Appendix A

TECHNICAL EVALUATION REPORT

EVALUATION OF SPENT FUEL RACKS STRUCTURAL ANALYSIS

OYSTER CREEK NUCLEAR GENERATING STATION
GPU NUCLEAR

NRC DOCKET NO. 50-219
NRC TAC NO. 48787
NRC CONTRACT NO. NRC-03-81-130

FRC PROJECT C5506
FRC ASSIGNMENT 26
FRC TASK 525

Prepared by

Franklin Research Center
20th and Race Streets
Philadelphia, PA 19103

FRC Group Leader: R. C. Herrick

Prepared for

Nuclear Regulatory Commission
Washington, D.C. 20555

Lead NRC Engineer: S. B. Kim

July 5, 1984

Revised August 15, 1984

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FOREWORD

This Technical Evaluation Report was prepared by Franklin Research Center under a contract with the U.S. Nuclear Regulatory Commission (Office of Nuclear Reactor Regulation, Division of Operating Reactors) for technical assistance in support of NRC operating reactor licensing actions. The technical evaluation was conducted in accordance with criteria established by the NRC.

The following staff of the Franklin Research Center contributed to the technical preparation of this report: Vu Con, Maurice Darwish, R. Clyde Herrick, Vincent Luk, Balar Dhillon (consultant), T. B. Belytschko (consultant).

1. INTRODUCTION

1.1 PURPOSE OF THE REVIEW

This technical evaluation report (TER) covers an independent review of GPU Nuclear's licensing report [1] on high-density spent fuel racks for the Oyster Creek Nuclear Generating Station with respect to the evaluation of the spent fuel racks' structural analyses, the fuel racks' design, and the pool's structural analysis. The objective of this review was to determine the structural adequacy of the Licensee's high-density spent fuel racks and spent fuel pool.

1.2 GENERIC BACKGROUND

Many licensees have entered into a program of introducing modified fuel racks to their spent fuel pools that will accept higher density loadings of spent fuel in order to provide additional storage capacity. However, before the higher density racks may be used, the licensees are required to submit rigorous analysis or experimental data verifying that the structural design of the fuel rack is adequate and that the spent fuel pool structure can accommodate the increased loads.

The analysis is complicated by the fact that the fuel racks are fully immersed in the spent fuel pool. During a seismic event, the water in the pool, as well as the rack structure, will be set in motion resulting in fluid-structure interaction. The hydrodynamic coupling between the fuel assemblies and the rack cells, as well as between adjacent racks, plays a significant role in affecting the dynamic behavior of the racks. In addition, the racks are free-standing. Since the racks are not anchored to the pool floor or the pool walls, the motion of the racks during a seismic event is governed by the static/dynamic friction between the rack's mounting feet and the pool floor, and by the hydrodynamic coupling to adjacent racks and the pool walls.

Accordingly, this report covers the review and evaluation of analyses submitted for the Oyster Creek plant by the Licensee, wherein the structural analysis of the spent fuel racks under seismic loadings is of primary concern due to the nonlinearity of gap elements and static/dynamic friction, as well as fluid-structure interaction. In addition to the evaluation of the dynamic structural analysis for seismic loadings, the design of the spent fuel racks and the analysis of the spent fuel pool structure under the increased fuel load are reviewed.

2. ACCEPTANCE CRITERIA

2.1 APPLICABLE CRITERIA

The criteria and guidelines used to determine the adequacy of the high-density spent fuel racks and pool structures are provided in the following documents:

- OT Position for Review and Acceptance of Spent Fuel Storage and Handling Applications, U.S. Nuclear Regulatory Commission, January 18, 1979 [2]

- Standard Review Plan, NUREG-0800, U.S. Nuclear Regulatory Commission

  Section 3.7, Seismic Design
  Section 3.8.4, Other Category I Structures
  Appendix D to Section 3.8.4, Technical Position on Spent Fuel Pool Racks
  Section 9.1, Fuel Storage and Handling

- ASME Boiler and Pressure Vessel Code, American Society of Mechanical Engineers

  Section III, Subsection NF, Component Supports
  Subsection NB, Typical Design Rules

- Regulatory Guides, U.S. Nuclear Regulatory Commission

  1.29 - Seismic Design Classification

  1.60 - Design Response Spectra for Seismic Design of Nuclear Power Plants

  1.61 - Damping Values for Seismic Design of Nuclear Power Plants

  1.92 - Combining Modal Responses and Spatial Components in Seismic Response Analysis

  1.124 - Design Limits and Loading Combinations for Class 1 Linear-Type Component Types

- Other Industry Codes and Standards

  American National Standards Institute, N210-76

  American Society of Civil Engineers, Suggested Specification for Structures of Aluminum Alloys 6061-T6 and 6067-T6.

2.2 PRINCIPAL ACCEPTANCE CRITERIA

The principal acceptance criteria for the evaluation of the spent fuel racks structural analysis for the Oyster Creek plant are set forth by the NRC's OT Position for Review and Acceptance of Spent Fuel Storage and Handling Applications (OT Position Paper) [2]. Section IV of the document describes the mechanical, material, and structural considerations for the fuel racks and their analysis.

The main safety function of the spent fuel pool and the fuel racks, as stated in that document, is "to maintain the spent fuel assemblies in a safe configuration through all environmental and abnormal loadings, such as earthquake, and impact due to spent fuel cask drop, drop of a spent fuel assembly, or drop of any other heavy object during routine spent fuel handling."

Specific applicable codes and standards are defined as follows:

> "Construction materials should conform to Section III, Subsection NF of the ASME* Code. All materials should be selected to be compatible with the fuel pool environment to minimize corrosion and galvanic effects.
>
> Design, fabrication, and installation of spent fuel racks of stainless steel materials may be performed based upon the AISC** specification or Subsection NF requirements of Section III of the ASME B&PV Code for Class 3 component supports. Once a code is chosen its provisions must be followed in entirety. When the AISC specification procedures are adopted, the yield stress values for stainless steel base metal may be obtained from the Section III of the ASME B&PV Code, and the design stresses defined in the AISC specifications as percentages of the yield stress may be used. Permissible stresses for stainless steel welds used in accordance with the AISC Code may be obtained from Table NF-3292.1-1 of ASME Section III Code."

