EVALUATION REPORT FOR NON-CONFORMING 2 x 2 STORAGE CELL MODULE

FOR

THE CALVERT CLIFFS UNIT 1 NUCLEAR PLANT

HIGH DENSITY SPENT FUEL STORAGE RACKS

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TABLE OF CONTENTS

1. INTRODUCTION

During the fabrication of the Calvert Cliffs Unit 1 Nuclear Plant high density spent fuel storage racks, a 2 x 2 cell module was damaged by an accidental drop during handling. The 2 x 2 cell module was set aside and later dismantled to remove the associated poison material. Eight of the nine high density fuel racks were assembled at the time the damaged 2 x 2 cell module was dismantled.

An examination of the removed outer stainless steel sheets indicated that the third vertical row of spot welds (see Figure 1) was defective. The vast majority of welds in the third rows (~ 90%) indicated a complete lack of fusion. An investigation of the problem indicated that some fifty (50) 2 x 2 cell modules may have a similar problem and that the assembled fuel racks contained up to thirteen of these suspect modules (out of a possible 25 modules). It was evident that the defective spot welds would reduce module stiffness and, hence, the natural frequencies of the non-conforming rack. The reduced natural frequencies could, in turn, increase the seismic acceleration values applied to the rack structure. Increased acceleration values and reduced rack stiffness properties would likely increase the stress levels in the 2 x 2 cell modules and the rack base structure.

Consequently it was concluded that the ability of a non-conforming fuel rack to accommodate the imposed seismic loads must be evaluated making the conservative assumption that each 2 x 2 cell module in the rack is deficient.

Two evaluations were determined to be necessary:

A. A structural analysis to evaluate the effect that the defective third row spot welds have on the results of the seismic analyses previously performed for the Calvert Cliffs Unit 1 fuel racks.

B. load test to determine the effect that the defective spot welds have on the ability of the 2 x 2 cell module to accommodate the local loads applied by the fuel assemblies during a seismic event. A load test was concluded to be necessary since sufficiently accurate local stress calculations could not be performed to make definitive conclusions.

