Mechanical Analysis for
US-APWR New and Spent Fuel Racks

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Abstract

This report considers the structural adequacy of the proposed US-APWR spent and new fuel racks under postulated loading conditions. Analyses and evaluations follow the U.S. Office of Technology Position paper and the NRC Standard Review Plan.
This report provides a discussion of the method of analyses, modeling assumptions, key evaluations, and results obtained to establish the margins of safety.

This report includes the following analysis results:

- Structural/Seismic Analysis
- Mechanical Accidental Analysis

It is confirmed that results of the above analyses satisfied the fuel racks requirements of the U.S. Office of Technology Position Paper and the NRC Standard Review Plan.

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List of Acronyms

ASME	American Society of Mechanical Engineers
B&PV	Boiler and Pressure Vessel
COF	Coefficient of Friction
DFR	Damaged Fuel Rack
DOF	Degree of Freedom
DFAC	Damaged Fuel Assembly Container
MHI	Mitsubishi Heavy Industries, LTD.
NFP	New Fuel Pit
NFR	New Fuel Pack
NOR	Number of Racks
NRC	Nuclear Regulatory Commission
OBE	Operating Basis Earthquake
OT	Office of Technology
RG	Regulatory Guide
SFP	Spent Fuel Pit
SFR	Spent Fuel Rack
SRP	Standard Review Plan
SSE	Safety Shutdown Earthquake
US-APWR	United States-Advanced Pressurized Water Reactor
WPMR	Whole Pool Multi-Rack

1.0 INTRODUCTION

This report considers the structural adequacy of the proposed Spent Fuel Racks (SFR) and the New Fuel Racks (NFR) for the United States-Advanced Pressure Water Reactor (US-APWR). The SFRs are placed inside the pit whereas the NFRs are placed outside the pit. All analyses and evaluations follow the US Office of Technology (OT) Position Paper (Reference 6-1) and the U.S. NRC Standard Review Plan (SRP) (Reference 6-2) whichever is more limiting. The dynamic analyses employ a time-history simulation code used by Holtec International for numerous previous licensing efforts in the US and abroad.

This report provides a discussion of the method of analyses, modeling assumptions, key evaluations, and the results obtained to establish the margins of safety.

This report establishes the structural integrity of the SFR and NFR under seismic loading. The objective of this report is to develop the loads on the fuel racks and to confirm that the loads do not pose a threat to active fuel.

The module layout for the SFR and NFR to be installed is illustrated in Figure 2-1. The SFR layout consists of Six (6) SFR's and two (2) Damaged Fuel Racks (DFR) with a combined storage capacity of 912 cells. The NFR layout consists of three (3) NFR's which provide a total storage capacity of 180 cells.

2.0 US-APWR FUEL RACKS

The SFR modules are shown in Figure 2-1. Spent fuel is stored in moderate density racks to be installed in the spent fuel pit (SFP) filled with borated water. The SFR has the capacity to store 900 fuel assemblies, and the center-to-center spacing between adjacent fuel assemblies is nominally 11.1 inches to maintain subcriticality. The cell wall thickness of the SFRs is 0.075 inches.

The DFR modules are shown in Figure 2-1 along with the SFR modules. Twelve locations are included to support damaged fuel assembly container (DFAC). The DFR storage cells are square in shape and have a cell wall thickness of 0.375 inches. The DFRs have a cell pitch of 24 inches. The DFAC shall be installed within the DFR in the SFP.
The DFAC shall have the capability to confine gross fuel particles, debris, etc.
The NFR modules are shown in Figure 2-1. New fuel is stored in low density racks installed in the dry new fuel pit (NFP). The NFRs store 180 fuel assemblies, and the center-to-center spacing between adjacent fuel assemblies is nominally 16.9 inches to maintain subcriticality. The cell wall thickness of the NFR is 0.209 inches. For conservatism, however, the structural calculations for the NFR presented in this report assume that the cell wall thickness is only 0.18 inches.

All SFRs and NFRs are freestanding and self-supporting. The principal construction materials for the racks are SA240-304 or -304L stainless steel sheet and plate stock, and SA564-630 precipitation hardened stainless steel bar for adjustable support spindles. The only non-stainless material utilized in the rack is the neutron absorber material, which is a boron carbide and aluminum metal matrix composite available under the patented product name Metamic™.

The SFRs and NFRs have been designed to meet the stress limits of, and have been analyzed in accordance with, Section III, Division I, Subsection NF of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code (Reference 6-3). The structural materials of the racks will be procured in accordance with the specifications of Section II of the ASME B&PV Code (Reference 6-4). All applicable structural welds will be performed using procedures developed and qualified in accordance with Section IX of ASME B&PV Code (Reference 6-5).

Figure 2-2 and 2-3 provide the isometric schematics of the SFR and NFR respectively. Each SFR and NFR module is supported by five pedestals, which are remotely adjustable. The rack module support pedestals are adjustable in length to accommodate minor variations in the pit floor flatness. Thus, the racks can be made vertical and the top of adjacent racks can easily be made co-planar with each other. Between the rack module pedestals and the supporting floor liner is a bearing pad, which serves to diffuse the dead load of the loaded racks into the reinforced concrete structure of the floor.

The overall designs of the rack modules are similar to those presently in service in the SFPs at many other nuclear plants. Altogether, Holtec International has provided over 50 thousand storage cells of these designs to various nuclear plants around the world.

The rack modules are designed as cellular structures such that each fuel assembly has a square opening with conforming lateral support and a flat horizontal-bearing surface. All of the spent fuel storage locations are constructed with multiple cooling flow holes to ensure that redundant flow paths for the coolant are available. The basic characteristics of the fuel racks are summarized in Table 2-1 through 2-3.

3.0 STRUCTURAL/SEISMIC CONSIDERATION

3.1 Methodology

3.1.1 Acceleration Time Histories

The response of a freestanding rack module to seismic inputs is highly nonlinear and involves a complex combination of motions (sliding, rocking, twisting, and turning), resulting in impacts and frictional effects. Linear methods, such as modal analysis and response spectrum techniques, cannot accurately replicate the response of such a highly nonlinear structure to seismic excitation. An accurate simulation is obtained only by direct integration of the nonlinear equations of motion using actual pit slab acceleration time-histories as the forcing function. Therefore, initial step in US-APWR fuel racks qualification is to develop synthetic time-histories for three orthogonal directions that comply with the guidelines of the NRC SRP (Reference 6-6). The synthetic time-histories must meet the criteria of statistical independence, envelope the target design response spectra, and envelope the target Power Spectral Density function associated with the target response spectra.

The SFRs and NFRs have been analyzed using four different sets of acceleration time histories, which correspond to different soil conditions.

3.1.2 Modeling Methodology

3.1.2.1 General Considerations

Once an admissible set of input excitations is obtained, the next step in the analysis process is to develop a suitable dynamic model. Reliable assessment of the stress field and kinematic behavior of the rack modules calls for a conservative dynamic model incorporating all key attributes of the actual structure. This means that the dynamic model must have the ability to execute concurrent sliding, rocking, bending, twisting and other motion forms compatible with the freestanding installation of the modules. Furthermore, the model must possess the capability to effect momentum transfers which occur due to rattling of fuel assemblies inside storage cells and the capability to simulate lift-off and subsequent impact of support pedestals with the pit liner (or bearing pad). The contribution of the water mass in the interstitial spaces around the rack modules and within the storage cells must be modeled in an accurate manner. The Coulomb friction coefficient at the pedestal-to-pit liner (or bearing pad) interface may lie in a rather wide range and a conservative value of friction cannot be prescribed a priori.

