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TECHNICAL EVALUATION REPORT

EVALUATION OF SPENT FUEL RACKS STRUCTURAL ANALYSIS

DUKE POWER COMPANY
McGUIRE NUCLEAR STATION UNITS 1 AND 2

NRC DOCKET NO. 50-369, 50-370
NRC TAC NO. 53531, 53532
NRC CONTRACT NO. NRC-03-81-130

FRC PROJECT C5506
FRC ASSIGNMENT 26
FRC TASK 527

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 17, 1984
Revised August 10, 1984

Franklin Research Center
A Division of The Franklin Institute
The Benjamin Franklin Parkway, Phila., Pa. 19103 (215) 448-1000

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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, Balar S. Dhillon (consultant), and T. B. Belytschko (consultant).

1. INTRODUCTION

1.1 PURPOSE OF THE REVIEW

This technical evaluation report (TER) covers an independent review of the Duke Power Company's licensing report [1] on high-density spent fuel racks for the McGuire Nuclear Station Units 1 and 2 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 McGuire Units 1 and 2 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 McGuire Units 1 and 2 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.

- o 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.

- o 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.

- o 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 kine.ic 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: The fuel assembly standing inside a fuel cell will impact its four inside walls repeatedly under earthquake loadings. These impacts are nonlinear in nature and when compounded with the hydrodynamic coupling effect will significantly affect the dynamic responses of the modules in seismic events.

b. Friction between module base and 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 held in place by virtue of the frictional forces between the module base and pool liner. These frictional forces act together with the hydrodynamic coupling forces to both excite and restrain the module during seismic events.

All modules at McGuire Nuclear Station have nearly square cross sections across the axes of fuel cells [1]. Modules of this design geometry generally behave in three-dimensional fashion under earthquake loadings. Hence, the modules will exhibit three-dimensional nonlinear structural behavior in seismic events, and all seismic analyses of modules should therefore focus on characterizing this behavior.

There are two types of modules at McGuire Units 1 and 2 [1]. The modules in Region 1 have a center-to-center storage cell spacing of 10.4 in. They are reserved for temporary core off-loading, temporary storage of new fuel, and storage of spent fuel above specified levels of reactivity. The modules in Region 2, with 9.125-in center-to-center spacing, are used to store irradiated fuel below specific reactivity levels. The designs of modules in Regions 1 and 2 are shown in Figures 1 and 2, respectively.

The Licensee conducted the seismic analysis of modules in two parts. The first part was a time history analysis of a simplified two-dimensional nonlinear finite element model of an individual fuel cell shown in Figure 3.