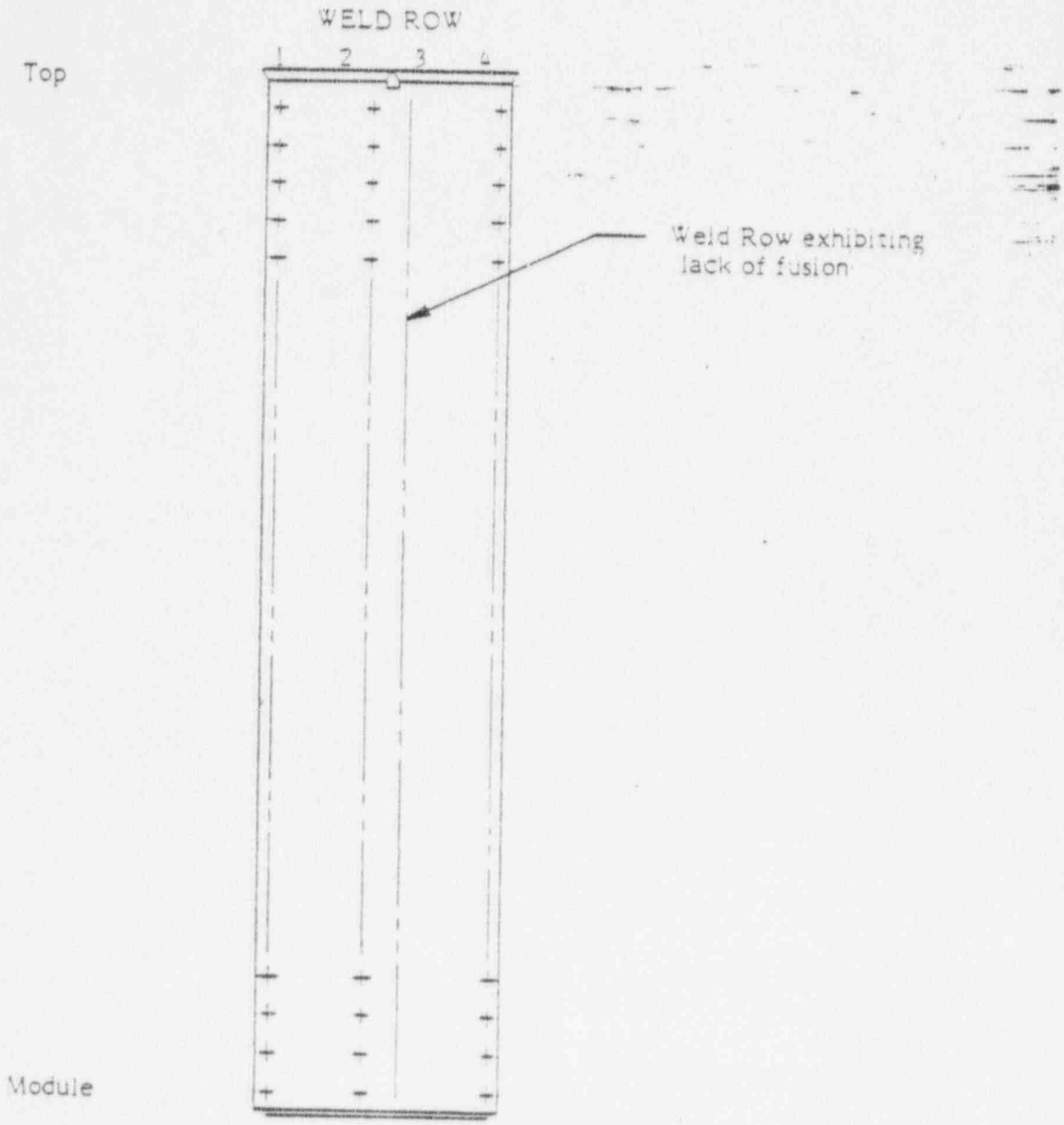

FIGURE 1 2 x 2 CELL MODULE SPOT WELD CONFIGURATION

This report presents a description of the structural analysis and load test evaluation methods, the results of these evaluations and the conclusions regarding the structural and functional adequacy of the non-conforming fuel rack.

2. METHODS OF EVALUATION

2.1 RACK STRUCTURAL ANALYSIS

The first step in the structural evaluation was to determine the effect of the defective third row welds on the module stiffness and, hence, the natural frequencies of the non-conforming rack. The reduced natural frequencies, in turn, established the seismic acceleration values to be applied to the module/rack base configuration. The following mathematical models were developed to determine the reduced stiffness and natural frequencies of the non-conforming 2 x 2 storage cell module and the seismic and stress analysis of the modified configuration of the fuel rack structure.

Non-Conforming 2 x 2 Storage Cell Module

The first model required for the structural evaluations was a detailed three dimensional finite element model of the non-conforming 2 x 2 storage cell module. In this model the outer stainless steel sheets of the 2 x 2 module were separated from the inner cell walls at the defective (missing) vertical spot welds. This model with its distributed lumped masses and boundary conditions is shown in Figure 2. This model was used to determine the reduced stiffness, reduced natural frequency, and seismic response (displacement, velocity, acceleration, member forces and stresses) of the non-conforming 2 x 2 module.

10 x 10 Rack Model

The second model required for the evaluation consisted of twenty five single mass cantilever beams (representing twenty five 2 x 2 modules) rigidly attached to the rack base structure and attached to each other at the top by spacer bars. Each single mass cantilever beam has the same dynamic (frequency) characteristics as that of the non-conforming 2 x 2 module. The distributed masses corresponding to the fuel assembly storage cells, poison elements and