Criteria for seismic and impact loads are provided by Section IV-3 of the OT Position Paper, which requires the following:

- o Seismic excitation along three orthogonal directions should be imposed simultaneously.

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* American Society of Mechanical Engineers Boiler and Pressure Vessel Codes, Latest Edition.

** American Institute of Steel Construction, Latest Edition.

- The peak response from each direction should be combined by the square root of the sum of the squares. If response spectra are available for vertical and horizontal directions only, the same horizontal response spectra may be applied along the other horizontal direction.

- Increased damping of fuel racks due to submergence in the spent fuel pool is not acceptable without applicable test data and/or detailed analytical results.

- Local impact of a fuel assembly within a spent fuel rack cell should be considered.

Temperature gradients and mechanical load combinations are to be considered in accordance with Section IV-4 of the OT Position Paper.

The structural acceptance criteria are provided by Section IV-6 of the OT Position Paper. For sliding, tilting, and rack impact during seismic events, Section IV-6 of the OT Position Paper provides the following:

"For impact loading the ductility ratios utilized to absorb kinetic energy in the tensile, flexural, compressive, and shearing modes should be quantified. When considering the effects of seismic loads, factors of safety against gross sliding and overturning of racks and rack modules under all probable service conditions shall be in accordance with the Section 3.8.5.II-5 of the Standard Review Plan. This position on factors of safety against sliding and tilting need not be met provided any one of the following conditions is met:

(a) it can be shown by detailed nonlinear dynamic analyses that the amplitudes of sliding motion are minimal, and impact between adjacent rack modules or between a rack module and the pool walls is prevented provided that the factors of safety against tilting are within the values permitted by Section 3.8.5.II.5 of the Standard Review Plan

(b) it can be shown that any sliding and tilting motion will be contained within suitable geometric constraints such as thermal clearances, and that any impact due to the clearances is incorporated."

3. TECHNICAL REVIEW

3.1 MATHEMATICAL MODELING AND SEISMIC ANALYSIS OF SPENT FUEL RACK MODULES

As described in the Licensee's report [1], the spent fuel rack modules are totally immersed in the spent fuel pool, wherein the water in the pool produces hydrodynamic coupling between the fuel assembly and the rack cell, as well as between the fuel rack module and adjacent modules. The hydrodynamic coupling significantly affects the dynamic motion of the structure during seismic events. The modules are free-standing, that is, they are not anchored to the pool floor or connected to the pool walls. Thus, frictional forces between the rack base and the pool liner act together with the hydrodynamic coupling forces to both excite and restrain the module in horizontal and vertical directions during seismic events. As a result, the modules exhibit highly nonlinear structural behavior under seismic excitation, for which it is necessary to adopt time-history analysis methods to generate accurate and reliable analytical estimates.

Pool slab acceleration data used in the analysis were derived from the original pool floor response spectra. Structural damping of 4% for the racks was assumed for the safe shutdown earthquake (SSE) condition.

A lumped mass dynamic model was formulated by the spent fuel racks' vendor in accordance with computer code DYNAHIS to simulate the major structural dynamic characteristics of the modules. Two sets of lumped masses were used, one to represent the fuel rack module and another to represent the fuel assemblies. The lumped masses of these racks were connected by beam elements. The lumped masses of fuel assemblies were linked to those of the rack by gap elements (nonlinear springs). Frictional elements (springs) were used to represent the frictional force between the rack base and pool liner. Hydrodynamic masses were included in the model to approximate the coupling effect between the water and the structure. The model was subjected to the simultaneous application of three orthogonal components of seismic loads derived from a stated earthquake with one vertical and one horizontal component.

An elastostatic model was first used to evaluate element stiffness characteristics for use in the dynamic model. The results generated from the dynamic model, in terms of nodal displacements and forces at nodes and elements, were then introduced to the elastostatic model to compute the detailed stresses and corner displacements in the module.

The resulting stresses at potentially critical locations of the module were examined for design adequacy in accordance with the acceptance criteria. The possibilities of impact between adjacent racks and the tipping of the module were also evaluated.

3.2 EVALUATION OF THE ELASTOSTATIC MODEL

3.2.1 Element Stiffness Characteristics

An analytic approach for stressed-skin models was adopted to evaluate the stresses and deformations in the rack modules [1, 3]. Essentially, the module was represented by lumped masses linked by beam elements possessing equivalent bending, torsional, and extensional rigidities and shear deformation coefficients. These properties were used to determine the stiffness matrix for the elastic beam elements.

Impact springs were used between the lumped masses of the fuel assemblies and those of the fuel rack to simulate the effect of impact between them. The spring rates of these impact springs were determined from the local stiffness of a vertical panel and computed by finding the maximum displacement of a 6.0-in-diam circular plate built in around the bottom edge and subject to a specified uniform pressure. The Licensee did not mention the corresponding compliance of the fuel assembly in determining the value of the impact springs. The effect of neglecting the compliance of the fuel assembly is conservative in that it would sharpen the impact force, i.e., produce a higher force for a shorter time.

Linear frictional springs in two orthogonal directions were placed at four corner positions on the rack base to represent the effect of the static frictional force between each mounting pad and the pool liner. Angular frictional springs about the vertical axis of each pad representing the distribution of pad friction under angular motion were not provided in the model. Review of the application of angular frictional springs indicated that their contribution to the displacement solution would be negligible.

3.2.2 Stress Evaluation and Corner Displacement Computation

Computer code "EGELAST", a proprietary code of the Joseph Oat Corporation, was used to compute critical stresses and displacements in the rack module and its support. Nine critical locations were identified on the cross section of rack chosen for stress evaluation, including the four corners of the cross section, the midpoint of each of the four sides, and its center. For every time step, the stress and displacement results from the dynamic model were input to "EGELAST" for computation. Stresses were evaluated at each of the nine critical locations at each selected cross section of the rack. Displacements were calculated at each of the four corners of the cross section. Maximum stresses and corner displacements were determined for all time steps.