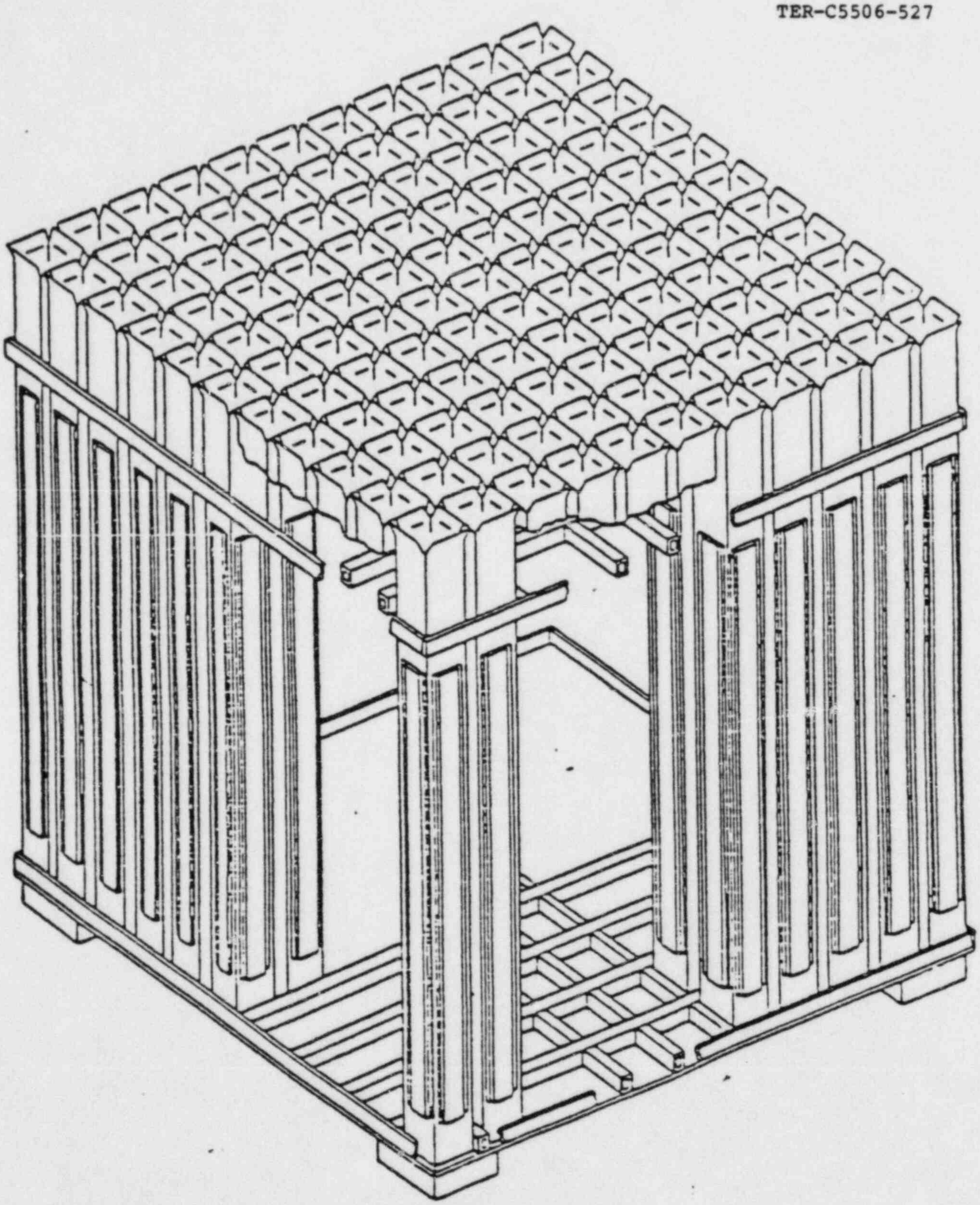


Figure 1. Fuel Storage Rack Assembly in Region 1

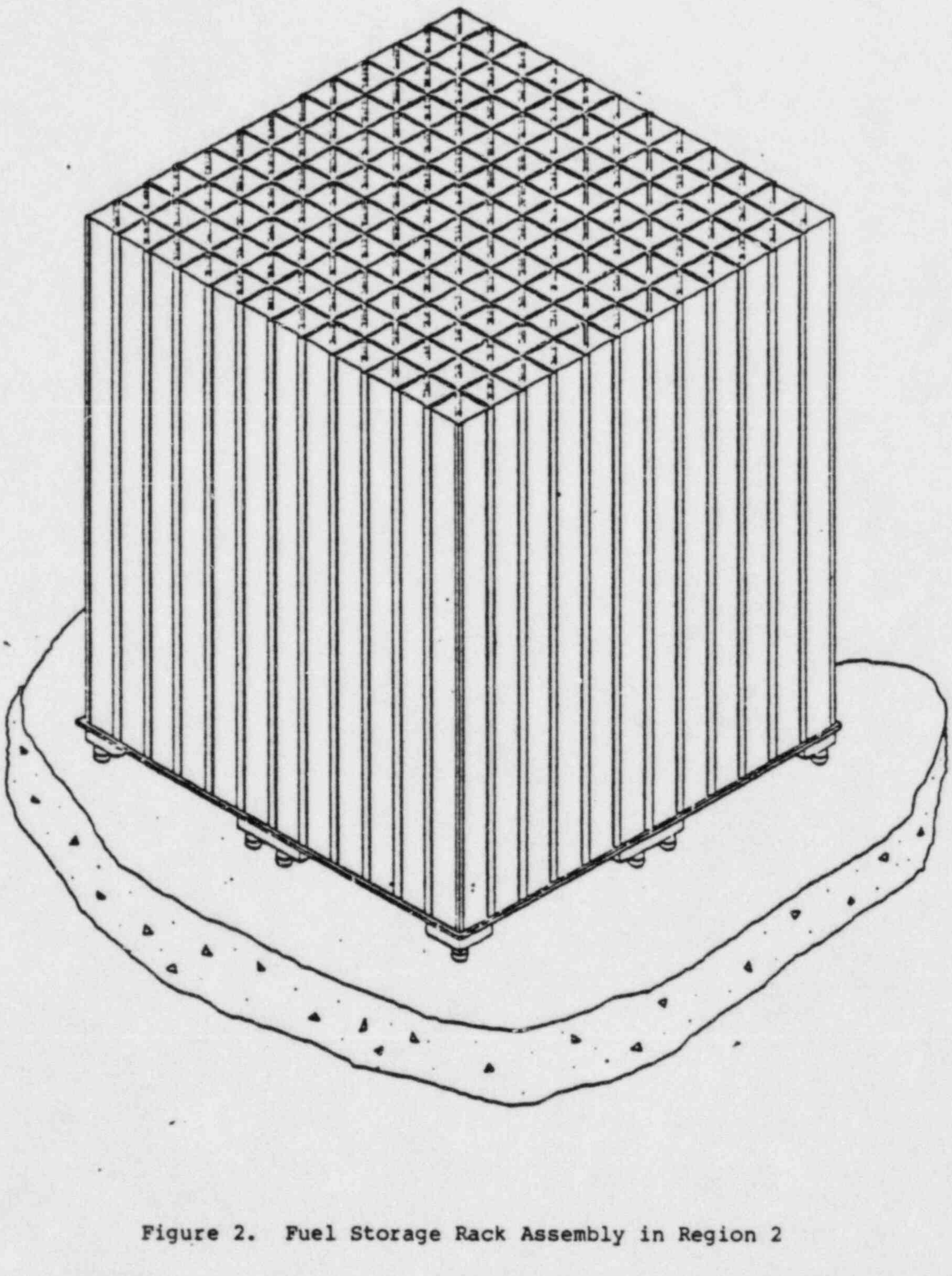


Figure 2. Fuel Storage Rack Assembly in Region 2

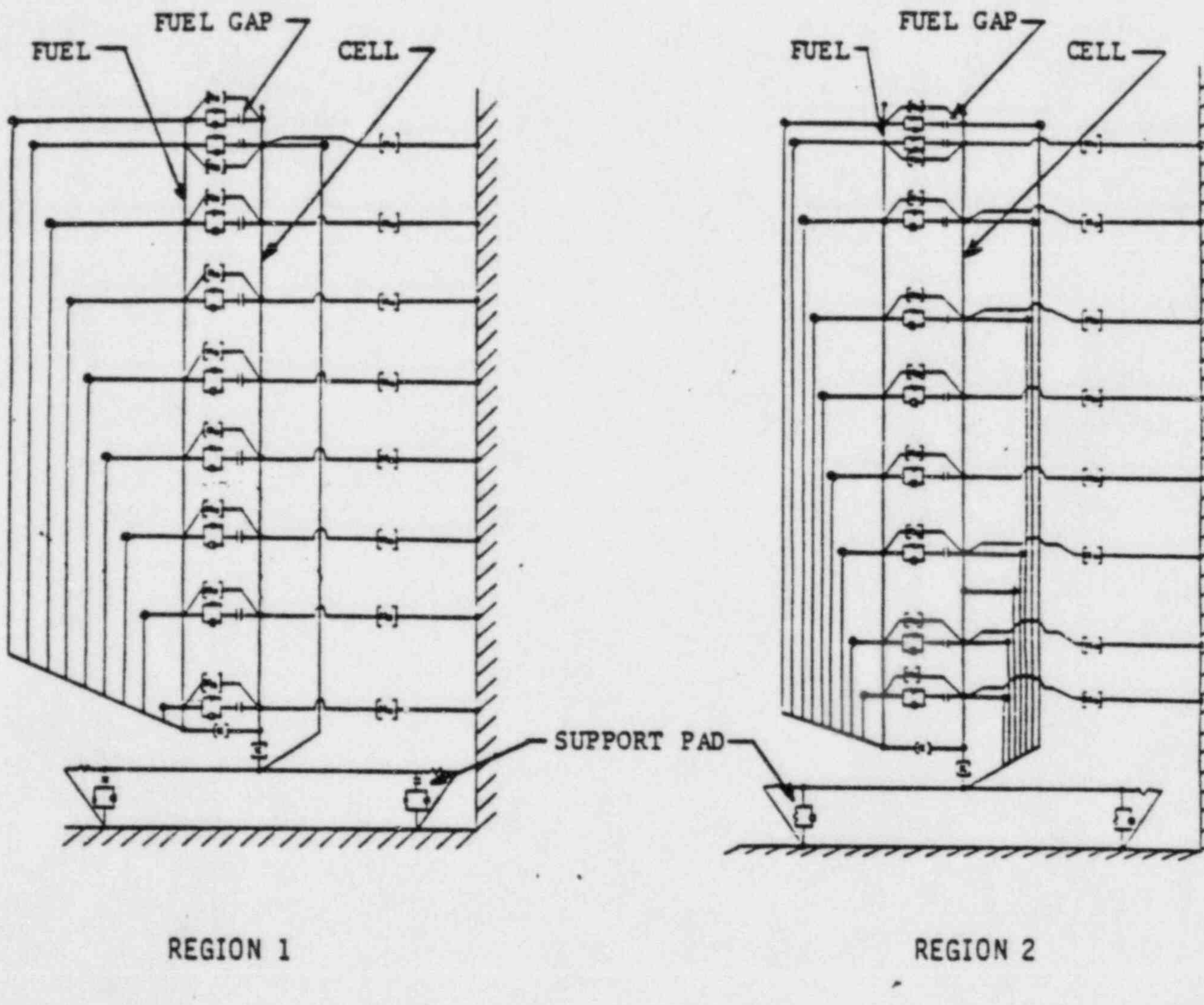


Figure 3. Two-Dimensional Nonlinear Model

The second part was a response spectrum analysis of a detailed three-dimensional linear finite element model of a rack assembly shown in Figure 4. Both modules consisted of two models to reflect the two different designs of modules in Regions 1 and 2. Structural damping of 2% was used in the seismic analysis for both the operating basis earthquake (OBE) and the safe shutdown earthquake (SSE).