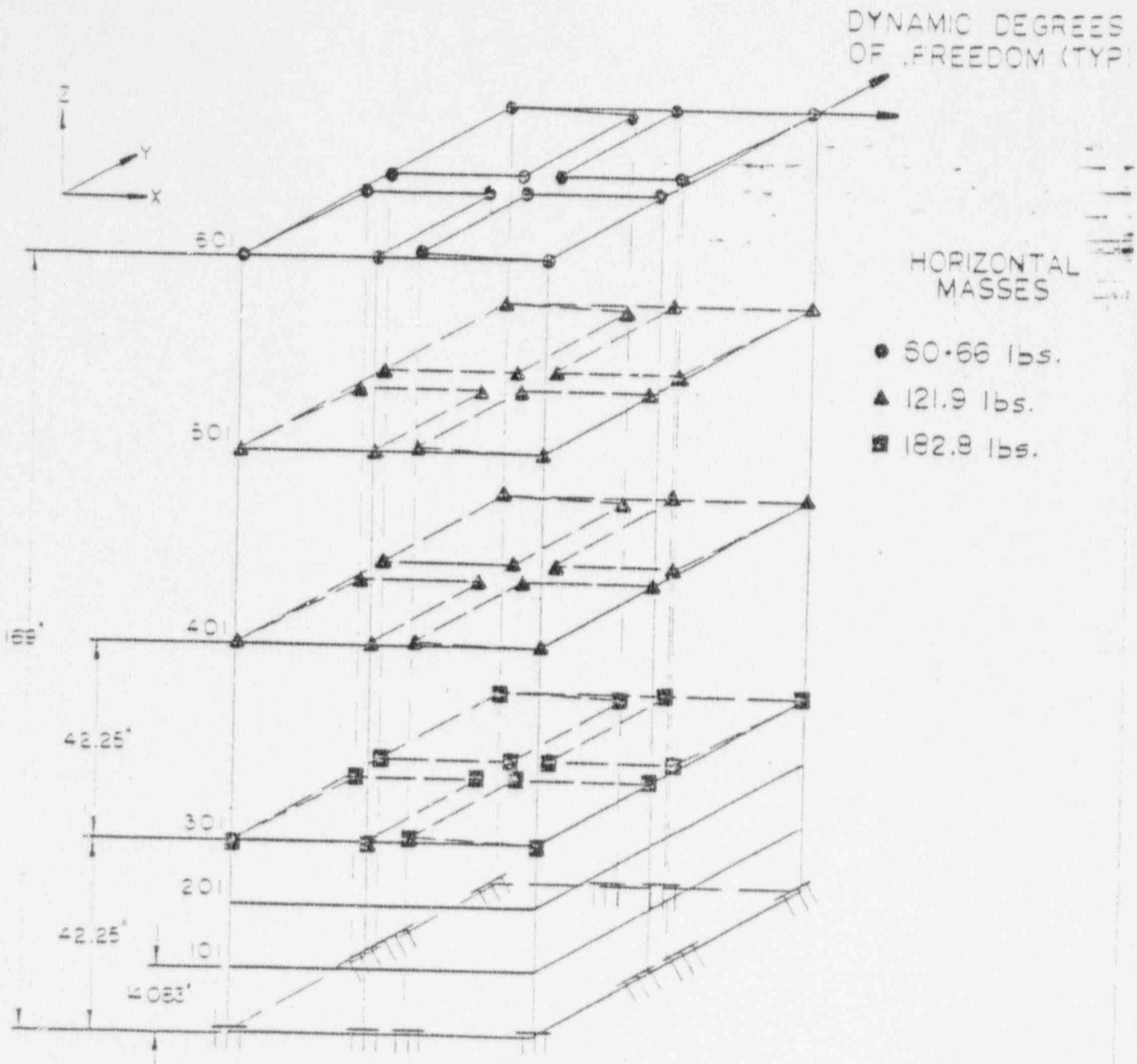

FIGURE 2 NONCONFORMING 2 x 2 CELL MODULE

FINITE ELEMENT MODEL - LUMPED MASSES AND BOUNDARY CONDITIONS

contained plus hydrodynamic mass are lumped at appropriate nodal points. The horizontal weights are distributed such that the resulting lumped mass multi-degree-of-freedom model best represents the dynamic characteristics of the fuel storage rack. This model was used to calculate the maximum stresses in the rack base structure and the reaction loads and stresses in the rack support feet. The seismic analyses are performed for the fully loaded racks only since this loading condition results in lower frequency, higher seismic accelerations, higher stresses and reaction loads. The boundary conditions and lumped mass locations for the horizontal seismic analyses are shown in Figure 3. The details of the mathematical model of the non-conforming 10 x 10 rack and the methods of seismic/stress analyses are same as those given in Section 7.1 of NES Document 81A0566, Revision 2, "Structure Design Analysis Reports for the Calvert Cliffs Unit #1 Nuclear Plant High Density Spent Fuel Storage Racks". Only the stiffness characteristics (moment of inertia) and section properties were modified to reflect the reduced stiffness and natural frequencies of the non-conforming configuration of the 2 x 2 cell module.