3.3 EVALUATION OF THE NONLINEAR DYNAMIC MODEL

3.3.1 Assumptions Used in the Analysis

The following assumptions were used in the analysis:

a. Adjacent rack modules were assumed to have motions equal and opposite to the rack module being analyzed. This defined a plane of symmetry in the fluid of each space between the module being analyzed and the adjacent modules and permitted the analysis of an isolated rack module.

b. All fuel rod assemblies in a rack module were assumed to move in phase. This was necessary for the lumped mass model and was assumed to produce the maximum effects of the fuel assembly/storage cell impact loads.

c. The effect of fluid drag was conservatively omitted.

Assumption "a" was made to reduce the collection of fuel racks in the spent fuel pool to a manageable three-dimensional problem--that of one rack module. The assumption offers a degree of conservatism in that it reduces the available clearance space between rack modules for dynamic displacement without impact to one-half the initial clearance. A further discussion of its effects upon hydrodynamic coupling is presented in Section 3.3.3 of this report.

Assumption "b", said to offer conservatism, is not necessarily conservative. Regardless of the initial position of each individual fuel assembly, all fuel assemblies within a fuel rack module will settle into in-phase motion soon after the rack module is set in motion. This is because each fuel assembly is a long vertical column which pivots about its base and moves within a very small clearance within the rack cell.

With respect to Assumption "c", review indicates that fluid drag is a complex issue [4, 5, 6]. The OT Position Paper [2], which forms the principal basis of acceptance criteria for this plant, indicates from a previous study [5] that viscous damping is generally negligible and that increased damping due to submergence in water is not acceptable without applicable test data and/or detailed analytical results. However, a more recent paper [6] indicates that the hydrodynamic damping of a perforated plate vibrating in water is comprised of two regimes, the smaller of which is proportional to the kinematic viscosity, while the larger is "a non-linear regime where the log decrement is proportional to the vibrational velocity and is independent of viscosity." Thus, even for the small displacements of a vibrating perforated plate where hydrodynamic flow about the plate is not developed, Reference 6 indicates that fluid damping independent of viscosity is present. This is supported by Fritz [4], who, in addition to developing relationships for coupled hydrodynamic mass in submerged flexible body vibration, developed the associated damping relationships based upon Darcy friction factors that also show damping to be proportional to velocity as well as fluid density. While Fritz's relationships indicate the damping magnitude to be very small, the motion of a fuel assembly throughout its clearance from the cell walls is sufficient to promote some hydrodynamic flow about, and through, the fuel assembly that is more fully developed than for the case of vibrating bodies.

Since the Licensee has not taken any credit for impact structural damping of the limber fuel assembly, it appears that a small amount of damping could be justified as either impact damping or equivalent fluid drag without compromising the conservatism of the analysis.

3.3.2 Lumped Mass Model

The lumped mass approach was used in the dynamic model, wherein the mass of the fuel rack was lumped at five equidistant locations as shown in Figure 1. For horizontal motion, the rack mass was proportioned at one-quarter of the total mass for each of the three middle mass nodes and at one-eighth of total mass each for the top and the bottom nodes. The mass of the base plate and support structure was lumped with the bottom node. For the fuel assemblies, five lumped masses were used in a similar pattern of distribution. For vertical motion, two-thirds of the racks' dead weight acted at the bottom mass node, with the remaining one-third applied at the top node. All of the dead weight (gravitational force) of the fuel assembly was at the bottom node.

3.3.3 Hydrodynamic Coupling Between Fluid and Rack Structure

When an immersed fuel rack is subject to seismic excitation, hydrodynamic coupling forces act between the fuel assembly and fuel rack masses, as well as between the fuel rack and adjacent structures. The Licensee applied the linear model of Fritz [4] to estimate these coupling effects. In evaluating the hydrodynamic coupling between adjacent racks, the Licensee also assumed that the rack was surrounded on all four sides by rigid boundaries separated from the rack module by an equivalent gap. As discussed previously in Section 3.3.1, the Licensee chose to model the dynamic condition wherein adjacent rack modules were assumed to have motions equal and opposite to the module being analysed. While this assumption neglects the fact that adjacent rack modules may have quite different dynamic response characteristics, such as to interact and respond as a global system, it does provide a very manageable reduction in the analytic modeling of the problem while addressing the case in which the