With regard to the models used in the analysis, the following issue was discussed at a meeting with the Licensee [3]:

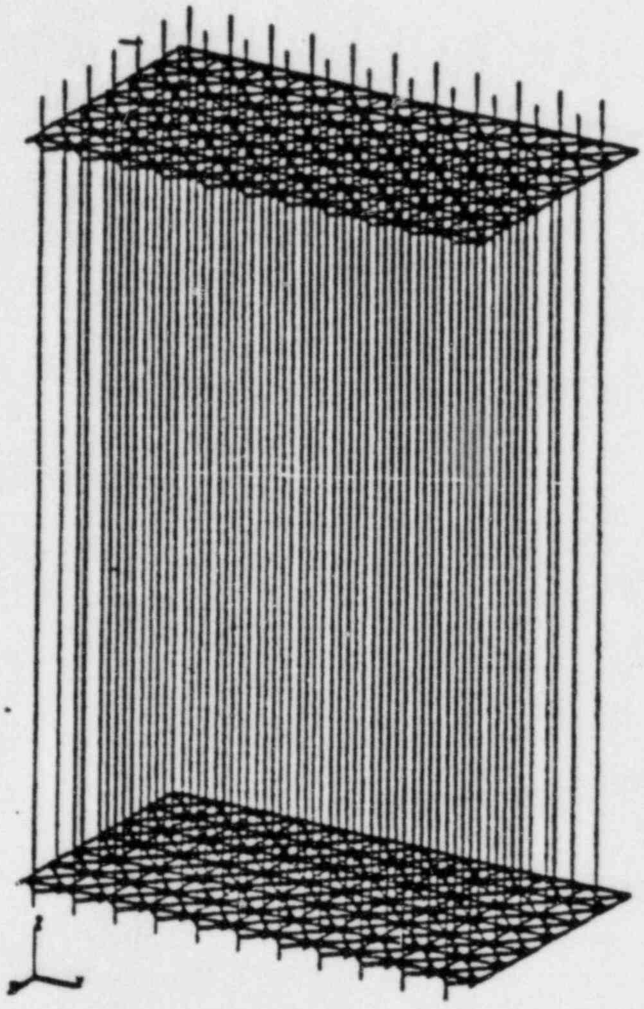
> The simplified two-dimensional model does not fully simulate the more complicated three-dimensional structure behavior exhibited by the modules. The two-dimensional model essentially uncouples the two mutually perpendicular horizontal motions which are nonlinearly interrelated under seismic loadings. Thus, an approach using two models (nonlinear, two-dimensional and linear, three-dimensional model) may have difficulty in resolving peak stresses.