2.2 LOCAL LOADING EFFECTS TESTING

Three local stress/loading conditions were of concern because of the missing vertical spot welds:

A. The bending stress in the outer cell wall at the top of the cell module

B. The bending stress in the outer cell wall at an intermediate cell elevation corresponding to a spacer elevation for the stored fuel assemblies

C. The combined shear/tension loads on the remaining cell wall spot welds.

Three basic tests were devised to evaluate the above local conditions for the OBE and DBE seismic loadings associated with fuel assembly and "loose pin" storage. For these tests, a 2 x 2 cell module of half-height was fabricated using standard production spot welds at all locations except for the third vertical row location on each outer sheet, which contained no welds. A full-height module could not be constructed because of the lack of sufficient formed pieces. The

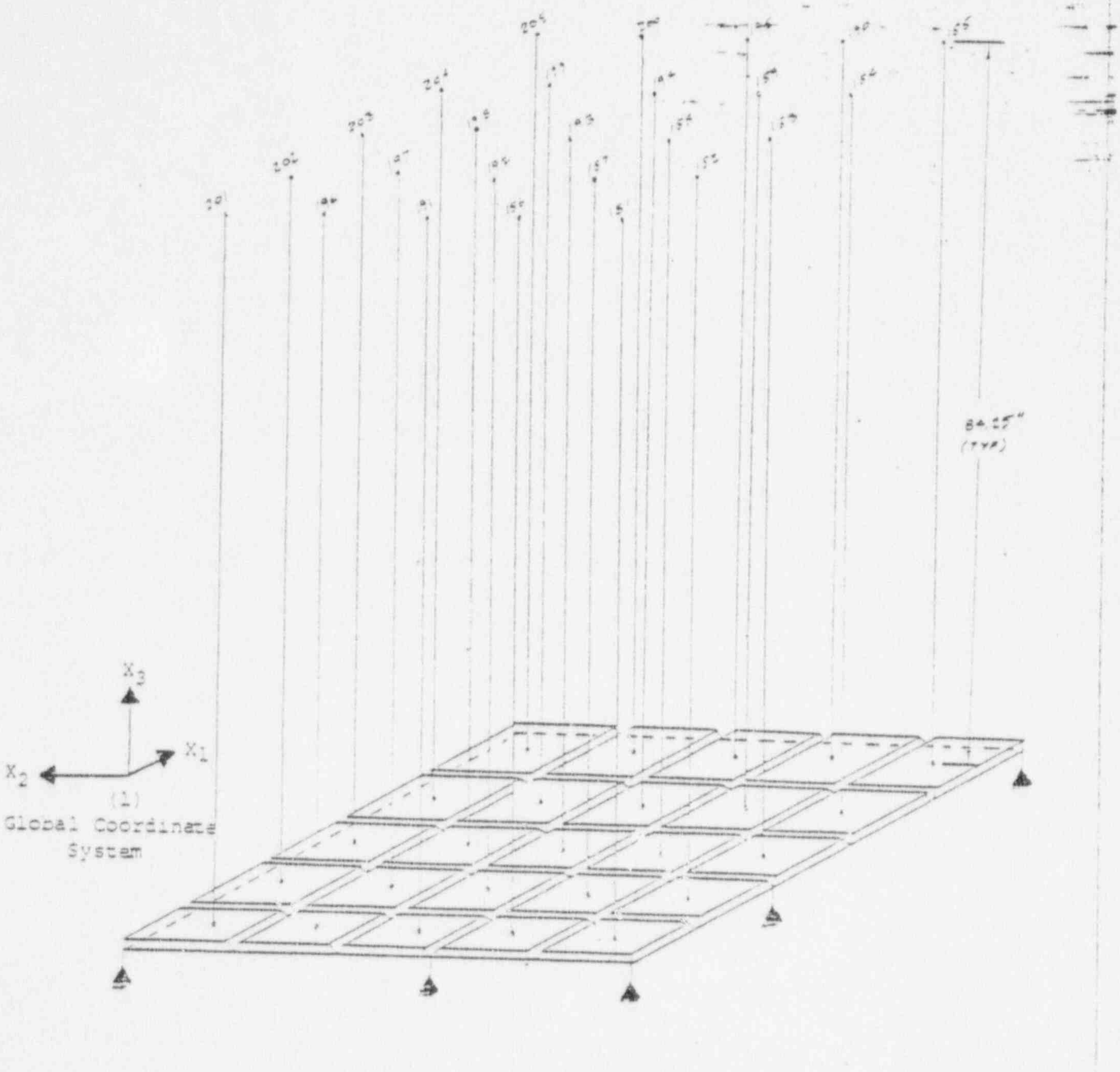

FIGURE 3 10 x 10 RACK FINITE ELEMENT MODEL

module, however, contained all of the principal items comprising a full size module except for the center spacer assembly. The 2 x 2 module, in turn, was welded to a carbon steel structure that supported the module in a horizontal attitude entirely from the module base plate (see Figure 1). Steel blocks were distributed inside the storage cells and on the module in accordance with the loading requirements specified for the three tests. The specified loadings are static equivalents of the maximum dynamic loads applied to the local areas and take into account the effects of virtual water mass and fuel assembly impact. A more detailed description of the loading tests, (and the specified load requirements) is presented in Attachment 1, Test Plan for Non-Conforming 2 x 2 Storage Cell Modules.

The effects of the loads were evaluated against the following general criteria:

A. For the OBE loads, no evidence of permanent deformation after the applied loads were removed.

B. For the DBE loads, no evidence that the 2 x 2 cell module and/or individual cells have lost structural integrity. Permanent deformation was permitted provided the module remains function (can store fuel in a safe geometry).

3. RESULTS OF EVALUATION