The three-dimensional (3-D) dynamic models of a single spent fuel rack introduced by Holtec International in 1980 have been used in many re-rack projects since that time. The details of this classical methodology are published in the permanent literature (Reference 6-7). Briefly, the 3-D model of a typical rack in the SFP handles the array of variables as follows:

(1) <u>Interface Coefficient of Friction</u>

Coefficient of friction (COF) values are assigned at each interface, which reflect the realities of stainless steel-to-stainless steel contact. The mean value of COF is 0.5, and the limiting values are based on experimental data, which are bounded by the values 0.2 and 0.8 (Reference 6-8).

(2) <u>Impact Phenomena</u>

Compression-only spring elements, with gap capability, are used to provide for opening and closing of interfaces such as the pedestal-to-bearing pad interface, the fuel assembly-to-cell wall interface, and rack-to-rack and rack-to-pit wall potential contact locations.

(3) <u>Fuel Loading Scenarios</u>

The dynamic analyses performed for the SFRs and NFRs conservatively assume that all fuel assemblies within the rack rattle in unison throughout the seismic event, which obviously exaggerates the contribution of impact against the cell wall.

(4) <u>Fluid Coupling</u>

Holtec International extended Fritz's classical two-body fluid coupling model (Reference 6-9) to multiple bodies and utilized it to perform the first two-dimensional multi-rack analysis. Subsequently, laboratory experiments were conducted to validate the multi-rack fluid coupling theory. This technology is incorporated in the Whole Pool Multi-Rack (WPMR) analysis, which permits simultaneous simulation of all racks in the pit. This treatment of in-pit hydrodynamics has been used in many Holtec re-rack submittals since 1988. In its simplest form the so-called "fluid coupling effect" (Reference 6-9 and 6-10) can be explained by considering the proximate motion of two bodies under water. If one body (mass m_1) vibrates adjacent to a second body (mass m_2), and both bodies are submerged in frictionless fluid, then Newton's equations of motion for the two bodies are:

$$(m_1 + M_{11})\, A_1 + M_{12}\, A_2 = \text{applied forces on mass } m_1 + O\,(X_1^2)$$
$$M_{21}\, A_1 + (m_2 + M_{22}) A_2 = \text{applied forces on mass } m_2 + O\,(X_2^2)$$

A_1, A_2 denote absolute accelerations of masses m_1 and m_2, respectively, and the notation $O(X^2)$ denotes nonlinear terms. The fluid adds mass to the body (M_{11} to mass m_1), and an inertial force proportional to acceleration of the adjacent body (mass m_2). Thus, acceleration of one body affects the force field on another. This force field is a function of inter-body gap, reaching large values for small gaps. Lateral motion of a fuel assembly inside a storage location is subject to this effect. The fluid coupling, in general, is always present when a series of closely spaced bodies (fuel racks) undergo transient motion in a submerged SFP. The fluid coupling effect encompasses interaction between *every* set of racks in the pit (i.e., the motion of one rack produces fluid forces on all other racks and on the pit walls). Stated more formally, both near-field and far-field fluid coupling effects are included in the analysis. During the seismic event, all racks in the pit are subject to the input excitation simultaneously. The motion of each freestanding module is autonomous and independent of others as long as they do not impact each other and no water is present in the pit. As noted in Reference 6-9 and 6-10, the fluid forces can reach rather large values in closely spaced geometries. It is, therefore, essential that the contribution of the fluid forces be included in a comprehensive manner. This is possible only if all racks in the pit are allowed to execute 3-D motion in the mathematical model. For this reason, single rack or even multi-rack models involving only a portion of the freestanding racks in the pit, are inherently inaccurate. The fluid coupling effects between all freestanding racks must be included in the model to properly account for the interaction of the hydrodynamic forces with the inertia and friction forces. The WPMR model removes this intrinsic limitation of the rack dynamic models by simulating the 3-D motion of all modules simultaneously. The derivation of the fluid coupling matrix relies on the classical inviscid fluid mechanics principles, namely the principle of continuity and Kelvin's recirculation theorem. The derivation of the fluid coupling matrix is not based on an artificial construct, but it has been nevertheless verified by an extensive set of shake table experiments (Reference 6-10).

3.1.2.2 Specific Modeling Details for Rack

The “building block” for the WPMR analysis is a 3-D multi-degree of freedom model for each single SFR. For the purposes of the WPMR dynamic analysis, each rack, plus contained rattling fuel, is modeled as a 22 degree of freedom (DOF) system. The rack cellular structure elasticity is modeled by a 3-D beam having 12 DOF (3 translation and 3 rotational DOF at each end so that 2-plane bending, tension/compression, and twist of the rack are accommodated). An additional two (2) horizontal DOFs are ascribed to each of five rattling fuel masses which are located at heights 0H, 0.25H, 0.5H, 0.75H and H, where H is the height of a storage cell above the baseplate. While the horizontal motion of the rattling fuel mass is associated with five separate masses, the totality of the fuel mass is associated with the vertical motion and it is assumed that there is no fuel rattling in the vertical direction. In other words, the vertical displacement of the fuel is coupled with the vertical displacement of the rack (i.e., degree of freedom “P3” in Figure 3-1) by lumping the entire stored fuel mass (in the vertical direction only) with the vertical rack mass at the baseplate level.

The beam model for the rack is assumed supported, at the base level, on five pedestals modeled with non-linear elements; these elements are properly located with respect to the centerline of the rack beam, and allow for arbitrary rocking and sliding motions. The horizontal rattling fuel masses transfer load to the SFR through compression only gap spring elements oriented to allow impacts of each of the five rattling fuel masses with the rack cell in either or both horizontal directions at any instant in time. Figure 3-1 illustrates the typical dynamic rack model with the degrees of freedom shown for both rack and for rattling fuel. In order to simulate this behavior, the stored fuel mass is distributed among the five lumped mass nodes, for all racks, as follows:

(1) Top of rack (node 2* in Figure 3-1) 12.5% of total stored fuel mass

(2) 3/4 height (node 3* in Figure 3-1) 25% of total stored fuel mass

(3) 1/2 height (node 4* in Figure 3-1) 25% of total stored fuel mass

(4) 1/4 height (node 5* in Figure 3-1) 25% of total stored fuel mass

(5) Bottom of rack (node 1* in Figure 3-1) 12.5% of total stored fuel mass

The stiffness of pedestal springs that simulate rack pedestal to the floor compression-only contact is modeled using contact and friction elements at the locations of the pedestals between pedestal and floor. A total of five contact springs (one at each pedestal location) and 10 friction elements (two per pedestal) are included in each 22 DOF rack model.

