TECHNICAL EVALUATION REPORT

EVALUATION OF SPENT FUEL RACKS STRUCTURAL ANALYSIS

ROCHESTER GAS AND ELECTRIC CORPORATION
R. E. GINNA NUCLEAR POWER PLANT

NRC DOCKET NO. 50-244	FRC PROJECT C5506
NRC TAC NO. 54762	FRC ASSIGNMENT 26
NRC CONTRACT NO. NRC-03-81-130	FRC TASK 531

Prepared by

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Prepared for

Nuclear Regulatory Commission
Washington, D.C. 20555

Lead NRC Engineer: S. B. Kim

October 10, 1984

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Date: 10-10-84	Date: 10-10-84	Date: 10-10-84

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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 N. Con, Maurice Darwish, R. Clyde Herrick, Vincent K. Luk, and Aly A. Okaily.

1. INTRODUCTION

1.1 PURPOSE OF THE REVIEW

This technical evaluation report (TER) covers an independent review of the Rochester Gas and Electric Company licensing report [1] on high-density spent fuel racks for the R. E. Ginna Nuclear 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 Ginna 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 Ginna 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

The submerged spent fuel rack modules exhibit highly nonlinear structural behavior under seismic excitation. The sources of nonlinearity can generally be categorized by the following:

a. The impact between fuel cell and fuel assembly - Standing inside a fuel cell, the fuel assembly repeatedly impacts the four inside walls of the cell under earthquake loadings. These impacts are nonlinear in nature and when componded with the hydrodynamic coupling effect will significantly affect the dynamic responses of the modules in seismic events.

b. Rack sliding on the pool liner - The modules are free-standing on the pool liner, i.e., they are neither anchored to the pool liner nor attached to the pool wall. Consequently, the modules are restrained horizontally by virtue of the frictional forces between the module base and the pool liner. The module will slide when these frictional forces are not large enough to overcome the horizontal seismic loads.

c. Vertical impact due to rack tipping - When the overturning moment generated by horizontal seismic loads becomes exceedingly large, some of the module supports may lift off momentarily from the pool liner. Although the rack tipping occurs in very short duration only, it will significantly affect the stress distribution of the module as well as the pool liner.

Only the six modules in Region 2, shown in Figure 1, are subjected to rerack modification [1]. All of these modules have identical cross-sectional dimensions, 84.3 in x 118.02 in. Modules having this design of nearly square cross sections generally behave in three-dimensional fashion in seismic events. Hence, the modules will exhibit three-dimensional nonlinear structural behavior under earthquake loadings, and all seismic analyses of modules should therefore focus on characterizing this behavior.

A time history analysis of the modules was performed by the Licensee using a special purpose computer program RACKOE [1]. The RACKOE model, shown in Figure 2, is a two-dimensional, nonlinear, finite element model representative of the module. Both OBE and SSE loading conditions were