The results of static and seismic structural/stress analysis of the non-conforming Calvert Cliffs Nuclear Plant Unit 1 high density fuel storage racks performed with the ANSYS and STARDYNE computer code are contained in Reference 1.

The detailed seismic/structural analyses calculations to evaluate the effect of the non-conforming 2 x 2 cell modules on the results of the seismic analyses previously performed for the Calvert Cliffs Unit #1 fuel racks are given in Reference 3.

The details of the tests for the local loading effects are contained in Reference 3.

3.1 RACK STRUCTURAL ANALYSES

The natural frequencies of vibration of the non-conforming 10 x 10 fuel storage rack are given in Table 1 along with their corresponding modal participation factors. The first mode frequency of 5.02 cycles per second represents the first mode frequency of the non-conforming storage rack structure including the flexibility characteristics of the rack base structure and support pads. The fundamental frequency of the non-conforming modular cell unit is 6.57 cycles per seconds. Referring to the horizontal seismic response acceleration spectra (Figure 5.1 of Reference 2), it can be seen that the first mode spectral acceleration values for the non-conforming rack (0.22G at 5.02Hz) is same as that for the design rack (0.22G at 5.39Hz).

The results of the non-conforming rack structural/stress analyses are summarized and compared with those of the design rack analyses (Reference 2) in Tables 2 and 3. Table 2 presents the analyses results and comparisons for fuel asssembly storage. Table 3 presents the analyses results and comparisons for loose fuel pin storage (165% of the weight of the normal fuel assembly).

TABLE 1

PERTINENT NATURAL FREQUENCIES
OF VIBRATION AND MODAL PARTICIPATION FACTORS (10 x 10 Rack Fully Loaded)

Mode Number	Frequency (CPS)	Modal Participation Factors X1 Direction	X2 Direction	X3 Direction
1	5.015	0.06330	0.6330	0.0024
2	5.041	0.6243	-0.6242	0.0
3	5.210	0.3304	0.3304	0.0001
4	5.229	0.2268	-0.2268	0.00
5	5.625	-0.0299	-0.0300	0.00
6	5.626	-0.0272	0.0272	0.00
7	6.017	0.0264	0.0264	0.0007
8	6.019	0.0229	-0.0229	0.000
9	6.338	-0.0138	0.0139	0.000
10	6.339	0.0139	0.0138	0.0004
11	35.723	0.0009	0.0009	0.0648
21	46.133	0.0152	0.0152	1.4927
22	60.234	-0.01598	0.01598	0.00