Also shown in Figure 3-1 is a model detail of a typical support with a vertical compression only gap element and two orthogonal elements modeling frictional behavior. These friction elements resist lateral loads, at each instant in time, up to a limiting value set by the current value of the normal force times the coefficient of friction. Figures 3-2 through 3-4 show schematics of the various (linear and non-linear) elements that are used in the dynamic model of a typical spent fuel rack. Specifically, Figure 3-2 shows the location of the compression-only gap elements that are used to simulate the potential for rack-to-rack or rack-to-wall contact at every instant in time. Figure 3-3 shows the four compression only gap elements at each rattling mass location, which serve to simulate rack to fuel assembly impact in any orientation at each instant in time. Figure 3-4 shows a two-dimensional elevation schematic depicting the five fuel masses and their associated gap/impact elements, the typical pedestal friction and gap impact elements. This figure combines many of the features shown in Figures 3-2 and 3-3, and it provides an overall illustration of the dynamic model used for the US-APWR fuel racks.

Finally, Figure 3-5 provides a schematic of the coordinates and the beam springs used to simulate the elastic bending behavior of the rack cellular structure in two-plane bending. Not shown are the linear springs modeling the extension, compression and twisting behavior of the cellular structure.

Mass Matrix

In addition to the structural mass, the following hydrodynamic effects of the SFP water are included in the total mass matrix:

(1) Rack-to-fuel hydrodynamic mass due to fluid motion inside each of the SFR cells.

(2) Hydrodynamic mass due to fluid movement around the SFRs in the interstitial spaces between modules.

(3) Hydrodynamic mass effects under the baseplate of each SFRs.

(4) There is no water in the NFP. Therefore, the above hydrodynamic effects do not apply to the NFRs.

Stiffness Matrix

The spring stiffnesses associated with the elastic elements that model the behavior of the assemblage of cells within a rack are based on the representation developed in (Reference 6-11). Tension-compression behavior and twisting behavior are each modeled by a single spring with linear or angular extension involving the appropriate coordinates at each end of the rack beam model. For simulation of the beam bending stiffness, a model is used consistent with the techniques of the reference based on a bending spring and a shear spring for each plane of bending, which connects the degrees of freedom associated with beam bending at each end of the rack. Impact and friction behavior is included using the piecewise linear formulations similarly taken from the reference.

The SFR and NFR are subject to the SSE earthquakes described in Section 3.1.1. Eight runs have been performed (Four each for the SFR and NFR) using a random value of Coefficient of friction, with an upper and lower bound limits of 0.8 and 0.2 respectively.

3.1.3 Simulation and Solution Methodology

The WPMR analysis process is the vehicle available for displacement and load analysis of each rack in the pit and also serves to establish the presence or absence of specific rack-to-rack or rack-to-wall impacts during the seismic event. Recognizing that the analytical work effort must deal with stress and displacement criteria, the sequence of model development and analysis steps that are undertaken for each simulation are summarized in the following:

(1) Prepare 3-D dynamic models of the assemblage of all rack modules in the pit. Include all fluid coupling interactions and mechanical couplings appropriate to performing an accurate non-linear simulation.

(2) Perform non-linear WPMR dynamic analyses for the assemblage of racks in the pit. Archive for post-processing appropriate displacement and load outputs from the dynamic model.

(3) Perform stress analysis of high stress areas for rack dynamic runs. Demonstrate compliance with ASME Code Section III, Subsection NF (Reference 6-3) limits on stress and displacement. The high stress areas are associated with the pedestal-to-baseplate connection. In addition, some local evaluations are performed for the bounding case to ensure that the fuel remains protected under all impact loads.

For the transient analyses performed in part (2) above, a step-by-step solution in time, employing a central difference algorithm is used to obtain a solution. The WPMR simulation model serves as the foundation for the analyses performed herein. The solver computer algorithm, implemented in the Holtec Proprietary Code MR2v300 (a.k.a. DYNARACK), is given in (Reference 6-11) and the documentation of MR2v300 is presented in (Reference 6-12).

Using the 22-DOF structural model for every rack that comprises a WPMR simulation, equations of motion corresponding to each degree-of-freedom are obtained using Lagrange's formulation of the dynamic equations of motion (Reference 6-11). The system kinetic energy includes contributions from the structural masses defined by the 22-DOF model. The final system of equations has the matrix form:

$$[M]\,\{d^2q/dt^2\} = \{Q\} + \{G\}$$

where:

[M] - total mass matrix (includes structural mass contribution). The size of this matrix will be (22 x NOR) x (22 x NOR). NOR = number of racks in the SFP or NFP.

{q} - the nodal displacement vector relative to the pit slab displacement

{G} - a vector dependent on the given ground acceleration

{Q} - a vector dependent on the spring forces (linear and nonlinear) and the coupling between degrees-of-freedom

The above column vectors have length (22 x NOR).
The equations can be rewritten as follows:

$$\{d^2q/dt^2\} = [M]^{-1}\,\{Q\} + [M]^{-1}\,\{G\}$$

This equation set is mass uncoupled, displacement coupled at each instant in time. The numerical solution uses a central difference scheme built into the proprietary computer program.

Results are archived at appropriate time intervals for permanent record and for subsequent post- processing for structural integrity evaluations as follows:

(1) All generalized nodal displacement coordinate values in order to later determine the motion of the rack.

(2) All load values for linear springs representing beam elasticity.

(3) All load values for compression-only gap springs representing pedestals, rack-to-fuel impact, rack-to-rack and rack-to-wall impacts.

(4) All load values for friction springs at the pedestal/bearing pad interface.

3.1.4 Conservatisms Inherent in the Methodology

The following item is a built-in conservatism:

(1) Spring rates are computed in a conservative manner to employ maximum values in the analysis. This tends to conservatively overestimate peak impact forces.

(2) All stored fuel assemblies are conservatively assumed to rattle in unison, which exaggerates the impact momentum between the fuel and the rack.

3.2 Kinematic and Stress Acceptance Criteria

3.2.1 Introduction

The SFR and NFR are designed as seismic Category I. The OT Position Paper (Reference 6-1) and the USNRC SRP 3.8.4 (Reference 6-2) state that the ASME Code Section III, Subsection NF (Reference 6-3), as applicable for Class 3 Components, is an appropriate vehicle for design. In the following sections, the ASME limits are set down first, followed by any modifications by project specification, where applicable.

3.2.2 Kinematic Criteria

The SFR and NFR should not exhibit rotations sufficient to cause the rack to overturn (i.e., ensure that the rack does not slide off the bearing pads or exhibit a rotation sufficient to bring the center of mass over the corner pedestal).

3.2.3 Stress Limits Criteria

For thoroughness, the SRP load combinations are used. Stress limits must not be exceeded under the required load combinations. The loading combinations shown in Table 3-1 are applicable for freestanding racks that are made of steel.

Note that there is no operating basis earthquake event for US-APWR; therefore, loading conditions associated with an Operating Basis Earthquake (OBE) event are not considered.

3.2.4 Stress Limits for Various Conditions Per ASME

Stress limits for Normal Conditions are derived from the ASME Code, Section III, Subsection NF. Parameters and terminology are in accordance with the ASME Code. The SFR and NFR are freestanding; thus, there is minimal or no restraint against free thermal expansion at the base of the rack. Moreover, thermal stresses are secondary which, strictly speaking, have no stipulated stress limits in Class 3 structures or components. Thermal loads applied to the rack are, therefore, not included in the stress combinations.

Material properties for analysis and stress evaluation are provided in Section 3.4.3.

3.2.4.1 Normal Conditions (Level A)

(1) Tension

Allowable stress in tension on a net section is

$$F_t = 0.6\ S_y$$

where S_y is the material yield strength at temperature. (F_t is equivalent to primary membrane stress.)