The value of impact damping (15%) used in the analysis was questioned when documentation of the damping values provided by the Licensee confirmed a range of only 10% to 15% [4]. However, the Licensee has submitted the following response which cites test data performed by Babcock & Wilcox Company (fuel suppliers) which is stated to be on file with the USNRC [5]:

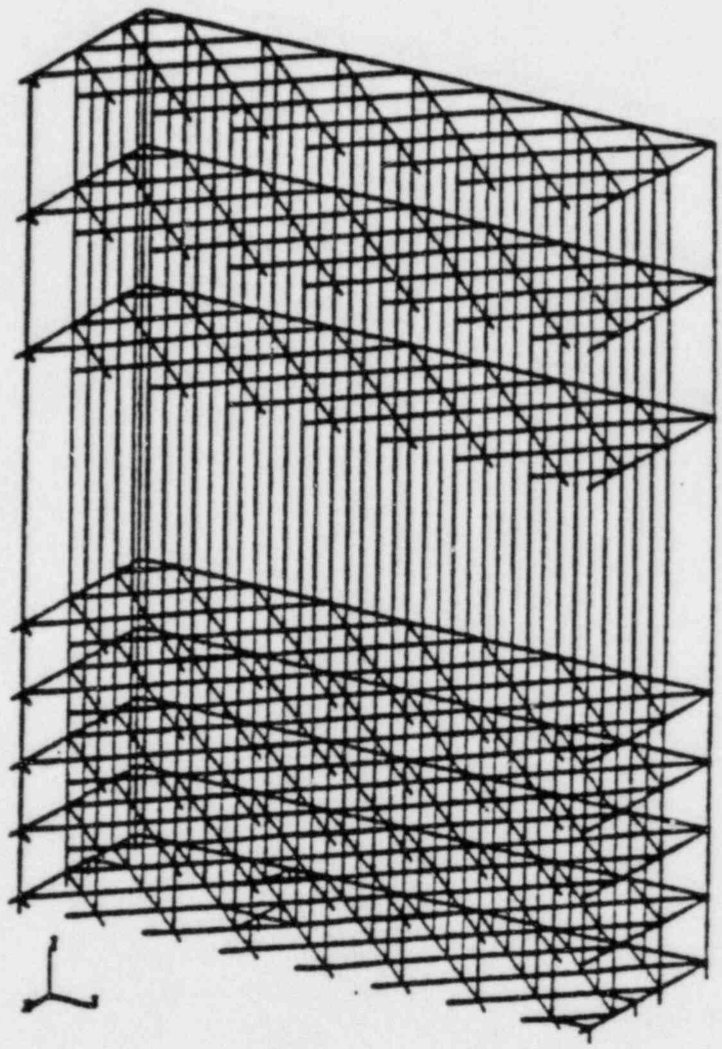
> "In determining the fuel assembly impact damping, B & W performed a series of tests. The upper and lower bounds for the tests are reported as .1462 and .1650 respectively with a median value for all tests of .1565. B & W Topical Report 10133P Rev. 1, filed with the NRC on 5/3/79, gives a fuel assembly impact damping value of 16% for a Mark C assembly. The report also notes that B & W Mark C charactristics are similar to the B & W Mark B assembly characteristics which are stored at McGuire, thus, the results are directly comparable. The Applicant maintains that use of a damping value of 15% is appropriate and the conservatisms of the analytical results used in the design of the proposed racks are preserved."

Since damping influences the amplitude of dynamic response, it is important to use values that do not overestimate the energy loss of the system.

The description and evaluation of the two models are addressed in detail in Sections 3.2 and 3.3. The displacement and stress results are discussed in appropriate subsections.



REGION 1



REGION 2

Figure 4. Three-Dimensional Linear Model

3.2 EVALUATION OF THE SIMPLIFIED TWO-DIMENSIONAL NONLINEAR MODEL

3.2.1 Description of the Model

The simplified two-dimensional model was developed to simulate the major structural characteristics of an individual fuel cell within a submerged rack assembly. Two versions of this model are shown in Figure 3 to reflect two different module designs in Regions 1 and 2. The model was developed in accordance with the WECAN (Westinghouse Electric Computer Analysis) code.

A time history analysis of the model was performed by the Licensee with the simultaneous application of a vertical and a horizontal component of seismic loads. Nonlinear gap elements were used in the model to represent the possible impact between the fuel cell and the fuel assembly, as well as the friction between the module base and the pool liner. The hydrodynamic coupling effect between fuel cell and fuel assembly, as well as between fuel cell and rigid wall, is simulated by appropriate coupling springs. A damping value of 15% was used to represent the impact damping of the fuel assembly manufactured by Babcock & Wilcox (B&W) Company. Justification of 15% impact damping was discussed in Section 3.1 of this report.

3.2.2 Assumptions Used in the Analysis

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

a. A structural damping value of 2% was used for both OBE and SSE events.

b. The fluid damping was conservatively neglected.

c. Only a constant value of friction coefficient was considered in each seismic analysis. The coefficient of friction remained unchanged whether the module was stationary or in motion. Analysis was performed for static friction coefficients of u = 0.2 and 0.8. These two cases would envelop the values of intermediate friction coefficients.

d. The initial status of the gap between fuel cells and fuel assembly is immaterial because all fuel cells would move in phase soon after an earthquake occurred. Adjacent modules would also move in phase in seismic events.

e. The modules stand on the pool liner occupying the bottom one-third of the water body in the fuel pool. Therefore, the sloshing effect is negligible.

The assumption in Item d may be valid when adjacent modules are fully loaded, but the out-of-phase response will most likely occur when some modules are either partially loaded or empty.