TABLE 2

SUMMARY OF STRUCTURAL EVALUATION OF NONCONFORMING 2 x 2 CELL MODULE FOR FUEL ASSEMBLY STORAGE

	Design Configuration	Nonconforming Configuration	Allowable Stress (ksi)
Frequency Analysis			
Frequency (HZ) of 2x2 Detail Model (Figure 2)	7.18	6.57	N/A
First Mode Frequency (HZ) of Fuel Rack Model (Figure 3)	5.39	5.02	N/A
Average Acceleration (G) for all 25 Masses (Figure 3)	1.04	1.04	N/A
Stress Analysis			
Rack Base Structure and Support Leg	same as Table 8.2 of Ref.2	same as Table 8.2 of Ref. 2	
Storage Cell Wall at Base:			
Bending Stress (ksi) fb_2/fb_3 due to OBE	3.59/3.59	5.15/5.15	23.96 (actual material)
Bending Stress (ksi) fb/fb_3 due to DBE	6.73/6.73	9.66/9.66	38.3 (actual material)

TABLE 2
(Continued)

	Design Configuration	Nonconforming Configuration	Allowable Stress (ksi)
Stress Analysis			
Combined Stress Ratio (OBE)	0.30	0.43	(actual material)
Combined Stress Ratio (DBE)	0.35	0.50	(actual material)
Storage Cell Wall at Base Considering Local Buckling Effects:			
Bending Stress (ksi) fb_2/fb_3 (OBE)	4.4/4.4	6.1/6.1	19.64 (actual material)
Bending Stress (ksi) fb_2/fb_3 (DBE)	8.24/8.24	11.4/11.4	31.42 (actual material)
Combined Stress Ratio (OBE)	0.45	0.62	(actual material)
Combined Stress Ratio (DBE)	0.52	0.73	(actual material)
Max. Stress (ksi) in weld between 2 x 2 cell wall and base plate (DBE)	15.07	15.07	33.6 (actual material)
Max. Stress (ksi) in weld between 2 x 2 cell wall base plate and base structure (DBE)	13.32	13.32	33.6 (actual material)

TABLE 3

SUMMARY OF STRUCTURAL EVALUATION OF NONCONFORMING 2 x 2 CELL MODULE FOR LOOSE FUEL PIN STORAGE

	Design Configuration	Nonconforming Configuration	Allowable Stress (ksi)
Frequency Analysis			
Frequency (HZ) of 2x2 Detail Model (Figure 2)	5.99	5.34	N/A
First Mode Frequency (HZ) of Fuel Rack Model (Figure 3)	4.49	4.26	N/A
Maximum Acceleration (G) for all 25 Masses (Figure 3)	1.097	0.87	N/A
Stress Analysis			
Rack Base Structure and Support Leg	same as Table F.2 of Ref.2	less than Table F.2 of Ref. 2	
Storage Cell Wall at Base:			
Bending Stress (ksi) fb_2/fb_3 due to OBE	5.88/5.88	5.92/5.92	23.96 (actual material)
Bending Stress (ksi) fb/fb_3 due to DBE	11.02/11.02	11.09/11.09	38.3 (actual material)

TABLE 3
(Continued)

	Design Configuration	Nonconforming Configuration	Allowable Stress (ksi)
Stress Analysis			
Combined Stress Ratio (OBE)	0.49	0.49	(actual material)
Combined Stress Ratio (DBE)	0.58	0.58	(actual material)
Storage Cell Wall at Base Considering Local Buckling Effects:			
Bending Stress (ksi) fb_2/fb_3 (OBE)	7.33/7.33	6.98	19.64 (actual material)
Bending Stress (ksi) fb_2/fb_3 (DBE)	13.73/13.73	13.10	31.42 (actual material)
Combined Stress Ratio (OBE)	0.75	0.71	(actual material)
Combined Stress Ratio (DBE)	0.87	0.83	(actual material)
Max. Stress (ksi) in weld between 2 x 2 cell wall and base plate (DBE)	27.12	17.22	33.6 (actual material)
Max. Stress (ksi) in weld between 2 x 2 cell wall base plate and base structure (DBE)	23.95	15.21 material)	33.6 (actual