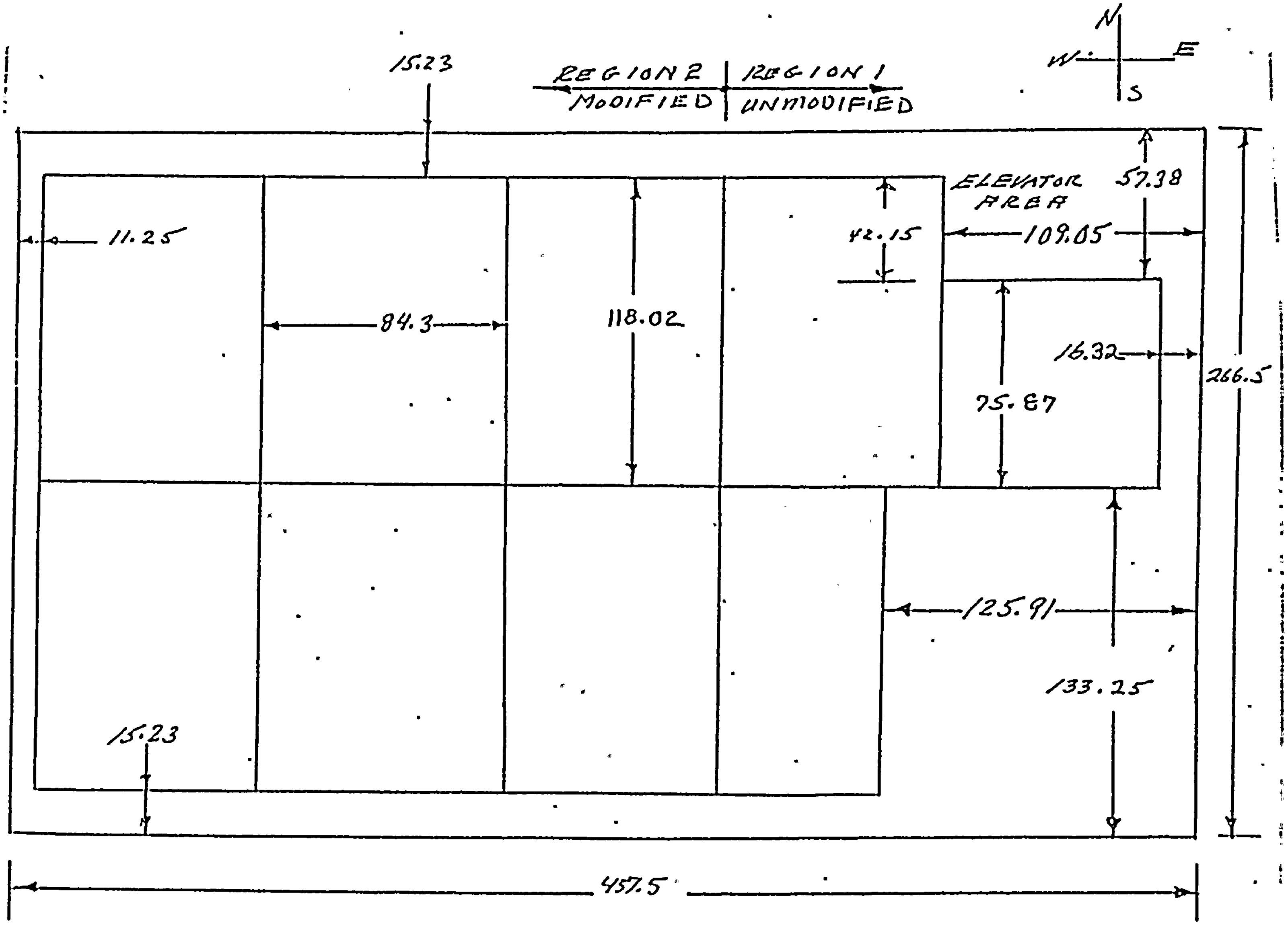

Figure 1. Pool Layout

evaluated by the Licensee. The OBE time history data was obtained by dividing the SSE time history data by two. The seismic analysis was performed for both the standard and the consolidated fuels.

The description and the evaluation of the RACKOE model are addressed in detail in Section 3.2. The displacement and stress results are discussed in appropriate subsections.

3.2 EVALUATION OF THE RACKOE MODEL

3.2.1 Description of the Model

A two-dimensional nonlinear model was developed in accordance with the special purpose finite element program, RACKOE. This program was designed to solve the equations of motion explicitly using Euler's extrapolation formula. A schematic view of the RACKOE model is shown in Figure 2.

The masses of the fuel cells and fuel assemblies are discretized in the RACKOE model. There are six concentrated mass nodes used to represent the fuel cells, with one node at the base of the module and the other five nodes at equal distance along the fuel cells. The nodes are linked by flexible elements. Similar arrangements are made to simulate fuel assemblies at five mass nodes. The mass nodes of fuel cells and fuel assemblies are connnected via (1) gap elements, to simulate impact between them, and (2) hydrodynamic masses, to represent hydrodynamic coupling between them. The friction between the module and the pool support stand is handled by friction elements which can only carry compressive loads. A horizontal spring is also used to represent frictional resistance of the module against sliding.

Separate analyses were conducted for the standard and the consolidated fuels. Individual analyses were performed for vertical and horizontal seismic loads. After determining the vertical natural frequency of the model to be greater than 33 Hz, an equivalent static response spectra method was used to perform the vertical seismic analysis. The horizontal seismic analysis was conducted using the time history method of analysis. Two different boundary conditions were considered in this analysis:

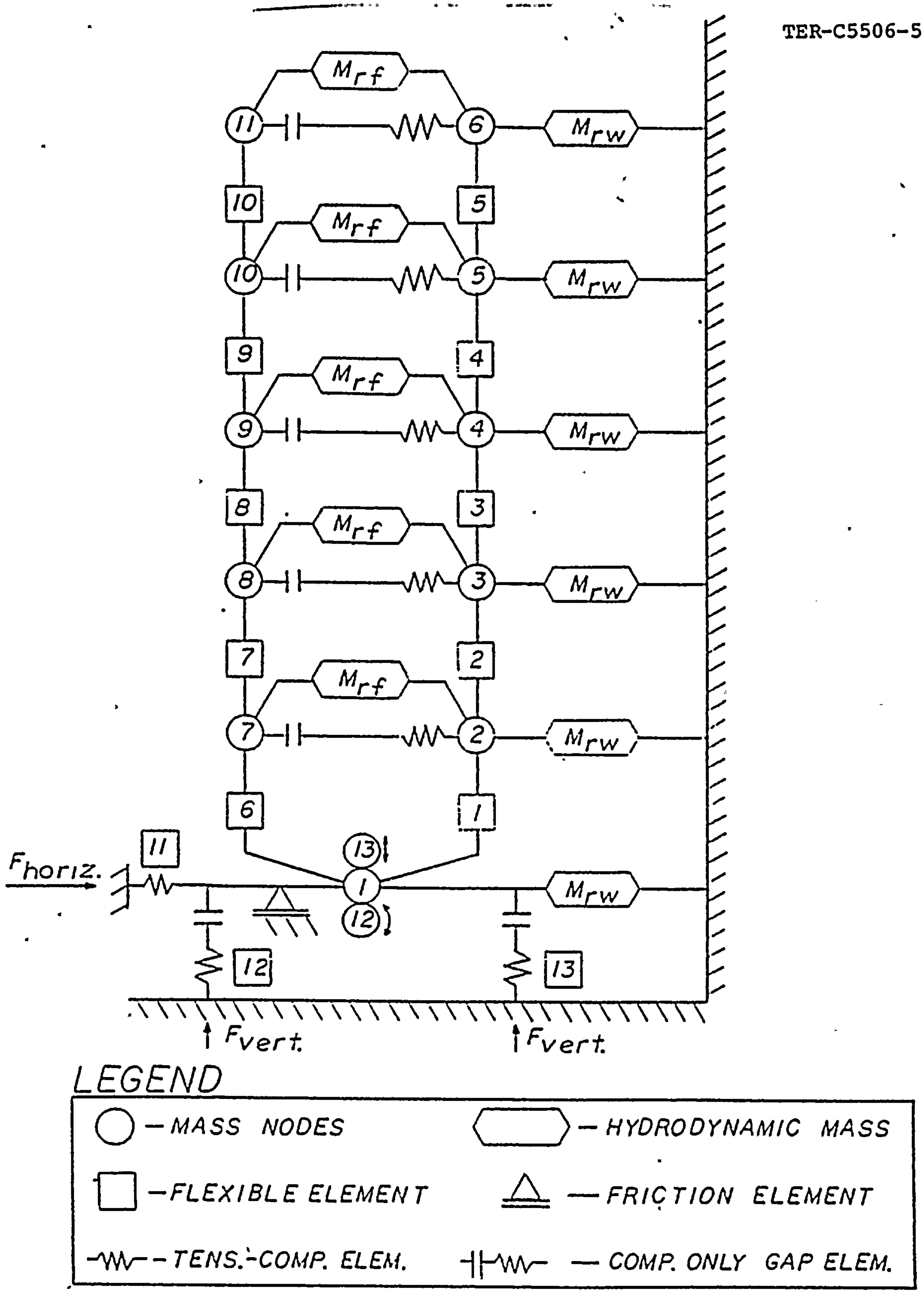

Figure 2. RACKOE Model of Spent Fuel Racks

1. The coefficient of friction between the module rack and the support stand is assumed to be 0.2. This is the minimum anticipated friction factor [3]. The results in this case will yield the maximum distance the module may slide in a seismic event.

2. The differential motion between the module base and the support stand is prevented. This boundary condition corresponds to the case when the coefficient of friction is greater than 0.5 [4]. Maximum stresses will be developed in the model in this case.

Different horizontal seismic analyses were performed for the east-west and north-south directions to account for the differences in structural configuration of the modules and seismic loadings in these two directions. The final results were obtained by combining the vertical reaction loads with the horizontal seismic loads using the square root of the sum of the squares method.

3.2.2 Assumptions Used in the Analysis

The following assumptions were used in the seismic analysis of the model:

a. The damping values used for this analysis were taken from Regulatory Guide 1.61 [5]. They are 2% for OBE and 4% for SSE events.

b. Only a constant value of friction coefficient was considered in each seismic analysis. The coeffcient of friction remained unchanged whether the module was stationary or in motion.

c. Adjacent modules would move in phase in seismic events.

d. The modules were installed very deeply in the fuel pool. Consequently, the sloshing effect is negligible.