(2) Shear

Allowable stress in shear on a net section is

$$F_v = 0.4\ S_y$$

(3) Compression

Allowable stress in compression on a net section of Austenitic material is

$$F_a = S_y\,(0.47 - kl/444r)$$

where kl/r < 120 for all sections and

l = unsupported length of component.

k = length coefficient which gives influence of boundary conditions, e.g.

k = 1 (simple support both ends)

k = 2 (cantilever beam)

k = 0.5 (clamped at both ends)

Note: Evaluations conservatively use k=2 for all conditions

E = Young's modulus

r = radius of gyration of component = c/2.45 for a thin wall box section of mean side width c.

(4) Bending

Allowable bending stress at the outermost fiber of a net section due to flexure about one plane of symmetry is

$$F_b = 0.60\ S_y$$

(5) Combined Bending and Compression

Combined bending and compression on a net section satisfies

$$f_a/F_a + C_{mx}f_{bx}/D_xF_{bx} + C_{my}f_{by}/D_yF_{by} < 1.0$$

where:

f_a = Direct compressive stress in the section

f_{bx} = Maximum bending stress for bending about x-axis

f_{by} = Maximum bending stress for bending about y-axis

C_{mx} = 0.85

C_{my} = 0.85

D_x = $1 - (f_a/F'_{ex})$

D_y = $1 - (f_a/F'_{ey})$

$F'_{ex,ey} = (\pi^2 E)/(2.15\ (kl/r)_{x,y}{}^2)$

and subscripts x and y reflect the particular bending plane.

(6) Combined Flexure and Axial Loads

Combined flexure and tension/compression on a net section satisfies

$$(f_a/0.6\ S_y) + (f_{bx}/F_{bx}) + (f_{by}/F_{by}) < 1.0$$

(7) Welds

Allowable maximum shear stress on the net section of a weld is

$$F_w = 0.3\ S_u$$

where S_u is the material ultimate strength at temperature. For the area in contact with the base metal, the shear stress on the gross section is limited to 0.4 S_y.

3.2.4.2 Upset Conditions (Level B)

Although the ASME Code allows an increase in allowables above those appropriate for normal conditions, any evaluations performed herein conservatively use the normal condition allowables.

3.2.4.3 Faulted (Abnormal) Conditions (Level D)

Section F-1334 (ASME Section III, Appendix F (Reference 6-13)), states that limits for the Level D condition are the smaller of 2 or 1.167 S_u/S_y times the corresponding limits for the

Level A condition if $S_u > 1.2\ S_y$, or 1.4 if $S_u \leq 1.2\ S_y$ except for requirements specifically listed below. S_u and S_y are the ultimate strength and yield strength at the specified rack design temperature. Examination of material properties for 304L stainless demonstrates that 1.2 times the yield strength is less than the ultimate strength. Since 1.167 x (66,100/21,400) = 3.60, the multiplier of 2.0 controls.

Exceptions to the above general multiplier are the following:

(1) Stresses in shear in the base metal shall not exceed the lesser of 0.72 S_y or 0.42 S_u. In the case of the austenitic stainless material used here, $0.72S_y$ governs.

(2) Axial compression loads shall be limited to 2/3 of the calculated buckling load.

(3) Combined Axial Compression and Bending - The equations for Level A conditions shall apply except that

$$F_a = 0.667 \times \text{Buckling Load/ Gross Section Area},$$

and $F_{ex,ey}$ may be increased by the factor 1.65.

(4) For welds, the Level D allowable maximum weld stress is not specified in Appendix F of the ASME Code (Reference 6-13). An appropriate limit for weld throat is conservatively set here as:

$$F_w = (0.3\ S_u) \times \text{factor}$$

Where:

Factor = (Level D shear stress limit)/(Level A shear stress limit)

$$= 0.72 \times S_y / 0.4 \times S_y = 1.8$$

3.2.5 Dimensionless Stress Factors

In accordance with the methodology of the ASME Code, Section NF, where both individual and combined stresses must remain below certain values, the stress results are presented in dimensionless form. Dimensionless stress factors are defined as the ratio of the actual developed stress to the specified limiting value. The limiting value of each stress factor is 1.0 based on an evaluation which uses the allowable strength appropriate to Level A or Level D loading as discussed above.

R1 = Ratio of direct tensile or compressive stress on a net section to its allowable value (note pedestals only resist compression).

R2 = Ratio of gross shear on a net section in the x-direction to its allowable value.

R3 = Ratio of maximum bending stress due to bending about the x-axis to its allowable value for the section.

R4 = Ratio of maximum bending stress due to bending about the y-axis to its allowable value for the section

R5 = Combined flexure and compression factor (as defined in Section 3.2.4.1(5) above).

R6 = Combined flexure and tension (or compression) factor (as defined in Section 3.2.4.1(6) above).

R7 = Ratio of gross shear on a net section in the y-direction to its allowable value.

At any location where stress factors are reported, the actual stress at that location may be recovered by multiplying the reported stress factor R by the allowable stress for that quantity. For example, if a reported Level A combined tension and two plane bending stress factor is R_6 = 0.85, and the allowable strength value is 0.6 S_y, then the actual combined stress at that location is Stress = R_6 x (0.6 S_y) = 0.51 Sy

3.3 Assumptions

The following assumptions are used in the analysis:

(1) Fluid damping is neglected, which is a conservative assumption since it yields larger rack displacement.

(2) Modeling the total effect of *n* individual fuel assemblies rattling inside the storage cells in a horizontal plane as one lumped mass at each of 5 levels in the fuel rack is a conservative assumption.

(3) Fluid coupling forces are calculated based on the nominal fluid gaps. The fluid gaps are not updated according to the rack displacements.

3.4 Input Data

3.4.1 Rack Data

Table 2-1 through 2-3 contains information regarding the SFR, NFR and DFR data used in the analysis. Information is taken from the Holtec rack drawings (Reference 6-14, 6-15 and 6-16).

3.4.2 Structural Damping

Associated with every stiffness element is a damping element that provides 4% of critical linear viscous damping for an SSE event. This is consistent with the design basis damping value for the SFR and NFR provided in Reference 6-17, and also in accordance with Regulatory Guide 1.61 (Reference 6-18).

3.4.3 Material Data

The necessary material data are shown in Table 3-2. This information is taken from ASME Code Section II Part D (Reference 6-4). The values listed correspond to a temperature of 200^{o}F.

3.5 Computer Codes

All computer codes used in this analysis are presented in Table 3-3.

3.6 Analyses

3.6.1 Acceptance Criteria

The dimensionless stress factors, discussed in Section 3.2.5, must be less than 1.0. In addition,

(1) Cell wall stress shall be shown to remain below the critical buckling stress

(2) Weld and base metal stresses must remain below the allowable stress limits corresponding to the material and load conditions, as discussed in greater detail in following sections.

3.6.2 Dynamic Simulations

As discussed earlier, eight simulations are performed. The combinations of the COFs and seismic inputs are shown in Table 3-4. The simulations consider SSE excitations and are required to satisfy the stress and kinematic criteria of Reference 6-1 and 6-2.

3.7 Results of Analyses

3.7.1 Time History Simulation Results

Table 3-5 presents the results for major parameters for the SFR and NFR for each simulation.

To insure that the fuel racks have adequate safety margins, all subsequent stress evaluations for the fuel racks are based on the worst-case results from all eight runs.