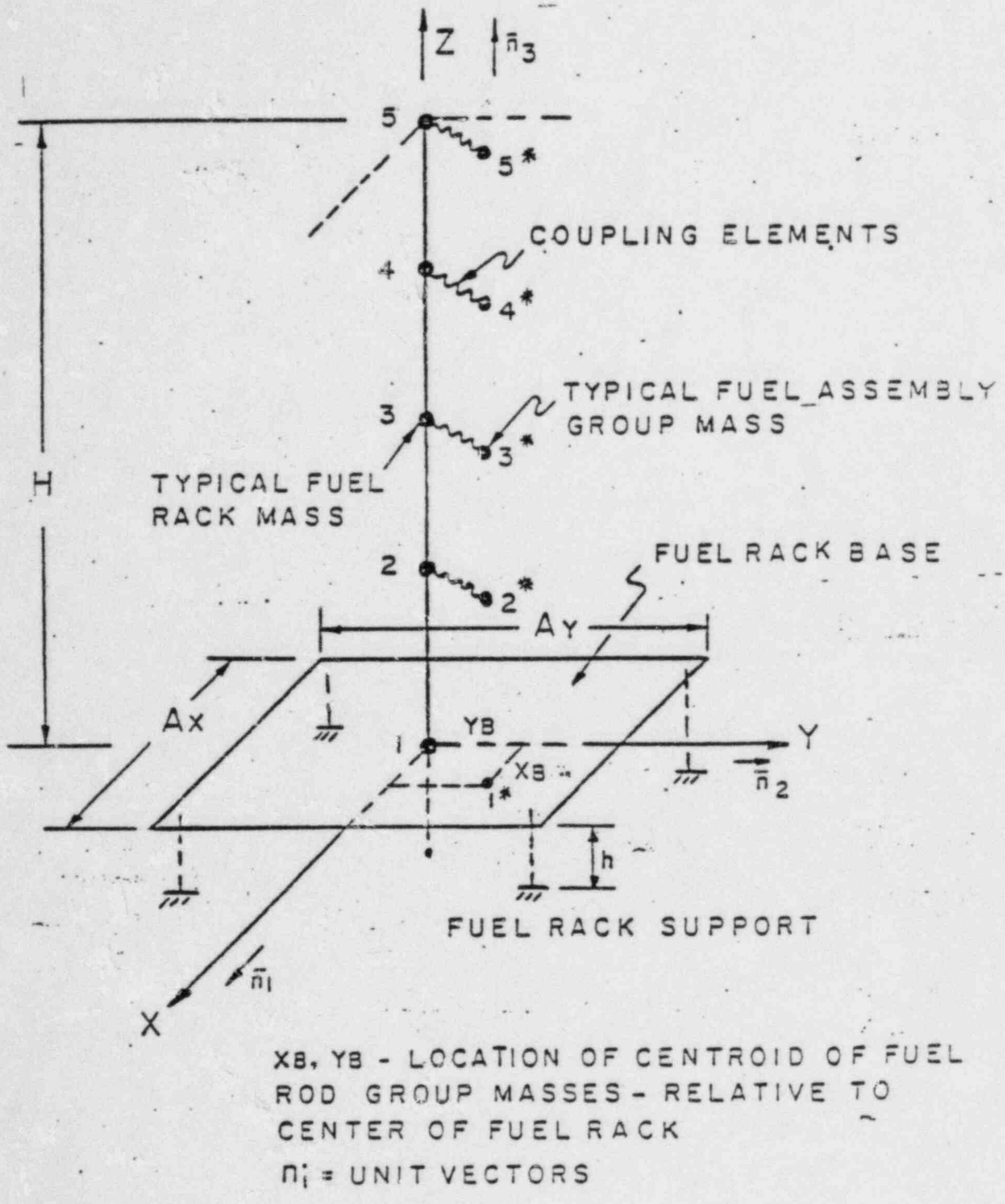

Figure 1. Dynamic Model

available space for dynamic rack displacement is at a minimum. Review and evaluation of this assumption has indicated that, while the associated conservatism cannot be evaluated directly within the scope of this review, the assumption is considered to provide an adequate modeling technique so long as the resulting dynamic displacements remain small compared to the available displacement space.

Fritz's [4] method for hydrodynamic coupling is widely used and provides an estimate of the mass of fluid participating in the vibration of immersed mass-elastic systems. Fritz's method has been validated by excellent agreement with experimental results [4] when employed within the conditions upon which it was based, that of vibratory displacements which are very small compared to the dimensions of the fluid cavity. Application of Fritz's method for the evaluation of hydrodynamic coupling effects between fuel assemblies and the rack cell walls, as well as between adjacent fuel rack modules or rack modules and a pool wall, has been considered by this review to serve only as an approximation of the actual hydrodynamic coupling forces. This is because the geometry of a fuel assembly within a rack cell, as well as the geometry of a fuel rack module in its clearance space, is considerably different than that upon which Fritz's method was developed and experimentally verified.

Although the limitations of Fritz's [4] modeling technique for hydrodynamic coupling of fuel assemblies within a rack cell, and of rack modules adjacent to other rack modules or a pool wall, indicate that the hydrodynamic coupling is accurate only for dynamic displacements that are small relative to the available displacement clearance, the Licensee provided the following [7]:

> "The fuel assembly is modelled as a blunt square body inside a square cross section container. The hydrodynamic coupling mass utilizes Fritz's well known correlations for infinitesimal motions. Inclusion of finite amplitude motions (which is the case for a rattling fuel assembly) is known to significantly reduce the peak rack seismic response (vide, "Dynamic Soupling in a Closely Spaced Two Body System Vibrating in a Liquid Medium", by A. I. Soler and K. F. Singh, Proc. of the Third International Conference on Vibration in Nuclear Plant, Keswick, D. K. 1982). Therefore, Fritz's equation used in the analysis lead to an upper bound on the solution."

3.3.4 Equations of Motion

The Licensee included 32 degrees of freedom in the lumped mass model. All rack mass nodes were free to translate and rotate about two orthogonal horizontal axes. The top and bottom rack mass nodes had additional freedom for translation and rotation with respect to the vertical axis. The bottom fuel assembly mass node was assumed fixed to the base plate, whereas the remaining four fuel assembly mass nodes were free to translate along the two horizontal axes.

The structural behavior of the lumped mass model was completely described in terms of 32 equations of motion, one for each degree of freedom, which were obtained through the Lagrange equations of motions. Review and evaluation has confirmed the acceptance of this approach.

3.3.5 Seismic Inputs

With respect to seismic excitation, the Licensee indicated in the original submittal [1] that the model was subjected to simultaneous application of the three orthogonal excitations. However, in response [8] to a list of questions, the Licensee stated that only the vertical seismic motion and the horizontal seismic motion components were considered and that the specified horizontal seismic component was broken into two additional components acting along the X and Y directions. In a communication* with the Licensee on May 25, 1984, it was learned that the horizontal seismic motion was assumed to act at an angle of 45° to the rack for division into X and Y components.

Evaluation of this approach has indicated that the placement of the horizontal seismic excitation of a 45° angle with respect to the fuel rack module was an arbitrary assumption. This was valid to show the dynamic response under that three-dimensional excitation, but unless the earthquake has a prescribed horizontal orientation with respect to the plant, the Licensee should have investigated and reported on the worst-case orientation.

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*R. C. Herrick telephone communication with Dr. Alan Soler on May 25, 1984.

Since the orientation with respect to the plant was not specified, the Licensee provided additional dynamic response runs for those rack modules believed to represent the worst case. The displacements for these runs are included in this report.

