the effects of large displacements on hydrodynamic forces. They developed a model which considered the effects of large displacements on fluid forces and compared results with those of a similar model based on small deflection theory. They concluded that large displacement effects coupled with fluid damping should be expected to decrease rack forces. S. Singh et al (1990) investigated the effects of changes in hydrodynamic mass with variations in gaps. They determined the change in hydrodynamic mass versus eccentricity for a rack with initially equal gaps on both sides. They showed that hydrodynamic mass increases as the rack moves to close the gap on one side, but the increase is not large until the gap becomes very small. They compared seismic responses of an increased hydrodynamic mass model and concluded that the change was not significant and that the practice of using a constant hydrodynamic mass based on initial gaps is reasonable. Finally, testing of the Framatome roller bearing support rack reported by Alliot (1986), indicated reasonably good agreement between hydrodynamic masses calculated from potential flow theory with those calculated from test results.

Friction: The lower and upper limits of coefficient of friction of 0.2 and 0.8 which are most commonly used in fuel rack seismic analysis are based on laboratory experiments performed by Rabinowicz in 1976. The tests used 304 stainless steel specimens immersed in water. Test variables included contact configuration, surface finish, temperature, iron oxide contamination and sliding speed. The results indicated that sliding speed was the only variable that had a significant effect with higher friction measured at lower speeds. Based on 199 measurements, Rabinowicz recommended that the fuel rack design be based on friction coefficient values between 0.2 and 0.8. However, it is not clear that the consideration of only these two values will provide bounding fuel rack seismic responses. Harstead et al (1983) analyzed a rack for several values of friction coefficient and concluded that a pattern of response could not be established. They recommended that seismic analyses should be carried out for several coefficients of friction. In addition, differences between static and dynamic friction coefficients as well as variations in friction coefficient with sliding have generally not been considered in fuel rack seismic analysis. The effects of these variations need further evaluation.

Impact stiffness: The literature review provided little information on the methods for developing impact stiffness values for the compression only springs used at gap interfaces. Soler and Singh (1983) calculated impact spring rate between fuel assembly and rack cell by assuming the impact is simulated by a uniform pressure acting over a circular section of the cell wall. Support leg spring rates were based on the local elasticities of the rack just above the support leg and the pool floor just below the support pad, and the support leg stiffness. The assumptions made in determining impact stiffnesses can be expected to vary significantly between different analysts. The sensitivity of seismic response for these parameters seems to be an area that requires further evaluation.

Three dimensional effects: The literature review revealed that recent fuel rack seismic analyses are based on three dimensional models. Soler and Singh (1983) emphasized the importance of 3-D response in fuel rack systems. They showed that large horizontal displacements can occur when the rack is supported by only one foot and pivots about that point. However, direct comparisons of 2-D to 3-D results were not found. Since 2-D analysis has been used in the past, further studies into this area may be desirable.

Damping: Fluid damping has generally been neglected in the analytical studies. This is a conservative assumption and is in accordance with current NRC recommendations. Dong (1976) noted that damping for single isolated structures decreases with increasing structure size and is generally small. Damping tends to be higher for multiple structures and increases with tight spaces between members.

He recommended additional experimental work in this area. Scale model tests of Japanese and French racks with seismic isolation supports measured damping. Bouche-Pillon et al (1983) reported 15% damping in 1/10 scale model tests. Alliot (1986) reported damping values of 4% for a fully loaded rack and 7% for an empty rack based on tests of a full size 5x9 rack.

Load Cases: Most fuel rack studies have considered cases of a fully loaded and half loaded racks with a lower bound and an upper bound friction coefficient. Gilmore (1982) reported that maximum pool floor loads and fuel impact loads result from the fully loaded case with maximum friction coefficient. Maximum rigid body sliding motion results from the fully loaded case with minimum friction coefficient. Soler and Singh (1983) reported that maximum full rack displacements occurred with the highest friction coefficient. They explained that this was due to the rack's greater tendency to stick and pivot about a single support foot. Their half loaded rack showed even greater displacements which they also attributed to rigid body rotations about the vertical axis. Pop et al (1990) also analyzed full and half full racks, but reported maximum displacements for the full rack case with lowest friction coefficient. The differences between the different investigator's results seem to confirm the difficulty in establishing general rules for defining bounding load cases. Further investigation into this area may be desirable.