3.7.2 Rack Structural Evaluation

3.7.2.1 Rack Displacements

The post-processor results summarized in Table 3- 6 provide the maximum absolute displacements at the top and bottom corners (in the E-W or N-S horizontal direction) relative to the pit slab.

3.7.2.2 Pedestal Vertical Forces

For SSE, the maximum vertical load on any SFR pedestal is 378,000 lbf and on any NFR pedestal is 257,000 lbf. These loads should be used to assess the structural integrity of the pit slab under the seismic event.

3.7.2.3 Pedestal Friction Forces

For SSE, the maximum Shear load on any SFR pedestal is 149,000 lbf and on any NFR pedestal is 126,100 lbf. These maximum results are used as an input loading to evaluate the female pedestal-to-baseplate weld (discussed in Section 3.7.3.2).

3.7.2.4 Impact Loads

The impact loads such as fuel-to-cell wall, rack-to-rack, and rack-to-wall impacts are discussed below.

(1) Fuel–to Cell Wall Impact Loads

For the five-lumped mass model (with 25% at the 1/4 points and 12.5% at the ends), the maximum g-load that the rack impacts on the fuel assembly can be computed as:

$$a = \frac{4F}{w} = 37.0g$$

where: a = maximum lateral acceleration in g's

F = maximum fuel-to-cell wall impact force (= 17,666 lbf)

w = weight of one fuel assembly (1,912 lbf)

The maximum fuel-to-cell impact force used here is the force generated in the DFRs, which bounds the fuel-to-cell impact force for the SFR. This force is very high and is used in the calculation for conservation purposes.

For the NFR, a maximum fuel assembly-to-cell wall impact load (2,190 lbf) generates an impact deceleration of

$$a = \frac{4F}{w} = 4.58g$$

The fuel impact decelerations calculated above are less than the impact load limits established by the fuel manufacture.

(2) Rack-to-Rack and Rack-to-Wall Impacts

The summary result files from MR2v300 (Reference 6-12) in all of the simulations have been scanned to determine the maximum impact on each side of rack. No rack to wall impacts occurs in both the SFR and NFR layouts. Rack to rack impact occurs for the SFR and NFR at the top and the baseplate due to seismic loading. The maximum impact force generated at the SFR and NFR are summarized in Table 3-7.

3.7.3 Rack Structural Evaluation

3.7.3.1 Rack Stress Factors

With time history results available for pedestal normal and lateral interface forces, the limiting bending moment and shear force at the baseplate-to-pedestal interface may be computed as a function of time. In particular, maximum values for the previously defined stress factors can be determined for every pedestal in the SFR and NFR. Using this information, the structural integrity of the pedestal can be assessed. The net section maximum (in time) bending moments and shear forces can also be determined at the bottom of the cellular structure. Based on these, the maximum stress in the limiting rack cell (box) can be evaluated.

These locations are the most heavily loaded net sections in the structure so that satisfaction of the stress factor criteria at these locations ensures that the overall structural criteria set forth in Section 3.2 are met.

The summary of the maximum stress factors for the SFRs and NFRs are provided in Table 3-8.
The need for an adjustment factor accounting for ASME Code slenderness ratio evaluation is addressed in Reference 6-19, and the adjusted factors are identified with * in Table 3-8. Note that the stress factors are computed conservatively using the material properties of SA240-304L.

All stress factors, as defined in Section 3.2, are less than the mandated limit of 1.0 for all racks for the governing faulted condition examined. Therefore, the rack is able to maintain its structural integrity under the worst loading conditions.

The maximum vertical load and shear load on a single pedestal for the SFRs and NFRs are given in Table 3- 5.

3.7.3.2 Weld Stress

Weld locations in the SFR and NFR are subjected to significant seismic loading at the bottom of the rack at the baseplate-to-cell connection, at the top of the pedestal support at the baseplate connection, and at the cell-to-cell connections. Bounding values of resultant loads are used to qualify the connections.

(1) Baseplate-to-Rack Cell Welds

Reference 6-3 (ASME Code Section III, Subsection NF) permits, for Level A or B conditions, an allowable weld stress $\tau = 0.3\ S_u$. Conservatively assuming that the weld strength is the same as the lower base metal ultimate strength, the allowable stress is given by $\tau = 0.3 \times (66{,}100) = 19{,}830$ psi. As stated in Section 3.2.4.3, the allowable weld stress for Level D is $0.54\ S_u$, which equals 35,694 psi.

Weld stresses are determined through the use of a simple conversion (ratio) factor (based on area ratios) applied to the corresponding stress factor in the adjacent rack material

$$\frac{0.075\,x(8.8+0.075)}{0.0625x0.7071x6.5}=2.32 \quad \text{(For the SFR)}$$

where

0.075”	is the cell wall thickness
8.8”+0.075”	is the mean box dimension
0.0625”x0.7071”	is the box-baseplate fillet weld throat size
6.5”	is the length of the weld

For the NFR, the cell wall thickness and weld size are 0.18” and 0.125” respectively. The ratio factor for the NFR then becomes 2.81.
The highest predicted cell to baseplate weld stress is calculated based on the highest R6 value for the rack cell region tension stress factor and R2 and R7 values for the rack cell region shear stress factors (refer to Section 3.2.5 for definition of these factors). These cell wall stress factors are converted into weld stress values as follows:

For SFR, SSE Simulation

$\{[R6 \text{ x } (1.2)]^2 + [R2 \text{ x } (0.72)]^2 + [R7 \text{ x } (0.72)]^2\}^{1/2}$ x S_y x Ratio
= $\{[0.267 \text{ x } (1.2)]^2 + [0.077 \text{x } (0.72)]^2 + [0.032 \text{ x } (0.72)]^2\}^{1/2}$ x (21,400) x
2.32= 16,184psi

For NFR, SSE Simulation

$\{[R6 \text{ x } (1.2)]^2 + [R2 \text{ x } (0.72)]^2 + [R7 \text{ x } (0.72)]^2\}^{1/2}$ x S_y x Ratio
= $\{[0.396 \text{ x } (1.2)]^2 + [0.100 \text{ x } (0.72)]^2 + [0.025 \text{ x } (0.72)]^2\}^{1/2}$ x (21,400) x
2.81= 28,922 psi

The above calculation is conservative because the maximum stress factors used above do not all occur at the same time instant. The R6 value used in the above equation is the maximum unadjusted value that is output directly from DYNAPOST (Reference 6-20). The reason that this value is used, as opposed to the maximum adjusted value from Section 3.7.3.1, is because the conversion ratio (2.32) is computed based on the full metal area of a single cell, not the effective cell area that is computed in Reference 6-19.

Table 3-9 shows that the calculated weld stresses are less than the corresponding allowable stress limit.

(2) Baseplate-to-Pedestal Welds

The rack weld between baseplate and support pedestal is checked using conservatively imposed loads in a separate finite element model. Table 3-9 summarizes the result derived in Reference 6-19.

(3) Cell-to-Cell-Welds

Cell-to-cell connections are by a series of connecting welds along the cell height. Stresses in storage cell to cell welds develop due to fuel assembly impacts with the cell wall. These weld stresses are conservatively calculated by assuming that fuel assemblies in adjacent cells are moving out of phase with one another so that impact loads in two adjacent cells are in opposite directions; this tends to separate the two cells from each other at the weld. Cell-to-cell weld calculations are performed in Reference 6-19 and are based on the maximum fuel-to-cell impact load from all runs. Both the weld and the base metal shear results are reported Table 3-9.