3.3.6 Integration Time Step

With respect to the integration time step, the Licensee indicated that a central difference scheme was used in the DYNAHIS program to perform the numerical integration of the equations of motion discussed in the previous section. In a May 7, 1984 meeting [9], the Licensee stated that a time step of 0.00002 sec was selected based on the lowest vibratory period of the fuel rack. Concurrent with this review, the Licensee investigated the effect of time step size on the stability of the dynamic displacement solution. The results of the investigation were presented and discussed at a working meeting [10] in the USNRC offices. Limited points on a curve of computed displacement amplitude versus the integration time step size appeared to confirm that the 0.00002-sec time step used for some of the computer solutions reviewed herein yielded a converged solution. However, concern was raised that the range of the time step size providing a satisfactory solution was very small [10].

In response to the concerns raised during the review, the Licensee continued a study of the computer solution toward providing verification of an adequate solution. A concluding summary of these actions is included in Section 3.3.10 of this report.

Section 3.2.1 of this report discusses the fact that the Licensee did not include the compliance of the limber fuel assembly in the estimation of the spring constant of the impact springs between the fuel assembly mass and the rack cell mass. Also, the Licensee did not employ any damping between these masses when at least some small value of impact damping could have been justified. Damping between these masses generally aids the convergence of the solution, but a smaller spring constant would provide a more significant effect. The mass of the fuel assembly, in association with a stiff impact spring, would respond in a very short time. This sharp response in the

Licensee's analytic model may contribute to the observed need for very small integration time steps and the associated narrow range in time step size between solution convergence and the effects of round-off error.

3.3.7 Frictional Force Between Rack Base and Pool Surface

The Licensee used the maximum value of 0.8 and the minimum value of 0.2 to cover the range of static coefficient of friction between rack base and pool liner. The Licensee indicated that the maximum coefficient of friction usually produces the maximum rack displacement [9]. However, the reported analysis results [1, 3] (see also Section 3.3.9 of this report) show that the opposite can be true. The Licensee should provide further clarification.

Rabinowicz, in a report to the General Electric Company, focused attention on the mean and the lowest coefficient of friction [11]. Rabinowicz also discussed the behavior of static and dynamic friction coefficients, indicating that the dynamic, or sliding, coefficient of friction is inversely proportional to velocity. Thus, the use of static and dynamic coefficients of friction could produce larger rack displacements; that is, the higher value of static friction could permit the buildup of energy that may require a larger displacement at a lower value of dynamic friction to dissipate.

A key to the importance of the complicating consideration of static and dynamic friction appears to be whether significant rack energy is dissipated in sliding friction. If only minimal rack energy is dissipated in sliding friction, then more complete methods of modeling friction would make very little difference in the resulting computed displacement.

3.3.8 Impact with Adjacent Racks

As indicated in the Licensee's submittals [1, 3], one of the Licensee's structural acceptance criteria is the kinematic criterion. This criterion seeks to ensure that adjacent racks will not impact during seismic motion. As shown in Figure 2, gaps between racks vary from rack to rack. In response to FRC's list of questions [13], the Licensee stated that an equivalent gap was

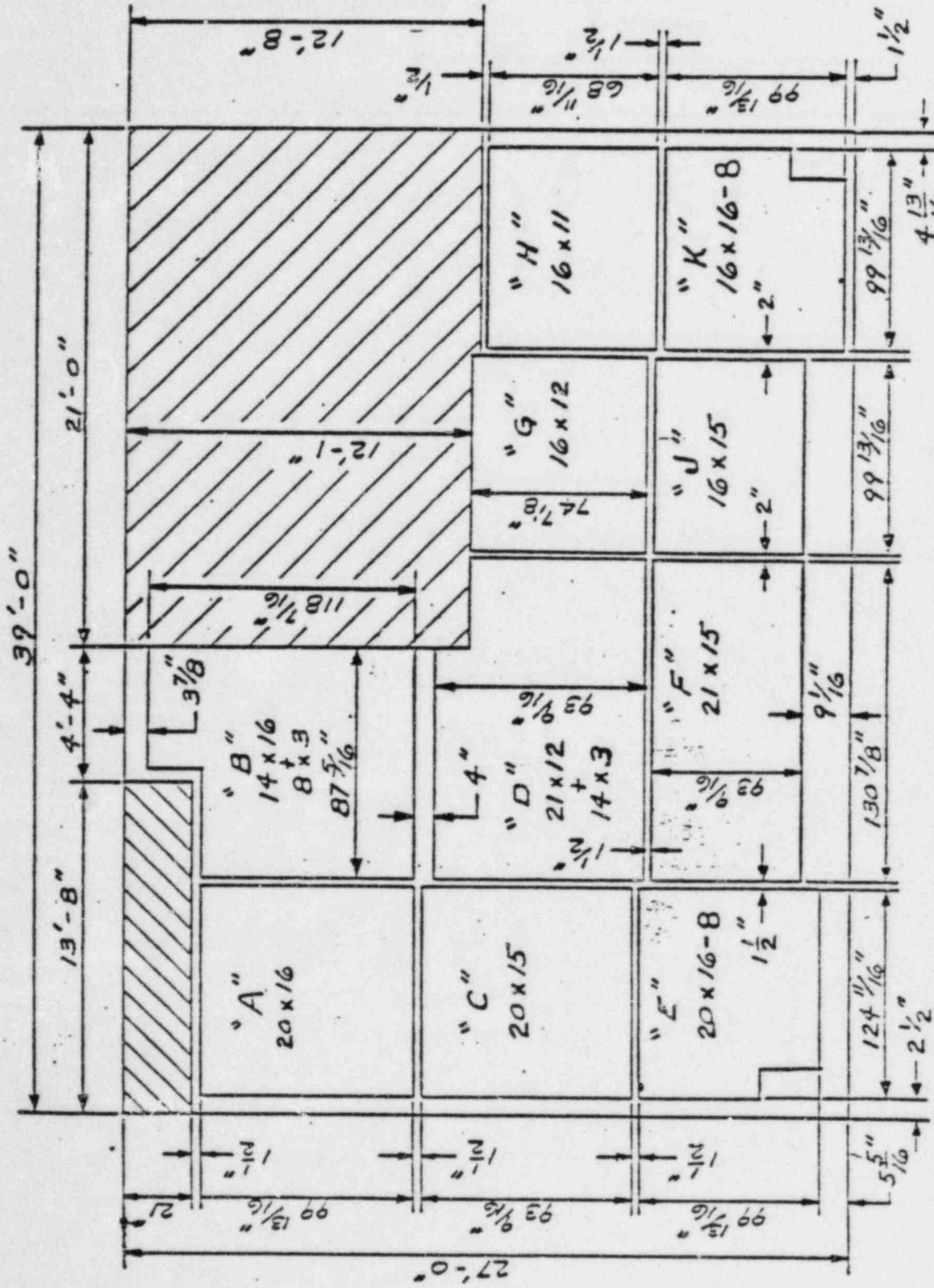

Figure 2. Module Layout

used to simplify the inter-rack interaction problem to a standard configuration [9]. This equivalent gap will form a bounding space around the rack, which fluid is assumed not to cross.