3.2.3 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 responses of the module in seismic events. As stated in Section 3.2.2, the modules were assumed to move in phase. This assumption led to consideration of the motion of an individual cell surrounded on all four sides by rigid boundaries which are separated from the cell by equivalent gaps as an equivalent representation of the entire rack assembly. The hydrodynamic coupling mass between the rack module and the pool wall, as shown in Figure 3, was calculated by evaluating the effects of the gap between the modules and the pool wall using the method outlined in the paper by Fritz [6].

The technique of potential flow and kinetic energy was used in assessing the hydrodynamic coupling mass between the fuel cell and the fuel assembly. This mass, which depends on the size of fuel assembly and the inside dimensions of the fuel cell, was calculated by equating the kinetic energy of the hydrodynamic coupling mass to that of the fluid flowing around the fuel assembly within the fuel cell. The concept of this method was discussed in a paper by De Santo [7].

Fritz's [6] 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 [6] 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 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 rack module in its clearance space, is considerably different than that upon which Fritz's method was developed and experimentally verified.

Thus, the limitations of Fritz's [6] modeling technique for hydrodynamic coupling of rack modules adjacent to other rack modules or a pool wall reinforce the position of this review that the Licensee's fuel rack dynamic model be considered conservative only for dynamic displacements that are small relative to the available displacement clearance.

3.2.4 Seismic Loading

The model was subject to a simultaneous application of a vertical and a horizontal component of seismic loads. The hydrodynamic coupling mass in the same horizontal direction is also incorporated in the analysis. In a meeting at Westinghouse in Pensacola, Florida, the Licensee stated that there were two distinct horizontal seismic response spectra as well as two different sets of hydrodynamic coupling masses in these two horizontal directions [3]. However, only one time history corresponding to one of the two horizontal response spectra was used in the analysis. Subsequent to the meeting, the Licensee provided the following [5]:

> "Of the two horizontal seismic response spectra, the E-W spectrum has larger acceleration values than the N-S spectrum in the frequency range of the fuel rack (4-8 H_z). Thus, the seismic analysis was conservatively performed with the E-W response spectrum, the E-W hydrodynamic mass (maximum hydrodynamic mass), and the minimum support and spacing (N-S in region 2 and E-W in region 1), to obtain the maximum fuel rack response."

This statement documents the use of response spectra providing conservative analysis.

3.2.5 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. It was found that the convergence of solution occurred at a time step of 0.00125 sec [4]. This time step is much greater than the 2.0×10^{-4} sec reported by Gilmore of Westinghouse in a similar analysis [8]. The Licensee explained that the wide range of time step for convergence might be responsible for these differing values.

3.2.6 Displacement and Stress Results

The Licensee claimed that the displacement of the module would be the same as that of the individual cell found in this model because of the in-phase motion assumption used in this analysis. The Licensee determined that the module slides a maximum distance of 0.10 in at u = 0.2 [1]. While this result may not be conservative because the two-dimensional model used in this analysis uncouples the two horizontal responses under seismic loadings, it does indicate that the displacements are relatively small.

The moments and shear forces generated from this model were used to calculate the load correction factors. The load results from the detailed model were then multiplied by these factors to yield the stress results in the structural analysis of the module, as discussed in Section 3.3 of this report. A detailed review of this method is given in Section 3.4 of this report.

3.3 EVALUATION OF THE DETAILED THREE-DIMENSIONAL LINEAR MODEL

3.3.1 Description of the Model

A model was developed to simulate the major structural characteristics of the entire module submerged in the fuel pool. Two versions of the model are shown in Figure 4 to represent two different module designs in Regions 1 and 2. The WECAN code was used to develop these two models. Three-dimensional beam elements were used to construct the models.

According to Reference 4, the seismic analysis was done on the 11x13 module in Region 1 and the 12x16 module in Region 2. The model of the module in Region 1 has two fine meshes of elements, one on the top and the other on the bottom of the model to represent the top and the bottom grip assembly of the module, respectively. There are eight horizontal meshes of elements in the model of the module in Region 2 to simulate the eight skip weld locations along the length of cells.

A response spectrum analysis of the three-dimensional models was performed. The three components of the seismic loads were applied to the models, one component at a time.

3.3.2 Assumptions Used in the Analysis

All the assumptions except the initial status of the gap between fuel cell and fuel assembly used in the analysis of the two-dimensional model are applicable here. A few additional assumptions used in this analysis are described below:

a. A composite distributive mass density was used in the analysis to embody the masses of the fuel cell, the fuel assembly, the poison material, and the hydrodynamic coupling mass.

b. No impact between the fuel cell and the fuel assembly was considered.

c. The module base was stationary with respect to the pool liner at all times.

3.3.3 Load Correction Factor

Since the detailed model did not account for the nonlinear effect of a fuel assembly impacting a fuel cell and the support pad movements, the internal loads and stresses for the module assembly obtained from this model were modified by load correction factors. The calculation was focused on the bending moments and shear forces obtained at the base plate of this detailed model. The bending moment load correction factor was defined as the ratio of the bending moment obtained at the base of the simplified model to the average bending moment derived at the base of the detailed model. Similar definition was used for the shear force load correction factor. The maximum loads from this detailed model were multiplied by these load correction factors and were used in the structural analysis to obtain the streses within the module assembly. Further discussion is provided in Section 3.4.

3.3.4 Module Assembly Lift-Off Analysis

Both partially and fully loaded modules were evaluated for module stability. The support pad vertical displacement was used as the parameter for this study. The Licensee found that the maximum lift-off was produced by partial loading of three rows of fuel [4]. This condition yielded a factor of safety against overturn much larger than the 1.5 minimum requirement.