3.7.3.2 Pedestal Thread Shear Stress

Section 3.7.2.3 specifies the maximum vertical force on a pedestal. Using this value the maximum average shear stress in the engagement region is calculated:

The allowable shear stress for Level D conditions is the lesser of:0.72 S_y = 15,408 or 0.42 x S_u=27,762 psi (based on S_y and S_u for SA240-304L at 200°F). Therefore, the former criteria controls, and the limiting result is detailed in Table 3-9.

3.7.4 Dead Load Evaluation

The dead load condition is not a governing condition for either SFR or NFR fuel racks since the general level of loading is far less than the SSE load condition. To illustrate this, it is shown Table 3-10 that the maximum pedestal load is low as compared to the peak seismic load and that further stress evaluations are unnecessary.

This load will induce very low stress levels in the neighborhood of the pedestal, compared with the load levels that exist under the SSE load condition. Since there are no primary shear loads on the pedestal and the Level A loads are approximately 18% of the Level D loads, while the Level A limits exceed 50% of the Level D limits, the SSE load condition bounds the dead load condition and no further evaluation is performed for dead load only. This evaluation bounds the NFRs as well.

3.7.5 Local Stress Considerations

(1) Cell Wall Buckling

The allowable local buckling stresses in the fuel cell walls (from vertical loading) are obtained by using classical plate buckling analysis on the lower portion of the cell walls. The following formula for the critical stress has been used.

$$\sigma_{cr} = K \frac{E}{1-\nu^2}\left(\frac{t}{b}\right)^2$$

where E = 27.6 x 10^6 psi, v is Poison's ratio=0.3, t = 0.075" for the SFR or =0.18" for the NFR, b = 8.8". The *K* factor varies depending on the plate length/width ratio and the boundary support conditions at the sides of the plate. At the base of the rack, the cell wall acts alone in compression for a length of about 12” up to the point where the poison sheathing is attached. Above this level, the sheathing provides additional strength against buckling, which is not considered here. Therefore, the length/width ratio for the 8.8” wide cell wall will be taken as 1.36. For all edges simply supported, which is a conservative assumption for cell wall, the *K* value is given by Table 15.2 of Reference 6-21 to be 3.62 for a long panel loaded as shown in Figure 3-6.

For the given data

σ_{cr} < 7,975 psi for the SFR

< 45,936 psi for the NFR

It is conservative to apply the above equation to the rack cell wall if we compare σ_{cr} with the maximum compressive stress anywhere in the cell wall. This local buckling stress limit is not violated anywhere in the body of the rack modules, since the maximum compressive stress in the outermost cell is

SSE Simulation:

σ = (1.2) x (21,400) x R6 (which is 0.267) = 6,857 psi for the SFR

= (1.2) x (21,400) x R6 (which is 0.396) = 10,169 psi for the NFR

which are less than 7,975 psi or 45,936 psi. Therefore, rack cell wall buckling does not occur.

(2) Secondary Stresses Produced by Temperature Effects.

The temperature gradients across the rack structure caused by differential heating effects between one or more filled cells and one or more adjacent empty cells are considered. This secondary stress condition is evaluated alone and not combined with primary stresses from other load conditions.

A thermal gradient between cells will develop when an isolated storage location contains a fuel assembly emitting maximum postulated heat, while the surrounding locations are empty. A conservative estimate of the weld stresses along the length of an isolated hot cell is obtained by considering a beam strip uniformly heated by 75°F which is conservative, and restrained from growth along one long edge. The temperature rise easily envelops the difference between the maximum local SFP water temperature (160°F bounding) inside a storage cell and the bulk pit temperature (137°F) based on the thermal-hydraulic analysis of the SFP (Reference 6-22).

The strip is subjected to the following boundary conditions (Refer to Figure 3-7):

(a) Displacement Ux (x,y) = 0 at x = 0 and at y = H/2 for all x

(b) Average force Nx (x) = 0 at x = L

Using shear beam theory and subjecting the strip to a uniform temperature rise T = 75°F, an estimate of the maximum value of the average shear stress in the strip can be calculated. The final shear stress result for the strip is found to be

$$\tau max = \frac{E\alpha\Delta t}{0.931}$$

(Maximum at x=L)

Therefore, an estimate of maximum weld shear stress in an isolated hot cell, due to thermal gradient is computed, as τ_{max}= 21,122psi.

Since this is a secondary thermal stress, we use the allowable shear stress criteria for faulted conditions (0.42xS_u=27,762 psi) as a guide to indicate that this maximum shear is acceptable.

4. MECHANICAL ACCIDENTS

This chapter provides information on the required mechanical accident performance characteristic of the US-APWR fuel racks.

4.1 Description of Mechanical Accidents and Acceptance Criteria

The US NRC OT position paper (Reference 6-1) specifies that the design of the racks must ensure the functional integrity of the fuel racks under all credible fuel assembly drop events. Four categories of mechanical accidents are considered. Each of these four categories is described in the following paragraphs.

(1) Straight shallow drop event (Figure 4-1)

In the so-called “straight shallow drop” event, an impactor (i.e., a fuel assembly plus its handling tool) is assumed to drop vertically and hit the top of the rack. Inasmuch as the racks are of honeycomb construction, the deformation produced by the impact is expected to be confined to the cell walls that are directly impacted. However, the “depth” of damage to the affected cell walls must be demonstrated to remain limited to the portion of the cell above the top of the “active fuel region”, which is essentially the elevation of the top of the neutron absorber. Stated in quantitative terms, this criterion implies that the permanent deformation of the rack cell walls should not extend more than 16.5 inches (downwards) from the top. To conservatively estimate the damage to the cell wall, the rack is assumed to absorb the maximum kinetic energy generated by the impactor.

(2) Straight deep drop event

The so-called “straight deep drop” event postulates that the impactor falls through an empty storage cell impacting the rack baseplate.
The deep drop event can be classified into two scenarios (i.e., the second and the third types of accidents), namely, drop in an interior cell away from the support pedestals (Figure 4-2), and drop through the cell located above a support pedestal (Figure 4-3).

(a) Deep drop scenario 1 (Figure 4-2)

In deep drop scenario 1, the impactor strikes the rack baseplate away from the support pedestal, where it is more flexible. If the baseplate is pierced by the fuel assembly or deforms sufficiently, the liner may be damaged leading to an uncontrollable loss of water. An additional consideration is that the baseplate deformation may lead to an abnormal condition, where the fuel assembly active zone is outside the neutron absorber-equipped space of the fuel rack. This condition must be considered in the criticality evaluations and must be limited to ensure criticality control. Severing and large deflection of the baseplate leading to a secondary impact with the pit liner are unacceptable results.

(b) Deep drop scenario 2 (Figure 4-3)

In deep drop scenario 2, the rack baseplate is buttressed by the support pedestals and presents a hardened impact surface, resulting in a high impact load. The principal design objective is to ensure that the support pedestal does not tear the liner that overlays the reinforced concrete pit slab.

(3) Stuck fuel event

In addition to the preceding drop accidents, a fourth “stuck fuel” accident is analyzed to determine the damage to the rack due to a 4,400 lbf uplift force applied to the rack by a stuck fuel assembly. Similar to the shallow drop accident, the damage to the cell wall shall be limited to the portion of the rack structure above the neutron absorber.