From Table 2 it can be seen that due to the reduced stiffness of the non-conforming 2 x 2 module, its frequency has reduced from 7.18 Hz (design configuration) to 6.57 Hz. The first mode frequency of the non-conforming rack is 5.02 Hz compared with that of 5.39 Hz for the design rack configuration. Since there is no change in the first mode spectral acceleration values, the average acceleration values for the non-conforming and design rack are the same. Since there is no change in the average acceleration value, the maximum stresses in the rack base structure and support leg and the maximum floor loading are the same as those presented in Tables 8.2 and 8.3 of Reference 2. Table 2 indicates that due to the reduced section modulus of the non-conforming 2 x 2 module the stresses at base of the cell wall are higher than the stresses for the design configuration. The combined stress ratios for bi-axial bending are calculated using the yield stress for the actual material (39.2 KSI). The combined stress ratios are less than 1.0 for both the OBE and DBE events. Local buckling stress analyses at the base of the cell wall were performed using the methods given in AISI "Stainless Steel Cold-Formed Structural Design Manual" (Reference 4). The combined stress ratios are less than 1.0 for both the OBE and DBE events. The stresses in the welds between the cell wall and the base plate and between the base plate and the rack base structure are less than the allowable stress values using the actual material yield stress value.

Initial Analysis for the fuel racks conservatively assumed that all the twenty-five 2 x 2 cell modules were defective. This conservative analysis indicated that for the loose pin storage condition, the cell wall at the base of the 2 x 2 module may buckle under a DBE event. It was concluded from an ultrasonic test program that a more reasonable assumption was that eight 2 x 2 modules could be defective. For subsequent seismic analyses, a conservative model was used with thirteen non-conforming 2 x 2 modules placed at the most critical locations in a rack along with twelve normal 2 x 2 modules. The moment of inertia of the thirteen nonconforming 2 x 2 modules was reduced to account for the cell wall buckling. These analyses were performed using the revised response spectra of Reference 5. The results of the analyses are given in Table 3.

From Table 3 it can be seen that for the loose pin storage condition, the fundamental frequency of the non-conforming 2 x 2 cell module is 5.34Hz compared with the 5.99 Hz for the design cell module configuration. The first mode frequency of the non-conforming rack (4.26 Hz) is slightly smaller than that of the design rack configuration (4.49 Hz). The maximum stresses in the rack base structure and support leg and the maximum floor loading will be smaller than those presented in Tables F.2 and F.3 of Appendix F (Reference 2). Table 3 indicates that due to the reduced section modulus of the non-conforming 2 x 2 module, the stresses at the base of the cell wall are higher than the stresses in the design configuration. The combined stress ratios for bi-axial bending are less than 1.0 for both the OBE and DBE events.

The local buckling stress analysis at the base of the cell wall indicates that the combined stress ratios are less than 1.0 for both the OBE and DBE events. The maximum stresses in the welds between the cell wall and base plate and between the base plate and rack base structure are less than the allowable stress values using the actual material yield stress value.

3.2 LOCAL LOADING EFFECTS TESTING

The results of the local loading effects testing are presented in Table 4. Table 4 lists the tests in the actual sequence that they were completed. This sequence was chosen during the test to expedite the performance of the tests.

As can be seen from Table 4, none of the OBE tests resulted in any observable deformation when the loads were applied and consequently no permanent deformation when the OBE loads were removed. Only one DBE test (Test 6) resulted in a minor permanent deformation which would have absolutely no effect on the function of the module (storage of fuel in a safe geometry).

After this deformation occurred (Test 6 was the second test to be performed) no other significant deformations were observable when the loads were applied for the remaining DBE tests and no additional permanent deformation occurred after the DBE loads were removed.

A visual examination of the module spot welds, the module to base plate welds and the welds attaching the top spacer to the four cells indicated that all welds were sound. In fact, the integrity of top spacer welds was verified by applying sufficient impact loads to shear each weld. For completeness, it was decided to repeat Test 9 with the top spacer displaced to a location where it was no longer supporting Cell 1. With the Test 9 load applied to Cell 1 a downward displacement of less than 1/8 inch was observed under this condition. Some permanent deformation was observed after the DBE load was removed. It was evident that even in the unlikely event that a top spacer is displaced during a DBE seismic event no significant structural deformation will occur in a non-conforming module.