3.3.5 Stress Results

The maximum responses of the detailed model from the seismic components in three directions were combined by the SRSS model in the structural analysis. The maximum loads experienced by the modules were obtained when u = 0.8 [4]. According to Reference 1, the stresses at most locations of the modules had margins of safety higher than 7% with the exception of the weld stresses tabulated in the following:

Description	Margin of Safety
1. Weld shear at leveling pad assembly, Region 1 modules	1%
2. Weld shear at top grid member, Region 1 modules	3%
3. Weld shear at leveling pad assembly, Region 2 modules	3%

The margins of safety for these weld stresses are very small.

3.4 SUMMARY EVALUATION OF THE SEISMIC ANALYSIS OF FUEL RACK MODULES

3.4.1 Background

During the initial review of the seismic dynamic response analysis of the rack modules, concern developed as to the ability of the methods employed to relate two-dimensional nonlinear displacement analysis to the three-dimensional linear mathematical model used to compute peak rack stresses, especially when stress safety margins in the spent fuel racks were reported as low as 1%, 3%, and 7%. Coupled with this concern was a lack of information about the detailed analysis procedures of a unique, proprietary analysis method.

In order to resolve these concerns, a visit was made to the facilities of the Licensee's spent fuel rack vendor to review the analysis procedures in detail and to evaluate the character and magnitude of the intermediate results transferred from one part of the analysis to another. A detailed review was performed. Appropriate discussion and conclusions are provided in the following sections.

3.4.2 Seismic Analysis Method

The Licensee's description of the analysis is as follows [1]:

"The dynamic response of the fuel rack assembly during a seismic event is the condition which produces the governing loads and stresses on the structure. The dynamic response and internal stresses and loads are obtained from a seismic analysis which is performed in two phases. The first phase is a time history analysis on a simplified nonlinear finite element model shown in Figure 2.3-1. The second phase is a response spectrum analysis of a detailed rack assembly finite element model shown in Figure 2.3-2. Two percent damping is used in the seismic analysis for both the OBE and SSE.

The simplified nonlinear finite element model is used to determine the fuel rack response. This nonlinear model has the structural characteristics of an individual cell within a submerged rack assembly. The nonlinearities of the fuel rack assembly which are accounted for in the model are due to changes in the gap between the fuel cell and the fuel assembly, the boundary conditions of the fuel rack support locations and energy losses at the support locations.

The fuel assembly to cell impact loads, support pad lift off, rack sliding, and overall rack response are obtained from the nonlinear time history model. In determining the maximum fuel rack response, the response value for each item of interest is searched for maximum values.

The detailed model is a three-dimensional finite element representative of a rack assembly consisting of discrete three-dimensional beams interconnected at a finite number of nodal points.

The results of the single cell nonlinear time history model are incorporated in the detailed model. Since the detailed model does not account for the nonlinear effect of a fuel assembly impacting the cell and the support pad movements, the internal loads and stresses for the rack assembly obtained from this model are corrected by load correction factors. The load correction factors are derived from the single cell nonlinear model results and are applied to the components in the structural analysis. The responses of the model from accelerations in three directions are combined by the SRSS method in the structural analysis. The loads in the major components are examined and the maximum loaded section of each of the components is found. These maximum loads from the detailed model are used in the structural analysis to obtain the stresses within the rack assembly."

3.4.3 Review of the Analysis Method

The focus of the meeting was on the methods used to relate the two-dimensional nonlinear analysis to the three-dimensional linear analysis for the purpose of evaluating stresses. Displacements were obtained directly from the nonlinear model where no conversion factors were needed.

A detailed review was made of the two-dimensional nonlinear dynamic model and of the source and formulation of parameters used therein. The two-dimensional model incorporates the nonlinear impacting parameters of a fuel assembly within a fuel rack cell and includes sliding and lift-off of the rack module mounting feet. Because the two-dimensional analysis must employ a time history solution to resolve the effects of the nonlinear elements, the two-dimensional model is a limited model not well suited for detailed stress analysis.

The three-dimensional linear model is a comprehensive model that is suitable for predicting stresses in all regions of the rack module. However, it is a linear model in which the fuel assembly masses are included directly with the rack masses without any consideration for their moving through clearance spaces and impacting the rack structure. Neither are the mounting feet considered to slide or impact vertically following a lift-off, should it occur. However, as a linearized model of the spent fuel rack module for internal stress analysis purposes, the three-dimensional model was reviewed and found to be acceptable.

The remaining review was directed to the methods of incorporating the dynamic loading effects from the two-dimensional nonlinear impacting model to the three-dimensional linear stress analysis model. This was accomplished by comparing two selected loading parameters of the two-dimensional and three-dimensional mathematical models and using these parametrs to establish a load correction factor with which to correct dynamic response analyses made using the three-dimensional linear model. A detailed review of the magnitudes of the load correction factors resulting from analysis of the spent fuel racks for the McGuire Nuclear Station revealed that the load correction factors actually reduced both the base moment and shear of the region 1 racks, but only the base moment of the region 2 racks. The values of the factors are:

	Region 1	Region 2
Base moment factor	0.805	0.708
Base shear factor	0.98	1.287

While the thought that a load correction factor, which relates impacting two-dimensional behavior to loads and stresses predicted by a linear, non-impacting, three-dimensional model, would actually reduce the load and stress predicted by the three-dimensional model may be a little surprising, this can be true. When one considers the fact that the linear three-dimensional model assumes that the fuel assumbly mass is rigidly fixed within the rack structure, then all of the mass in the rack participates in the linear response of the rack. In the two-dimensional nonlinear model, the rack structure responds first to the seismic stimuli, followed by an increment of time later impacting of the fuel assembly within the rack cell (should it occur) after the clearance gap between the fuel assembly and the rack cell walls closes. Thus, the actual combined dynamic response of the rack and the fuel assembly is highly dependent upon the dynamic parameters of the system, including the case where the base moments and shears could be reduced over that of a linear model. Also, in the nonlinear model, a spring-damper model was used for the cell-fuel composite. This model provided a more compliant coupling which is more representative of reality. This serves to reduce the stress in the nonlinear model.