4.2 Analysis Methods

The subsections that follow describe the analysis methods to be used in performing licensing-basis calculations to demonstrate that the mechanical accident performance requirements for the fuel racks are satisfied. These are intended to be minimum requirements, and more sophisticated analysis models may be used. Similar mechanical accident analyses have been used for previous fuel rack licensing at many nuclear plants worldwide by Holtec International.

4.2.1 Calculation of Incident Impact Velocity

A dropped fuel assembly is modeled as a single lumped mass under the influence of gravity in a drag inducing medium. The effects of virtual mass, gravity, and fluid drag are accounted for in the model. The virtual mass is assumed equal to the buoyant mass of the fuel assembly. The drag force is based on the exposed frontal area of the fuel assembly. The governing equation for a body of mass subject to gravity and drag effects is:

$$(M + M_v)\frac{d^2x}{dt_2} + \frac{C_D}{2} d_w A_D \left(\frac{dx}{dt}\right)^2 = (M - M_v)g$$

where:

M = Dry mass of the impactor

M_v = Virtual mass of the object (Buoyant mass)

C_D = Effective drag coefficient due to all contributing effect

d_w = Mass density of the water

A_D = Area subject to drag forces

v = Velocity of the object

g = Gravitational acceleration

x = Distance

t = Time

For a drop from a given height, the initial conditions are:

$$t = 0, x = 0, \frac{dx}{dt} = 0$$

The above nonlinear second order differential equation is readily solved to obtain the incident impact velocity.

4.3 Analyses Results

The postulated drop accidents involve two types of racks that are fabricated with same material type and differing thicknesses. Drop analyses have been conservatively performed based on the bounding impact energy and configuration.
In the analyses, the enveloping conditions, such as the maximum drop height (36 inches for the NFRs) and maximum impactor weight (2,450 lbs for the SFRs), are used for a conservative approach.

The initial impact velocities for both shallow and deep drop scenarios are summarized in Table 4-1.

For all analyzed events, the impactor is conservatively modeled as a rigid solid with no energy absorption capacity. The detailed calculations are contained in Reference 6-23 for the drop accident analyses, and Reference 6-19 for the stuck fuel analyses.

4.3.1 Straight Shallow Drop Event

In the straight shallow drop of a fuel assembly, using a very conservative energy balance calculation, it is demonstrated that permanent damage to any fuel storage cells is less than the distance from the top of the rack to the beginning to the active fuel region (16.5 inches). Therefore, there is no effect on the subcriticality of the fuel in adjacent cells due to this accident.

4.3.2 Straight Deep Drop Events

In the straight deep drop accident away from the location, the baseplate deformation of the racks is less than the distance between the baseplate and liner (12 inches). Therefore, a dropped fuel assembly will not cause the baseplate to impact the liner.

In the straight deep drop accident over a pedestal, the resulting impact is less than the peak pedestal load from WPMR analysis under SSE conditions (378,000 lbf) (Reference 6-19). The pedestals were shown to satisfy the allowable stress limits for Level D conditions. Therefore, this accident is not governing for the fuel racks.

4.3.3 Stuck Fuel Event

Result of the analysis show that the maximum stress in the rack cell due to a stuck fuel assembly is only 2,420 psi, which is well below the material yield stress. Therefore, the fuel racks are adequate to withstand a 4,400 lbf uplift force due to a stuck fuel assembly.

4.4 Results of Analyses

Several mechanical accidents have been analyzed and found to produce localized damage well within the design limits for the racks.

The straight shallow drop event produces some localized plastic deformation in the top of the storage cell, but the region of permanent strain is limited to the portion of the rack structure above the top of the active fuel region.

The analysis of the straight deep drop event at cell locations selected to maximize baseplate deformation indicates that the baseplate will not experience puncture and the downward displacement of the baseplate will not lead to a secondary impact of the fuel assembly with the pit liner.

Finally, the stuck fuel accident analysis indicated that any damage to the cell wall would occur well above the “poison zone” of the rack.

5. CONCLUSIONS

From the results of the WPMR and mechanical accident analyses, the following conclusions are made regarding the new design and layout of the SFR, DFR and NFR for the US-APWR:

(1) All rack cell wall and pedestal stress factors are below allowable stress factor limit of 1.0.

(2) There are no rack-to-wall impacts involving the SFR and NFR racks.

(3) All weld stresses are below the allowable limits.

(4) The SFR and NFR do experience rack-to-rack impacts during SSE events at the baseplate because they are in contact by design. However, the impact loads are much lower than the capacity limit of the baseplate.

(5) The SFR do experience rack-to-rack impacts during SSE events at the top of rack elevation. However, the impact loads are less than 2/3 of the buckling capacity of the storage cells.

(6) A stuck fuel assembly does not cause a bounding stress condition.

(7) The fuel racks possess acceptable margins of safety under the postulated mechanical accidents.

It is therefore considered demonstrated that the design of the SFR, DFR and NFR meets the requirements for structural integrity for the postulated Level A and Level D conditions defined.

6. REFERENCES

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Table 2-1 Spent Fuel Rack Data*

1	Storage Cell Center-to-Center Pitch	11.1”
2	Storage Cell Inner Dimension (Width)	8.8”
3	Inter-Cell Flux Trap Gap	1.866”
4	Storage Cell Length	196”
5	Storage Cell Wall Thickness	0.075”
6	Neutron Absorber Material	METAMIC™
7	Neutron Absorber Length	( )
8	Neutron Absorber Width	( )
9	Neutron Absorber Thickness	0.106 “
10	Distance from Top of Rack Baseplate to Bottom of Neutron Absorber	12”
11	Neutron Absorber Sheathing Thickness	
	Internal Wall	0.024”
	Periphery Wall	0.075”
12	Baseplate Thickness	1”
13	Baseplate Flow Hole Diameter	5”
14	Rack Pedestal Type (Fixed or Adjustable)	Adjustable
15	Rack Pedestal Height (Female + Male)	( )
16	Rack Female Pedestal Dimensions	
	Corner Pedestals	20” x 20” x 5”
	Center Pedestals	10” x 10” x 5 ”
17	Rack Male Pedestal Diameter	5”

* All of the dimensions are nominal values.

Table 2-2 New Fuel Rack Data*

1	Storage Cell Center-to-Center Pitch	16.9”
2	Storage Cell Inner Dimension (Width)	8.8”
3	Inter-Cell Flux Trap Gap	7.74”
4	Storage Cell Length	196-1/64”
5	Storage Cell Wall Thickness	0.209”**
6	Neutron Absorber Material	N/A
7	Neutron Absorber Length	N/A
8	Neutron Absorber Width	N/A
9	Neutron Absorber Thickness	N/A
10	Distance from Top of Rack Baseplate to Bottom of Neutron Absorber	N/A
11	Neutron Absorber Sheathing Thickness	N/A
12	Baseplate Thickness	1”
13	Baseplate Flow Hole Diameter	5”
14	Rack Pedestal Type (Fixed or Adjustable)	Adjustable
15	Rack Pedestal Height (Female + Male)	( )
16	Rack Female Pedestal Dimensions	
	Corner Pedestals	18” x 18” x 3-1/2”
	Center Pedestals	10” x 10” x 3-1/2”
17	Rack Male Pedestal Diameter	4-1/2”

* All of the dimensions are nominal values.
** Calculations are based conservatively on storage cell wall thickness of 0.18”.