The assumption in Item c may be valid when adjacent modules are identically loaded, but an out-of-phase response will most likely occur for differently loaded modules, either empty, partially, or fully loaded.

3.2.3 Impact Between Adjacent Modules

The pool layout shown in Figure 1 indicated that there is no gap between adjacent modules in the pool. The Licensee stated that, because of the strong hydrodynamic coupling effects in the case of no gap, adjacent modules were forced to vibrate in phase, thus precluding any impact between adjacent modules [5]. This claim is generally true for identically loaded modules, but out-of-phase vibration will most likely occur when the modules are loaded in different patterns, either empty, partially, or fully loaded. The out-of-phase motion will probably result in some form of impact between adjacent modules. In light of this probability, an impact analysis is needed in order to demonstrate that the impact does not cause any damage to the module structure or its contents [2].

The Licensee responded [5] by performing an impact analysis. The RACKOE model shown in Figure 2 was modified to include the compression-only springs at the top of the module to represent the presence of the adjacent module. The compressive force obtained in these springs was used to calculate the impact area on the wall of fuel cells based on the allowable compressive stress requirement. The length of wall required to resist the compressive force was calculated to the 16.0 inches in the east-west direction and 16.9 inches in the north-south direction. These impact wall lengths are acceptable since there is not much space between adjacent modules. The Licensee also demonstrated that the impact between adjacent modules would not adversely affect the stress distribution within the module structure [6].

3.2.4 Hydrodynamic Coupling Between Fluid and Cell Structure

The hydrodynamic coupling effect between adjacent modules and between the fuel cell and fuel assembly plays a significant role in affecting the dynamic response of the module in seismic events. The Licensee applied the linear model of Fritz [7] to estimate these coupling effects. This modeling technique assumes that the hydrodynamic coupling mass between two vibratory structures is inversely proportional to the gap between them. This assumption will generate an infinite coupling mass when there is no gap between adjacent modules. In light of this virtual impossibility, a 1-in gap was assumed between adjacent modules in evaluating the coupling mass between them. This approach is more realistic and also serves a conservative purpose.

Fritz's [7] 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 [7] when employed within the conditions upon which it was based, that of vibratory displacements which are very small compared with 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.

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

3.2.5 Solution Stability and Integration Time Step

The Licensee performed a time step study in an effort to find the correct integration time step to yield a converged solution. The study was conducted using consolidated fuel model with maximum friction in the north-south direction for the SSE condition [3]. The following results were obtained for three time steps: 0.001, 0.0005, and 0.00025 second.

	Time Step (sec)		
	0.001	0.0005	0.00025
Max. Vertical Reaction (lb)	549,000	456,000	427,000
Max. Horizontal Reaction (lb)	293,000	293,000	240,000
Max. Vertical Liftoff (in)	0.042	0.017	0.05

The time step of 0.0005 second was chosen to be used throughout the seismic analysis.

3.2.6 Liftoff Analysis

A liftoff analysis was performed by the Licensee to study the effect of the liftoff of module upon the stress distribution within the module structure. A modified RACKOE model, shown in Figure 3, was used in this analysis [8]. This simplified model used a single mass to simulate the module and its contents. This approach basically assumes a stiff beam to represent the entire module. This assumption is reasonably valid because the module is very stiff in the vertical direction. Furthermore, the Licensee demonstrated that identical results were obtained from a model containing five concentrated mass nodes to represent the module structure and its contents [6].

3.2.7 Displacement and Stress Results

For the operating life of the plant, the Licensee predicted that the maximum distance that the modules can slide is 0.95 in [4]. The closest obstruction, excluding adjacent modules, is the west wall which has an installed gap of 11.25 in. Consequently, the module sliding and tilting will not impact the pool wall. Since there is no gap between adjacent modules, this predicted sliding of modules will probably cause some form of impact between adjacent modules. As discussed in Section 3.2.3, an impact analysis was performed to insure that no damage was caused by the impact to the module structure and its contents.