In summary, although the Licensee's analysis method appears to provide an approach toward providing an estimate of the stresses where separate nonlinear, impacting displacement solutions and linear stress analysis must be combined, there are a number of criticisms that limit its acceptance:

- o The analysis method is unconventional and is therefore not widely used in seismic analyses to permit extensive experience in many applications.
- o No examples validated by alternate analysis methods were provided to confirm the analysis method.

- The three-dimensional stress analysis, the results of which are ratioed by the load correction factors from the two-dimensional, nonlinear analyses, still analyzes one earthquake direction at a time. Thus, the maximum stress at a point must be computed as the square root of the sum of the squares of the separate values for each earthquake direction. Peak stresses due to sharp impact forces may not be resolved well.

For these reasons, the method cannot be accepted as a reliable generalized method without further validation.

3.4.4 Detailed Review of Rack Stress Analysis

Although the methodology is not acceptable at this time as a general analysis method, this does not preclude the acceptability of this particular stress analysis. An essential element of the stress analysis is that it include all forces associated with the seismic excitation. These include (1) horizontal forces which arise from the acceleration of the racks and (2) vertical and horizontal forces on the mounting pads which result from a combination of horizontal reactions and from rocking motions of the rack modules. The vertical forces generated by the mounting pads lifting off and impacting the floor are of particular importance.

Any stress analysis that includes all of the loads sustained in a seismic event in which any resultant computed loadings are equal to or greater than the actual seismic loadings will provide a conservative analysis. In response to a request [9] during the review, the Licensee provided summations [10] of the vertical forces in an effort to show that the equivalent maximum mounting pad forces of the linear three-dimensional stress model equal or exceed the maximum mounting pad forces of the two-dimensional nonlinear model.

The data supplied by the Licensee [10] were as follows:

- Region 1, 11 x 13 Rack, East/West Seismic

	Linear Model	Nonlinear Model
Total load	242,84*	240,100
Dead weight	120,00*	121,100
Ratio (total/dead wt.)	2.023	1.98

*Data assumed to be reported in error and to represent 242,840 and 120,000, respectively.

o Region 1, 11 x 13 Rack, North/South Seismic

	Linear Model	Nonlinear Model
Total load	218,088	200,057
Dead weight	118,779	121,100
Ratio (total/dead wt.)	1.84	1.65

o Region 2, 12 x 16 Rack, East/West Seismic

	Linear Model	Nonlinear Model
Total load	345,400	335,600
Dead weight	154,000	155,500
Ratio (total/dead wt.)	2.24	2.16

o Region 2, 12 x 16 Rack, North/South Seismic

	Linear Model	Nonlinear Model
Total load	413,200	457,500
Dead weight	156,400	155,500
Ratio (total/dead wt.)	2.64	2.94

In reviewing these results, a recognized consultant retained for the review of the nonlinear analysis methods offered the following [11]:

> "The results presented for the Region 1 racks clearly meet this condition; (it is assumed that the linear forces given for East/West Seismic are mistyped and should read 242840 and 120000 rather than 24284 and 12000).
>
> The results presented for Region 2 racks do satisfy this requirement for the East/West component but for the North/South the loads in the linear model are only 90.3% of those predicted by the nonlinear model: 413200 for linear vs 457500 for nonlinear. There are several factors which contribute to the conservatism of the stress analysis of the North/South component in Region 2: the East/West component, which is more severe, was used for the nonlinear calculation; the Region 2 linear model includes the mass of a consolidated fuel canister which is much heavier than the standard fuel assembly which was used in the nonlinear model; East/West support spacing, which is smaller, is used in generating the nonlinear forces. There are also other elements of conservatism in the fuel rack analysis which apply to all of the components-item 3 on page 3 of letter of Mr. H. B. Tucker.
>
> It would have been desirable for the Licensee to provide some numerical estimates that show that these factors of conservatism are sufficient to

negate the loss of 9.7% of the vertical load in Region 2. Obviously, if no stresses exceed the allowable with Rm scaled up enough to yield a total load of 457500 pounds, there is no problem. Similarly, a nonlinear calculation which demonstrates that the factors of conservatism are sufficient to reduce the nonlinear load to 413200 would eliminate any questions. However, in view of the many factors of conservatism, this small underestimate of one of the loads may not require further substantiation. In Region 1, everything is fine."

In summary, while the methodology used for the stress analysis cannot be accepted without further validation, the detailed review of the stress analysis for these particular rack modules coupled with the conservatisms seen to be present indicate that the stress analysis is acceptable.

3.5 REVIEW OF SPENT FUEL POOL STRUCTURAL ANALYSIS

3.5.1 Spent Fuel Pool Floor Analysis

The McGuire Nuclear Station fuel pool slab is a reinforced concrete plate structure lined with stainless steel. The Unit 1 floor consists of a 4-ft 6-in reinforced concrete slab supported on 6-ft 6-in deep by 4-ft 6-in wide reinforced concrete beams, and has 4-ft 0-in wide walls at the perimeter.

The Unit 2 floor is a 11-ft 0-in thick reinforced concrete slab supported on a bedrock foundation. The additional thickness in Unit 2 is due to construction considerations.

The analysis was presented to demonstrate structural integrity of the floor systems for the postulated loading conditions with the new high-density racks.