Fuel Assembly Representation: Several early studies have investigated and demonstrated the importance of modeling fuel "rattling" effects as opposed to the earlier practice of simply including the mass of the fuel as part of the rack. Studies by Hossain (1980), Durlofsky and Sun (1981) and Harstead et al (1983) concluded that fuel to rack impacts have a significant effect on the overall rack response and generally increase rack loads. The analytical methodologies presented by Gilmore, Soler, Kabir, and Pop included "rattling" fuel assembly representations connected to the rack by nonlinear gap spring elements. Fuel assemblies were typically modeled as single beams based on the gross assumption that all fuel assemblies vibrate in phase. Gilmore's model was slightly refined with a two beam representation of the fuel. Soler's model was the simplest. Half of the fuel mass was included as a single rattling mass at the top of the rack and the other half was included with the rack base mass. There were no direct comparisons of the different modeling techniques. The single beam rattling fuel model appears conservative. Further investigation would be needed to justify less conservative models.

7. RECOMMENDATIONS FOR ADDITIONAL ANALYTICAL STUDIES

This literature review has identified numerous technical papers describing analytical methods for determining the seismic response of spent fuel racks. The methods are based on fundamental principles of structural mechanics and dynamics. However, experimental verification of the accuracy of the methods is very limited.

Shaker table testing of full size and scale model spent fuel rack components has been performed in France and Japan. The tests were limited and geared primarily toward the development of seismic base isolation support designs. The Japanese sliding support pad rack design appears to be similar to U.S. free-standing rack designs. The test was limited in the sense that it included only a single scale model fuel rack in a pool of water and it did not include "rattling" fuel assemblies. Furthermore, the friction coefficients at the support pads were designed to be as low as possible. Nevertheless, this test was the closest simulation to an actual fuel rack seismic test found in the literature. The Fujita paper did not include sufficient details of the design or test parameters for correlation to an independent analysis. If the detailed test data could be obtained, some limited analytical correlation studies could be performed.

Based on currently available information, it appears that additional experimental programs would be needed to verify the adequacy and determine the ranges of validity of current analysis methods for predicting the seismic response of free standing spent fuel racks. However, before proceeding with a test program, additional analytical studies are recommended to provide a better understanding of the issues of concern. The objectives of the analytical studies would be:

1. To investigate the sensitivity and stability of response to variations in modeling parameters, methods and assumptions. The results of the sensitivity studies would be useful both in defining conservative methods

of analysis and in identifying key areas requiring experimental verification.

2. To investigate and quantify potential conservatisms in current analysis methods. The results of these studies would be used to demonstrate the extent to which known conservatisms compensate for uncertainties in the analysis. The need for experimental verification of specific parameters would be identified.

3. Wherever possible, to develop better guidelines for defining acceptable conservative analytical methods, models and assumptions for NRC staff use in the review of high density spent fuel rack licensing amendments.

In order to perform these studies, a reference spent fuel rack analytical model will be developed using a finite element program with nonlinear dynamic analysis capability. The model parameters will be representative of recent spent fuel rack designs. Modeling techniques and assumptions will reflect current analysis methods as described in Section 4.0 of this report. The studies will concentrate on the sensitivity of nonlinear seismic response to variations in parameters. Since a large number of parametric analyses will be performed, the size of the model will be as small as possible but will have a sufficient number of degrees of freedom to characterize its overall structural characteristics and its anticipated responses such as sliding, tilting and impacting with adjacent structures. A set of seismic time history floor motions will be developed as input to the analyses. The motions will represent realistic seismic design spectra at spent fuel pool locations.