3.3.9 Rack Displacement Results

For the Licensee's mathematical model, the no-collision-of-adjacent-racks criterion requires that the maximum rack displacement be smaller than half of the gap between racks. If both adjacent racks are analyzed, then the sum of their displacements should be less than the rack clearance. While it is acceptable to use an average, or equivalent, gap for the purpose of assessing the contribution of fluid action around a fuel module with unequal spacing from other modules, the actual minimum operating gap must be used for comparison with the computed displacements. Although the module may, under the influence of seismic excitation and induced fluid forces, move toward the position of equal gaps from its initial position, repeated collision with adjacent modules could take place before any minimum gap is widened. Thus, comparison of the computed fuel module displacements with the minimum operating gap is essential. However, it appears that the Licensee compared displacements to the equivalent gap.

During the review, the Licensee provided rack module dynamic displacement data in addition to those provided in the Licensee's reports [1, 3]. The additional dynamic displacement data [12] were supplied when it was discovered that the data under review from the Licensee reports [1, 3] were computed at an integration time step of 0.00003 sec instead of 0.00002 sec as reported by the Licensee's response [9] to a request for additional information. Both sets of data are reported and discussed below. Also, the Licensee provided additional displacement solutions toward verification that the solutions for the 0.00002-sec integration time step represent a valid solution not adversely affected by a lack of convergence or computer round-off error. This additional information is presented and discussed in Section 3.3.10 of this report.

The following module displacement data were selected from the Licensee's reports [1, 3]:

Representative Displacement Data from Licensing Report [1]

Rack Type	Cell/Module	Array Size (cells)	Height of Rack Baseplate from Pool Liner (in)	Coefficient of Friction	Maximum X-Displacement (in)
E	312	20x16	11.5	0.8	0.1254
				0.2	0.655
F	315	21x15	6	0.8	1.298
				0.2	0.535

All racks were fully loaded in these cases.

It was noted that rack module F had a maximum computed displacement of 1.298 in, whereas the installed clearance with the adjacent module was 1.5 in as shown by the Licensee's Figure 2.1 [1]. Thus, 1.298 in was greater than half the 1.5-in gap (0.75 in), but the combined displacement of E and F was less than the total clearance.

Comparison of the rack displacement data for racks E and F listed above indicated dramatically different displacements exhibited by two similar racks. Assuming the maximum coefficient of friction for each rack is 0.8, rack F yielded a displacement 10 times larger than that of rack E. For rack E, the maximum displacement occurred with the minimum friction coefficient of 0.2. The major difference between modules E and F appeared to be the height of the support leg, 11.5 versus 6.0 in.

As noted above, the displacement amplitude for the additional data points computed with an integration time step of 0.00002 sec is considerably less than that reported in the Licensee's reports [1, 3], and was computed using a time step of 0.00003 sec. The additional data points follow:

Additional Displacement Data Provided by Joseph Oat Corporation

Rack Type	Coefficient of Friction	Earthquake Horizontal Direction	Integration Time-Step (sec)	Maximum X-Displacement North-South (in)
F	0. [illegible]	45° to north-south	0.00002	0.172
F	0.8	0° to north-south	0.00002	0.847

The first item in the listing of additional data, and showing a dynamic response displacement of 0.172 in, was computed for rack module F under the same physical conditions as yielded 1.298 in in the original data. The difference appears, from the Licensee's study, to be due to the lack of convergence of the numerical solution with the larger time step. While, as discussed in Section 3.3.6, more data points on the convergence curve of the Licensee's study are required to provide full confidence that adequate convergence is reached with an integration time of 0.00002 sec, the Licensee presented [10] evidence indicating that convergence may have been reached. Thus, instead of a displacement of 1.298 in, a fully converged solution would be on the order of 0.17 in to remove questions of possible impacting under the conditions as mentioned above.

The second data point in the above listing of additional data supplied by the Joseph Oat Corporation provided the maximum dynamic displacement computed for rack module F where the full horizontal earthquake was applied across the short dimension (north-south) of the rectangular fuel module. This was computed using an integration time step of 0.00002 sec. Note the increase in displacement that resulted from applying the earthquake directly across the smaller dimension of the module instead of directing it at an approximate angle of 45° to that direction.

Note also that the displacement of 0.847 in is still larger than 0.75 in (half of 1.50-in clearance between modules) and would indicate the possibility of rack module impacts, depending upon the amplitudes of displacement of rack module E. However, computations were not reported for rack module E for a time step of 0.00002 sec, or for application of the earthquake in the north-south direction.

Computed displacements for intermediate values of friction coefficient, such as 0.4 and 0.6, may show a trend and therefore be useful in establishing a relationship between the coefficient of friction and rack displacement. While these were not provided by the Licensee, it is not believed that the reporting of displacement data for intermediate values of friction would alter the conclusions of this review.

3.3.10 Summary and Conclusions of the Dynamic Displacement Solution

In the study of solution convergence and stability, the Licensee experienced difficulty in working with the very small time steps required by the 32 degree-of-freedom (DOF) model with the conservatisms as discussed in Section 3.3.6. In the course of this study, the Licensee turned to a 14 DOF model of the same spent fuel rack (rack module F), where the time step of integration and proof of convergence were more readily shown, to validate the former 32 DOF solution by showing that the two models provide essentially the same displacement results.