3.5.2 Licensee's Assumptions

The Licensee made the following assumptions for the analysis:

1. The slab is modeled as a mesh composed of beam elements.

2. The stiffness of the pool liner was ignored in the analysis of concrete slab.

3. Original plant response spectra are used in consideration of seismic loadings.

4. Dynamic rack loads are taken from the Westinghouse rack module tables.

3.5.3 Analysis Procedure

The Unit 1 pool slab was modeled by beam elements with boundaries at centerlines of walls and deep beams. The slab area with the greatest clear span and largest load/area ratio was analyzed as the most critical case.

The static loads were gravity loads from water, concrete, and racks. Dynamic loads were obtained from OBE and SSE spectra curves for McGuire Nuclear Station, and from dynamic rack loads given in the Westinghouse rack module tables. The Licensee provided additional information [5] as follows:

> "The McGuire Auxiliary Building is a poured in place reinforced concrete structure as stated in Section 3.8.4.1.1 of the McGuire FSAR. Contained in this building are auxiliary systems, control rooms, and spent fuel pools for both units along with related piping and electrical cables. The mass added as a result of fuel densification is negligible compared to the mass of the structures and equipment comprising the Auxiliary Building, thus, the seismic response spectra applicable to the spent fuel pool floor slab is not altered. The method of dynamic analysis is described in Section 3.7.2.1 of the McGuire FSAR."

A thermal gradient was imposed across the pool slab during normal operation. A loading condition with pool temperature reaching 212°F was also evaluated.

The analysis was performed by using the "STRUDL" computer code.

The results of the analysis were summarized by the Licensee in Table 3.1-1 [1], which indicates that the fuel pool floor system has sufficient capacity to sustain the loading or the new rack conditions with a design margin of 1.3.

The Unit 2 slab system is a different type of structure than Unit 1. In a recent response [5], the Licensee provided the following information regarding Unit 2:

> "As stated in Section 3.1, paragraph 4, of the license submittal, the Unit 2 pool floor is supported continuously on bedrock. All dead, live and seismic loads are transmitted directly through the floor to the bedrock foundation. In response to an earlier question concerning the model and loading system used in the analysis of the spent fuel pool floor (reference response to Question No. 1, letter dated June 19, 1984), reference was made only to the Unit 1 pool floor slab. The Unit 2 pool floor slab analysis was not addressed since the Unit 1 pool floor represented the limiting condition."

The Licensee indicated that the pool floor system has significant design margin to sustain the additional floor loading.

3.6 REVIEW OF HIGH-DENSITY FUEL STORAGE RACKS' DESIGN

Comments and conclusions following the review of Sections 2.3.1.3 and 2.3.1.4 of Section 2.3 [1] entitled "Design Evaluation" are contained in the following subsections:

3.6.1 Fuel Handling Crane Uplift Analysis

In Section 2.3.1.3 [1], the Licensee stated that the rack can withstand the maximum uplift load of 3000 lb of the fuel handling crane without violating the criticality acceptance criteria. The uplift load is assumed to be applied to fuel cell. The Licensee stated that the resulting stresses are within the acceptable stress limits, and there is no change in rack geometry of a magnitude which causes the criticality acceptance criteria to be violated.

However, the reviewed report [1] does not provide the stress level or the extent of the rack deformation under the uplift load.

3.6.2 Fuel Assembly Drop Accident Analysis

In Section 2.3.1.4 [1], the Licensee discussed the unlikely event of dropping a fuel assembly, wherein two accident conditions are postulated.

The first accident condition considers that the weight of the fuel assembly, control rod assembly and handling mechanism (3000 lb) impacts the top end fitting of a stored fuel assembly from a drop height of 6 ft. Although the Licensee did not provide the analysis or analysis methods, the Licensee stated [1] that "calculations show that the impact energy is absorbed by the dropped fuel assembly, the cells and the rack base plate assembly." Although independent analysis was not performed, rack modules under fabrication were inspected at the Licensee's vendor facilities during the review. Based upon this inspection of the rack construction, the rack modules are considered to be acceptable for a 6-ft fuel assembly drop as described above.

The second accident condition considered by the Licensee is that of a dropped assembly (3000 lb) falling straight through an empty cell and impacting upon the base plate from a drop height of 234 in. For this case, the Licensee provided the following additional information [5]:

> "Analysis has been performed which shows that the 234 in fuel assembly accidental drop satisfies the design criteria of not resulting in perforation of the pool liner. In the analysis it is shown that the energy of the falling fuel assembly is satisfactorily absorbed by the crushing of the fuel rack base plate and the deformation of the lower portion of the fuel assembly (lower fitting and lower portion of the guide tubes and instrument tube). The load tranmitted to the pool liner is such that the stress developed in the liner does not result in perforation. It should be noted that the analysis performed is conservative in that the fuel assembly is assumed to be under free fall (water resistance within the cell is neglected), and it is assumed that no energy is dissipated by the breaking of welds which hold the base plate to the rest of the rack."

For both accidents above, the Licensee indicated that the spent fuel pool liner would not be perforated and that the criticality acceptance criterion [1] was not violated.

4. CONCLUSIONS

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

- 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 in which the displacements are small compared to the available clearance space. As the Licensee's reported displacements are small, an acceptable use of the hydrodynamic coupling was employed.

- Computed displacements are small relative to clearance between rack modules or between rack modules and the spent fuel pool walls. Thus, the use of two-dimensional dynamic rack module analysis was satisfactory for displacement.

- While the methodology employing two-dimensional nonlinear models and linear three-dimensional models correlated by load correcting factors to introduce the nonlinear impacting load characteristics to the three-dimensional linear model was not considered to be acceptable without further validation as a stress analysis method, a detailed step-by-step review of the stress analysis coupled with additional load tabulations requested and supplied indicates that, with the conservatisms noted to be present, the stress analysis is acceptable.

- The spent fuel pool floor system has design margin to sustain the additional floor loadings.

5. REFERENCES

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