As discussed in Section 6.4.3 of this report, an area of potentially significant weakness in current analysis methods is the treatment of multiple rack interactions. This area will be investigated by developing and analyzing a multiple rack model that is comparable to the reference single rack model. The responses of the two models to the same seismic input will be compared and evaluated to determine the significance of the differences in results. For the single rack model, different fluid coupling assumptions based on motion of adjacent racks (in-phase vs. out-of-phase) will be tested to determine whether bounding assumptions for a single rack model can be developed. Parametric studies will be performed to investigate the effects of variations in seismic input and modeling parameters on multiple rack response.

Another area of potentially significant weakness is the treatment of friction between the racks and the pool floor. Using the reference single rack model, parametric studies will be performed in which the coefficient of friction will be varied incrementally between a lower bound and an upper bound value. Variations in seismic input and modeling parameters will also be considered. The results of this study will demonstrate the adequacy of the assumption that the analysis of a fuel rack model with only the minimum and maximum friction values will provide the bounding seismic response. Additional studies will be performed to test the sensitivity of response to differences between static and dynamic friction coefficients or variations of friction coefficient with velocity of sliding.

Additional parametric studies will be performed to test the sensitivity and stability of response to variations in other modeling parameters and assumptions. These studies will investigate variations in impact stiffness, damping, load cases and fuel assembly representation. These studies will provide additional information to determine conservative modeling practices and sensitive areas for which additional testing is needed. It is anticipated that the studies on damping and fuel representation will identify and quantify some of the conservatisms in current analysis methods.

Analytical studies to identify the extent of the differences in response between two dimensional and three dimensional analyses are recommended. Although current seismic analysis methods use 3-D models, a number of fuel racks in the past have been qualified by 2-D methods. Up to a certain threshold level of seismic input, a 2-D analysis may be adequate. Studies to determine that level could provide greater confidence in the adequacy of fuel racks qualified by 2-D analysis.

Further analytical studies into the adequacy of the application of potential theory with small deflections (Fritz, 1972) to represent fluid interaction effects in spent fuel racks are not recommended at this time. A number of analytical studies have been performed to investigate the effects of large displacements. The studies of Soler and Singh (1982) and of S. Singh et al (1990) demonstrated the conservatism of the current method. Alliot (1986) reported reasonable agreement between hydrodynamic masses calculated from potential theory with those calculated from test results. Due to the complexity of the phenomenon, however, future experimental verification of the theory in scale model fuel rack tests may be advisable.

The results of the above recommended studies will provide quantitative information to better assess the weaknesses as well as the strengths (conservatisms) of the current state-of-the-art spent fuel rack analysis methods. The information will be used to identify the areas in which further testing will provide the greatest benefit. In addition, the results should provide information which can be used to develop better guidelines for defining acceptable conservative analytical methods, models and assumptions for NRC staff use in the review of high density spent fuel rack licensing amendments.

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11. ABSTRACT *(200 words or less)*

This report presents the results of a literature review on spent fuel rack seismic analysis methods and modeling procedures. The analysis of the current generation of free standing high density spent fuel racks requires careful consideration of complex phenomena such as rigid body sliding and tilting motions; impacts between adjacent racks, between fuel assemblies and racks, and between racks and pool walls and floor; fluid coupling and frictional effects. The complexity of the potential seismic response of these systems raises questions regarding the levels of uncertainty and ranges of validity of the analytical results.

BNL has undertaken a program to investigate and assess the strengths and weaknesses of current fuel rack seismic analysis methods. The first phase of this program involved a review of technical literature to identify the extent of experimental and analytical verification of the analysis methods and assumptions. Numerous papers describing analysis methods for free standing fuel racks were reviewed. However, the extent of experimental verification of these methods was found to be limited. Based on the information obtained from the literature review, the report provides an assessment of the significance of the issues of concern and makes recommendations for additional studies.