The Licensee provided the following discussion [7]:

> "the computed peak displacement of .843" (coefficient of friction .8, horiznta1 acceleration aligned with the narrow direction) .00002 sec. time increment solution could not be further refined due to round-off errors. To obtain the converged value and to demonstrate convergence, Oat ran the problem on a 14 degree-of-freedom model. The results are summarized below.
>
> | Cat File No. | Time Step (sec) | Maximum Displacement (inch) |
> |---|---|---|
> | DGPT60 | .0003 | .6631 |
> | DGPT61 | .0002 | .6631 |
> | DGPT62 | .0001 | .6631 |
>
> The successful convergence of the 14 D.O.F. model results is attributed to the elemination of rotary inertia terms from the equations of motion.

The equations of motion are derived in the published paper, "Seismic Response of Free Standing Fuel Rack Construction to 3-D Floor Motion", by A. I. Soler and K. P. Singh, Nuclear Engineering and Design, American Nuclear Society (c. 1984).

The displacements reported in the foregoing are upper bound solutions in view of the fact that several simplifying assumptions, which render the analysis conservative, have been employed in obtaining the results. Lower than permitted values of system dampling, no credit for additional damping in the fuel assemblies, and synchronized impact of all fuel assemblies in a module, are among the many assumptions which make the computed values quite conservative."

In comparing the displacement computed by the 32 DOF model (0.843 in) with that of the 14 DOF model (0.663 in), it is not known whether the displacement of 0.843 in for rack module F represented a fully converged solution. Because the lack of full convergence generally tends to increase the magnitude of the computed displacement, the comparison of the values of 0.843 and 0.663 is accepted as providing reasonably good agreement. The fact the computed displacements for the 14 DOF model are the same value for three time step values indicates that the numerical solution for that model exhibited satisfactory stability and convergence. A recognized consultant retained to review the numerical analysis procedures concurs with these statements [14].

Although the 14 DOF model has not been reviewed in sufficient depth for acceptance as a general method for dynamic displacement and stress, it is believed that the model is sufficiently defined to provide valid solutions of the dynamic displacement. Thus, it is the position of this review that the results of the 14 DOF model serve only to confirm that the previous 32 DOF solution is the valid, sufficiently converged solution required for the spent fuel racks.

With respect to the possibility of impacts, the lower displacement value of 0.663 in that was computed with the 14 DOF model exhibiting good convergence coupled with the conservative assumptions in the analysis is accepted as indicating that the rack displacement due to a combination of sliding and tilting is less than one-half of the 1.5-in clearance gap between the adjacent rack modules.

3.3.11 Stress Results

According to References 1 and 2, all critical stresses are within the allowables required by the stress criteria described in Section 2. Of all cases reported, the full rack with maximum coefficient of friction of 0.8 yields the highest stress factors. Note that the stresses represent the large displacements associated with the non-convergence solution for at least rack module F.

3.4 REVIEW OF SPENT FUEL POOL STRUCTURAL ANALYSIS

3.4.1 Spent Fuel Floor Structural Analysis

The Oyster Creek fuel pool slab is a reinforced concrete plate structure with additional beams and end walls. The analysis was presented to demonstrate structural inte rity for all postulated loading conditions and compliance with ACI-349 and NUREG-0800.

3.4.2 Licensee's Assumptions

The Licensee made the following assumptions for the analysis:

1. The floor slab was modeled with plate elements, and the reinforced concete beams are represented by beam elements. The walls were not represented in the model. The slab was assumed to be clamped at the reactor wall and simply supported at the remaining walls.

2. The stiffness and strength properties were based on complete cracking of concrete.

3. All the racks were fully loaded and a 40-ft column of water was included in dead weight.

4. The dynamic model analysis was based on nine master degrees of freedom, which corresponded to the locations of concentrated loads (racks). The dynamic mass included the reinforced concrete mass and the virtual mass of water. The dynamic analysis considered both seismic excitation and impact loading from rack analysis.

The effect of assumed boundaries in the first assumption was conservative for slab moments on the north-south span, but may not be conservative for the east-west span, especially when the effects of hydrostatic and hydrodynamic loads on the walls are considered.

The other assumptions were reviewed and found to be satisfactory.

3.4.3 Dynamic Analysis of Pool Floor Slab

The Licensee described the general formulation of the dynamic model analysis procedure. The dynamic analysis was performed for both vertical seismic excitation and impact loading from racks. A 9 DOF model is used with 4% damping for OBE events and 7% damping for SSE events. The maximum slab deflections at the nine selected coordinates were compared to the corresponding displacements from the static finite element analysis, and the amplification factors were obtained.

The results of the Licensee's analysis indicated a fundamental frequency of 28.3 Hz and the amplification factors of 0.005 for the seismic event and 0.919 for the rack impact loads.

The exceptionally low value of amplification factor (0.005) was shown by the Licensee [10] to be produced by the summation of nearly equal positive and negative contributions related to the particular earthquake used. A slightly differnt earthquake would produce a much larger amplification factor. However, there is ample margin in the structure.

In addition to the dynamic analysis considered by the Licensee, this review of the seismic analysis of the spent fuel rack modules and the analysis of the spent fuel pool structure has revealed the existence of high dynamic vertical forces in the mounting feet of the fuel rack modules. Dynamic loadings supplied by the Licensee in response to questions submitted through the NRC indicated that the instantaneous vertical force on a mounting foot of module F, for example, reaches a value of approximately 242,000 lb.* Since the mounting foot on which this occurs is not defined, it must be applied to the worst case, that of the mounting foot incorporating a single 4.5-in-diam mounting pad and located adjacent to the spent fuel pool drainage channel. The resulting pressure on the liner and concrete exceeds 15,000 psi,* which is greater than the strength of the concrete and may cause crushing of the

* Maximum value for rack module F from the analysis using 0.00003 sec integration time steps and yielding large displacements.

concrete under the mounting pad and pool liner. In addition, since the load may be applied to the spent pool floor immediately adjacent to the edge of the drainage channel, the Licensee should provide assurance that the corner of the drainage channel will not fail in shear if it cannot be proven that the high dynamic load will not be confined to another mounting foot of the fuel rack module.