During the review, the Licensee submitted a revised stress analysis report [9] providing detailed analyses of stress in the spent fuel rack module. While the stress report [9] incorrectly addressed acceptance criteria based upon Appendix D to Section 3.8.4 of NRC's Standard Review Plan, the report's transmittal letter [10] referenced a separate stress summary that compared the rack's stresses to the correct acceptance criteria provided by the OT Position Paper [2]. This separate stress summary, comparing calculated stresses to allowable values, indicated that the maximum design margins for base metal and weld stresses are greater than 0.47 for standard fuel and 0.25 for consolidated fuel. A detailed review of the stress report indicated that the methodology and level of stresses are satisfactory.

3.2.8 Eccentrically Loaded Modules

The Licensee allowed the modules to be eccentrically loaded as the situation demanded. An analysis was performed by the Licensee to study the

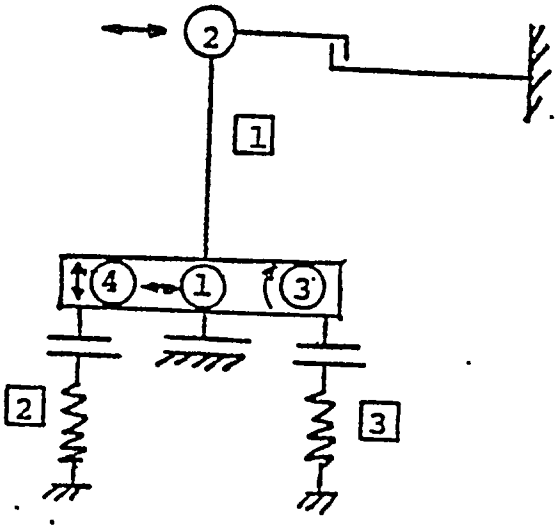

Figure 3. Simplified RACKOE Model for Liftoff Analysis

effect of such loading configurations upon the stress distribution within the module structure [4]. The RACKOE model was modified by inputting a different stiffness matrix of pedestals to reflect the eccentric loading pattern. The Licensee identified the worst eccentric loading case as when the module was loaded with two rows of consolidated fuel and subjected to seismic excitations in the east-west direction. The analysis results showed that this loading configuration produced a slightly greater liftoff distance of the pedestal than a fully loaded module, but it yielded a lower horizontal seismic load, vertical pedestal reaction, and horizontal displacement of the module top than did the fully loaded module.

3.3 REVIEW OF SPENT FUEL POOL STRUCTURAL ANALYSIS

The Licensee's justification for not performing a structural analysis of the spent fuel pool under the anticipated increased loads of the modified spent fuel storage racks is based on the following:

a. For the pool walls, the overall loads are reduced significantly compared to the original design loads due to removal of the seismic restraint supports. Meanwhile, there are relatively large dimensions between the free-standing racks and the walls compared to the maximum sliding distance of 0.5 in which consequently cause only very small hydrodynamic forces.

b. The floor of the spent fuel pool is a stainless steel lined, 3-ft-thick, reinforced concrete slab. The slab is founded on bedrock (Ginna FSAR, Section 2.8.3). The structure of the pool was evaluated for the original FSAR and again for the higher loads associated with a subsequent rack replacement (Reference 1 of April 2, 1984).

c. Because the rack will be modified to a free-standing design, only the increased concrete bearing stresses of the floor were evaluated. These were found to be acceptable (maximum concrete bearing stress is 2337 psi and the allowable is 3570 psi).

3.4 REVIEW OF HIGH DENSITY FUEL STORAGE RACKS' DESIGN

With respect to an accidental drop of a fuel assembly from above the rack module and through a rack cell, the Licensee stated [9] that the impact of the fuel assembly on the fuel support plates for that cell would damage it so that the particular cell could not be used for storage of spent fuel until repairs were completed. The Licensee indicated that spent fuel in other cells would not be adversely affected.

The Licensee assured that the spent fuel pool liner would not be perforated as follows [11]:

> "We have determined the fuel assembly velocity required to perforate the stainless steel liner using methodology developed for tornado missile impact analysis. Using the submerged weight of a fuel assembly dropped from 30 inches above the top of the rack, but neglecting all drag forces due to water or impact with cell walls or bottom plate, the velocity of the fuel assembly on impact is not sufficient to perforate the liner."

4. CONCLUSIONS

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

- The Licensee's analysis assumes that the fuel rack modules are positioned within the spent fuel pool without clearance space between the modules. Without clearance, the rack modules will impact to some extent. However, an impact analysis indicated that stresses associated with impacting are satisfactory.
- The review of the Licensee's stress analysis indicated that the analysis and level of stresses are acceptable.
- The review of the spent pool structure is satisfactory for the higher density fuel loading.

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