TABLE 4

TEST RESULTS

Test No.	Test Description	Seismic Event	Specified Cell ** Loading (lbs)	Cell * No.	Test Results
1	Local Effect, Intermediate Area (Fuel Assembly)	OBE	573	3 and 4	No deformation was observed in intermediate regions of Cells 3 and 4.
6	Local Effects, Intermediate Area (Fuel Assembly)	DBE	1075	3 and 4	Bottom outer sheet of module developed outward bulges (≈ 1/16 to 1/8") under Cell 4 over middle 2/3 of module length. Bulge remained after load was removed.*** This deformation for a DBE condition would not affect functional performance of module/rack.
2	Local Effect, Top Area (Fuel Assembly)	OBE	885	1 only	No deformation was observed in top areas of module and Cell 1.
4	Local Effect, Top Area (Loose Pin)	OBE	1243	1 only	No deformation was observed in top areas of module and Cell 1.
7	Local Effects, Top Area (Fuel Assembly)	DBE	1660	1 only	No deformation was observed in top areas of module and Cell 1.
3	Spot Weld (Fuel Assembly)	OBE	755	All	No deformation was observed in vicinities of module spot welds. No deformation observed in any area of module.

* See Figure 1 of Test Plan (see Attachment 1)

** Actual cell loadings were equal to or greater than the specified cell loading.

*** This bulge remained for the remainder of the tests. There was no indication that it increased in dimension (depth, width, or length)

TABLE 4
(Continued)

Test No.	Test Description	Seismic Event	Cell Loading (lbs)	Cell * No.	Test Results
5	Spot Weld (Loose Pin)	OBE	1170	All	No deformation was observed in vicinities of module spot welds. No deformation observed in any cell of module.
8	Spot Weld (Fuel Assembly)	DBE	1530	All	No deformation was observed in vicinities of module spot welds. No deformation observed in any area of module.
9	Local Effects, Top Area (Loose Pin)	DBE	2331	1 only	No permanent deformation was observed in top area of Module and Cell 1.
10	Spot Weld (Loose Pin)	DBE	2192	All	No permanent deformation was observed in vicinities of module spot welds. No permanent deformation observed in area of module. Only minor changes in the outer sheet appearances were observable.

4. CONCLUSIONS

Based on the results of the structural analysis and local loading effects evaluations, the following conclusions have been made:

1. The results of the structural analysis indicate that the stresses in the non-conforming storage rack structure resulting from the loadings associated with the normal and abnormal conditions are within the allowable stress limits for the actual material used in the rack fabrication. Consequently the non-conforming rack is structurally adequate to meet the requirements for Seismic Category I structures.

2. The results of the non-conforming 2 x 2 module local loading effects testing indicate that under OBE loading conditions there will not be any permanent deformation of the 2 x 2 module.

3. The results of the non-conforming 2 x 2 module local loading effects testing indicate that the small permanent deformation in some local areas of the 2 x 2 module resulting from DBE loading conditions will not adversely affect the structural and functional integrity of the storage rack.

4. The Calvert Cliffs Unit 1 non-conforming high density fuel storage rack is structurally adequate to perform its function (the storage of fuel in a safe geometry) during and after all anticipated loading conditions.

5. REFERENCES

1. Calvert Cliffs Unit 1 Fuel Storage Racks, Structural Analysis Project 5134, Task 770, NES Computer Output Binder No. S-55, October 1980.

2. Nuclear Energy Services, Inc. Document 81A0566 "Structural Analysis Design Report for the Calvert Cliffs Unit 1 Nuclear Plant High Density Fuel Storage Racks," Revision 2.

3. Calvert Cliffs Unit 1 Fuel Storage Racks Structural Analysis Design Calculation Notebook, Volume 1, Project 5134, Task 300.

4. American Iron and Steel Institute, "Stainless Steel Cold-Formed Structural Design Manual," 1974 Edition.

5. Bechtel Power Corporation, "Acceleration Spectra for the Auxiliary Building of BG&E's Calvert Cliffs Units No. 1 and 2," Job 6750, November 20, 1976.