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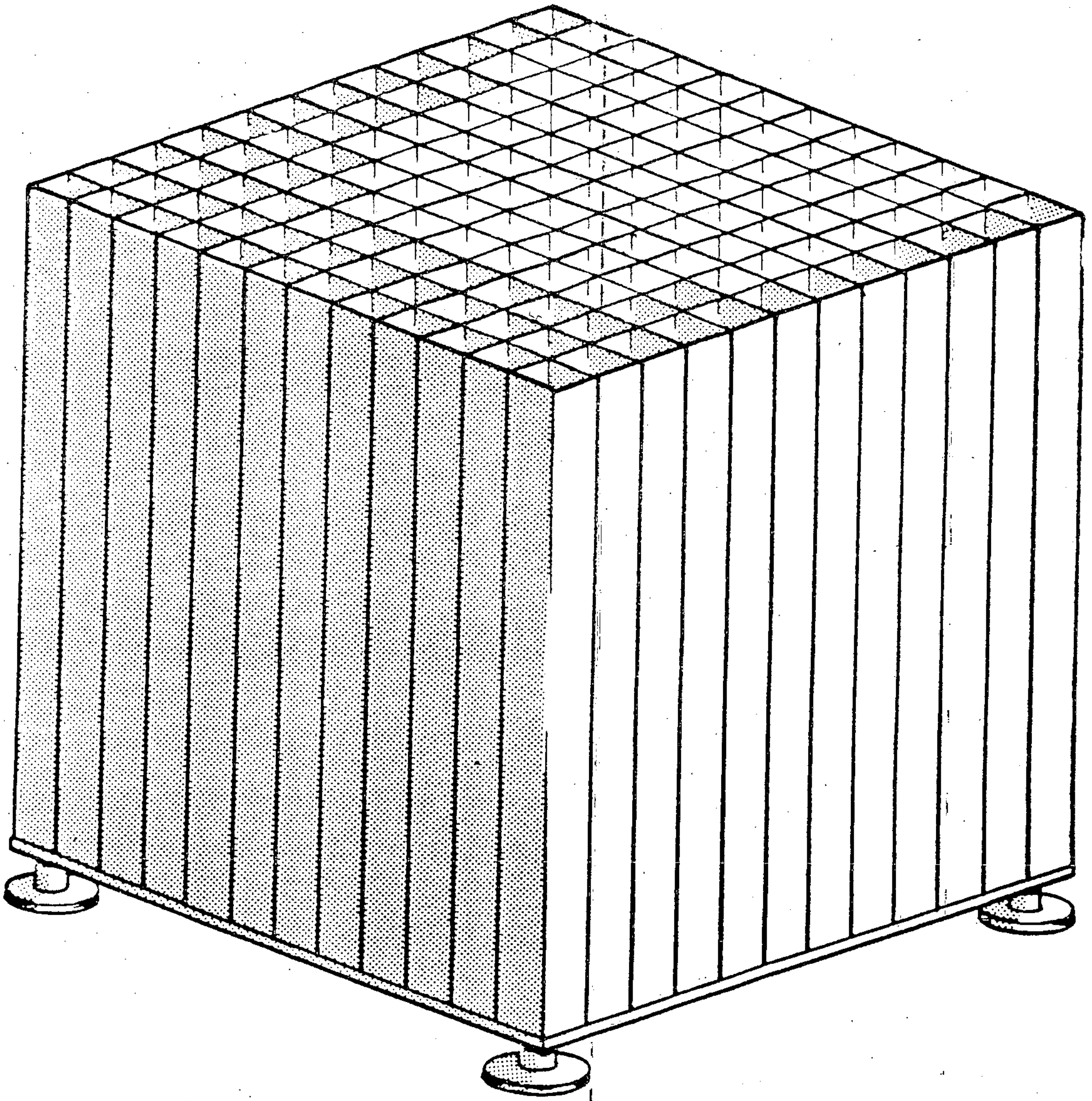