It may be noted that the Licensee discussed [10] analysis methods by which the loads and stresses above could be shown to be satisfactory. However, if the dynamic rack module displacement is shown in a fully converged solution to be much lower, the corresponding loads and stresses discussed here will be lower.

3.4.4 Results and Discussion

The following critical loading combinations were considered by the Licensee:

a. $1.4\ D + 1.9\ E$
b. $0.75\ (1.4\ D + 1.4\ T_o)$
c. $0.75\ (1.4\ D \pm 1.4\ T_o \pm 1.9\ E)$
d. $D \pm T_o + E')$

where:

D = dead load of slab plus 40-ft column of water and dead weight of fully loaded racks

T_o = thermal loading due to 21° temperature differential across the slab depth

E = OBE seismic load

E' = SSE seismic load.

The moments due to thermal gradient were based on an eqivalent homogenous slab with all floor curvatures suppressed and slab rigidity based on cracked condition.

The results of the analysis were summarized in Tables 8.2 through 8.7 of Reference 1. Table 8.7 of Reference 1 gives the critical pool floor structural integrity checks. It shows that the actual factored values of slab and beam moments and shears are lower than the ACI allowable values by a factor ranging from approximately 1.5 to 3.0.

3.5 REVIEW OF HIGH-DENSITY FUEL STORAGE RACKS' DESIGN

Comments and conclusions regarding Section 7 [1], entitled "Other Mechanical Loads," are contained in the following subsections.

3.5.1 Fuel Handling

In Section 7.1.1 [1], the Licensee discusses the mechanical loading due to fuel handling. A downward load of 1700 lb is considered to be acting on the rack; the load is applied on a 1-in characteristic dimension. No details were given in the report regarding the basis of this characteristic length. However, it is understood that this characteristic length is based on the two fuel cell wall thicknesses, each of 0.063 in.* Independent checking performed by the reviewer indicates that the local stress in the rack due to a 1700-lb downward load is in close agreement with the 14,000-psi stress shown in the report. Therefore, it can be concluded that the approach is conservative and that the analysis is satisfactory.

3.5.2 Dropped Fuel Accident I

Section 7.1.2 [1] demonstrates that the fuel assembly (600 lb), when dropped from 36 in above the storage location onto the base, will not penetrate the base plate.

The 600-lb weight used in this calculation is not in agreement with the fuel assembly weight (800 lb) used in Section 7.1.1 [1]. It is understood that the effective weight to be used should include the buoyancy effect (estimated as 75 lb acting upwards), resulting in a net effective load of about 725 lb, which is larger than the 600 lb used.

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*R. C. Herrick telephone communication with K. Singh on May 18, 1984.

Detailed calculations on this subject are given in the seismic analysis report by A. I. Soler [3], but the reviewed report did not mention these calculations.

It can be concluded that, even by using the larger load, the base plate penetration estimated as 0.446 in will be increased slightly but will be less than the base plate nominal thickness of 0.625 in; therefore, the base plate will not be pierced.

3.5.3 Dropped Fuel Accident II

Section 7.1.3 of the report [1] discusses the effect of a fuel assembly dropping from 36 in above the rack and hitting the top of the rack. The report indicates that the maximum local stress is limited to 21 ksi and is less than the yield stress of the material of 25 ksi. Although no details were given in the reports [1, 3] about the possibility of local buckling that could alter the cross-sectional geometry of the racks, the Licensee explained satisfactorily [10] that any such deformation will not jeopardize the fuel assemblies.

3.5.4 Local Buckling of Fuel Cell Walls

Section 7.2 of the report [1] demonstrates that the racks have adequate margin of safety for local buckling under a seismic (safe shutdown earthquake [SSE]) event. In view of the conservative assumptions used and the large margin of safety available, it can be concluded that local buckling under the SSE loading is not possible.

3.5.5 Analysis of Welded Joints in Rack

Section 7.3 [1] discusses the integrity of the welded joints in the rack under thermal and seismic loading.

Under thermal loading, the stresses in the welds are small.

Examination of the computer plots for the analysis of the simulated seismic effect on the racks reveals that the supporting pads lift alternately off the ground. The Licensee showed [10] the existence of the analysis for these loads. These analyses are considered to be satisfactory.

4. CONCLUSIONS

Based on the review and evaluation, the following conclusions were reached:

- Although the Licensee's mathematical model for structural dynamics of the spent fuel rack modules under seismic loadings considers the three-dimensional dynamics of one rack module, it represents, nevertheless, a state-of-the-art approach because of the intensive computer resources and computer run-time required for non-linear, time-history, structural dynamics solutions.

- The seismic dynamic model considers only the case of fluid coupling to adjacent rack modules wherein the motion of each adjacent module normal to the boundary is assumed to be equal and opposite in its displacement to the module being analyzed. Although this assumption neglects the fact that adjacent fuel rack modules may have quite different dynamic response characteristics, it does provide a very manageable reduction in the analytical modeling of the problem while addressing the case in which the available space for dynamic rack displacement is at a minimum.

- The limitations of the modeling technique employed for hydrodynamic coupling of fuel assemblies within a fuel rack cell and of fuel rack modules to other rack modules and the pool walls indicate that the modeling technique contributes known accuracy only for the condition where the displacements are small as compared to the available clearance space. However, the solutions provided appear to become upper bounds where the displacements are not small.

- The Licensee took no credit for damping between the fuel assemblies and the rack cell walls, whereas the properties of the limber fuel assembly may permit the use of structural impact damping.

- The Licensee did not include the compliance of the limber fuel assembly in the estimation of the spring constant for the impact springs between the fuel assembly masses and the fuel rack masses. While this omission increased, in a sense, the conservatism of the analyses by increasing the sharpness of the impact forces, it may have also increased the need for a smaller time step of integration and thus narrowed the range of time step size between solution convergence and accumulation of computer round-off error.

- The rack module displacements reported by the Licensee are large, but do not indicate the possibility of impact between adjacent rack modules or the pool walls.

- The spent fuel pool was considered to have sufficient capacity to sustain the loadings from the high-density fuel racks.

It is concluded that structural analysis of the spent fuel rack modules and spent fuel pool meets the acceptance criteria.

5. REFERENCES

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