FIGURE 1: Typical Spent Fuel Rack Module

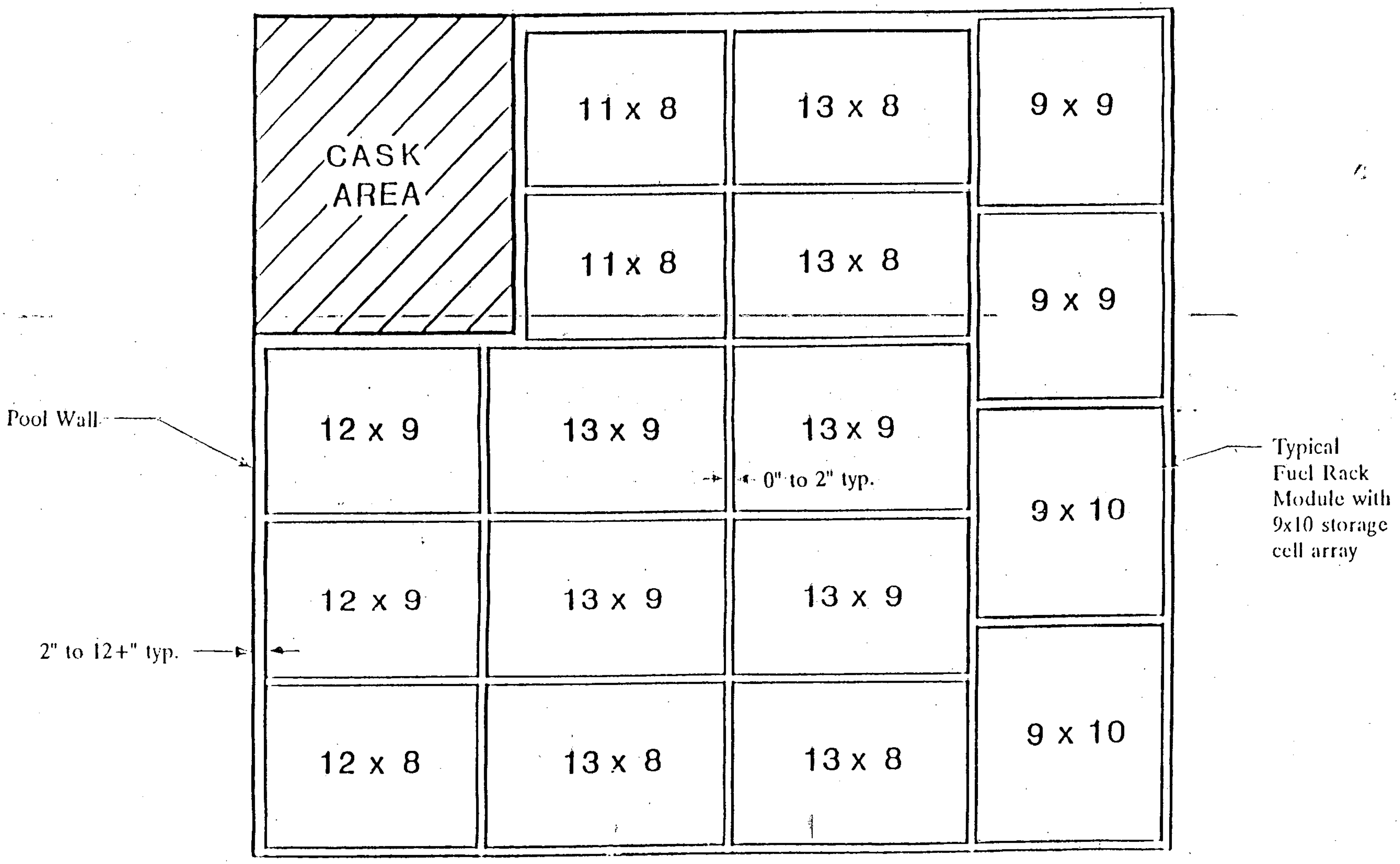

FIGURE 2: Typical Spent Fuel Pool Module Arrangement