Table 2-3 Damaged Fuel Rack Data*

1	Storage Cell Center-to-Center Pitch	24”
2	Storage Cell Inner Dimension (Width)	9-1/4”
3	Inter-Cell Flux Trap Gap	N/A
4	Storage Cell Length	206-3/4”
5	Storage Cell Wall Thickness	3/8”
6	Neutron Absorber Material	N/A
7	Neutron Absorber Length	N/A
8	Neutron Absorber Width	N/A
9	Neutron Absorber Thickness	N/A
10	Distance from Top of Rack Baseplate to Bottom of Neutron Absorber	N/A
11	Neutron Absorber Sheathing Thickness	N/A
12	Baseplate Thickness	3/4”
13	Baseplate Flow Hole Diameter	1-1/2”
14	Rack Pedestal Type (Fixed or Adjustable)	N/A
15	Rack Pedestal Height (Female + Male)	N/A
16	Rack Female Pedestal Dimensions	N/A
	Corner Pedestals	N/A
	Center Pedestals	N/A
17	Rack Male Pedestal Diameter	N/A

* All of the dimensions are nominal values.

Table 3-1 Loads and Load Combinations for Fuel Racks

Loading Combination	Service Level
D + L D + L + T_o D + L + T_o + E	Level A
D + L + T_a + E D + L + T_o + P_f	Level B
D + L + T_o + F_d D + L + T_a + E'	Level D†

† The functional capability of the fuel racks must be demonstrated.

Where

D = Dead weight induced loads (including fuel assembly weight)

L = Live load (not applicable for the fuel rack, since there are no moving objects in the rack load path). Note that it is accepted practice to consider the fuel weight as a dead weight

E = Operating Basis Earthquake (OBE)

E' = Safety Shutdown Earthquake (SSE)

To = Differential temperature induced loads, based on the most critical transient or steady state condition under normal operation or shutdown conditions.

Ta = Differential temperature induced loads, based on the postulated abnormal design conditions.

Td = Force caused by the accidental drop of the heaviest load from maximum possible height.

Pf = Force on the racks caused by postulated stuck fuel assembly. This force may be caused at any angle between horizontal and vertical.

Table 3-2 Material Data (ASME – Section II, Part D)

Material	Young's Modulus E (psi)	Yield Strength Sy (psi)	Ultimate Strength Su (psi)
Rack Material Data (200°F)			
SA240, Type 304L	27.6×10^6	21,400	66,100
Support Material Data (200°F)			
SA-240, Type 304L (Upper Part of Support Feet)	27.6×10^6	21,400	66,100
SA-564, Type 630 (Hardened at 1100°F)	28.5×10^6	106,300	140,000

Table 3-3 Computer Codes for US-APWR fuel racks mechanical analysis

Code	Version	Description
GENEQ	1.3	Generates artificial time histories from input response spectra set.
CORRE	1.3	Uses results from GENEQ and demonstrates required statistical independence of time histories.
PSD1	1.0	Uses results from GENEQ and compares regenerated Power Spectral Densities with target.
WORKING MODEL	2004	Is a Rigid Body Dynamics code used to improve baseline correction.
VMCHANGE	4.0	For a dry pool, develops a zero matrix of size = (number of racks x 22 DOF per rack).
MULTI	1.55	Incorporates appropriate non-zero values due to structural effects that are put in appropriate locations in the output matrix from VMCHANGE to form the final mass matrix for the analysis. The appropriate non-zero right-hand sides are also developed.
MASSINV	2.1	Calculates the inverse of the mass matrix.
MSREFINE	2.1	Refines the inverse of the mass matrix.
PREDYNA1	1.5	Generates various input lines for the input file required to run the dynamic solver.
PD22	1.22	Generates rack-to-fuel compression-only impact springs, rack-to-ground impact springs, and rack elastic deflection springs for each rack being analyzed and creates the appropriate lines of input for the solver.
SPG16	3.0	Generates compression-only rack-to-rack impact springs for the specific rack configuration in the pool for the solver.
MR216 (A)	3.0	Is a solver for the dynamic analysis of the racks; uses an input file from the cumulative output from PREDYNA, PD22, and SPG16, together with the mass matrix, right-hand side matrix, and the final time histories from GENEQ.
DYNAPOST	2.0	Post-Processor for MR216; generates safety factors, maximum pedestal forces, and maximum rack movements.
ANSYS	11.0	Is a general purpose commercial FEA code.
LS-DYNA	971	General purpose commercial FEM code optimized for shock and impact analyses

Table 3-4 Simulation List

Soil Condition	Rack	Coefficient of Friction	Seismic Input
Hard	**SFR+DFR**	Random	SSE
Medium 1			SSE
Medium 2			SSE
soft			SSE
Hard	**NFR**	Random	SSE
Medium 1			SSE
Medium 2			SSE
soft			SSE

Table 3-5 Summary of Time History Simulation Results

Coefficient of Friction (COF)	Soil Condition	Max. Stress Factor	Max. Vertical Load on Single Pedestal (Lbf)	Max. Shear Load on Single Pedestal (lbf) (X or Y)	Max. Fuel to Cell Wall Impact (lbf) (SFR / DFR)
SFR+DFR					
Random	Soft	0.762	279,000	149,000	840 / 16,616
	Medium 1	0.455	289,000	123,000	1,674 / 17,666
	Medium 2	0.560	378,000	149,000	1,306 / 16,033
	Hard	0.427	361,000	120,000	1,271 / 14,116
NFR					
Random	Soft	0.132	74,300	27,500	868
	Medium 1	0.448	179,000	89,600	2,190
	Medium 2	0.468	200,000	98,800	2,063
	Hard	0.589	257,000	126,000	1,451

Table 3-6 Rack Displacements

Soil Condition	Location on Rack	Maximum Rack Displacement Relative to floor (in)	COF
SFR+DFR			
Medium 2	Base Plate	0.41	Random
	Top of Rack	4.64	
NFR			
Medium 1	Base Plate	3.32	Random
	Top of Rack	7.73	

Table 3-7 Rack Impact Loads

	Soil Condition	Maximum Impact Load on One Side of Rack (lbf)	COF	Location of Rack
SFR+DFR				
Rack-to-Rack	Medium 1	248,990 / 53,720	Random	Base Plate / Top Corner
Rack-to-Wall	-	No Impact	-	-
NFR				
Rack-to-rack	Medium 1	104,000 / 124,000	Random	Base Plate / Top Corner
Rack-to-Wall	-	No Impact	-	-

Table 3-8 Maximum Stress Factors

COF	Pedestal Stress Factor	Cell Wall Stress Factor	Soil Condition
SFR+DFR			
Random	0.762	$\left(0.267\times\left(\frac{1}{0.707}\right)\right)=0.378*1$	Soft
NFR			
Random	0.589	0.396 *2	Hard

*1: Adjustment factor accounting for ASME Code slenderness ration evaluation.

*2: Since the with-thickness ratio of NFR is not greater than 51.4, no additional adjustment for the stress is necessary. Therefore the stress factor of 0.396 is considered as the maximum stress factor.

Table 3-9 Stress Evaluation for Fuel Racks

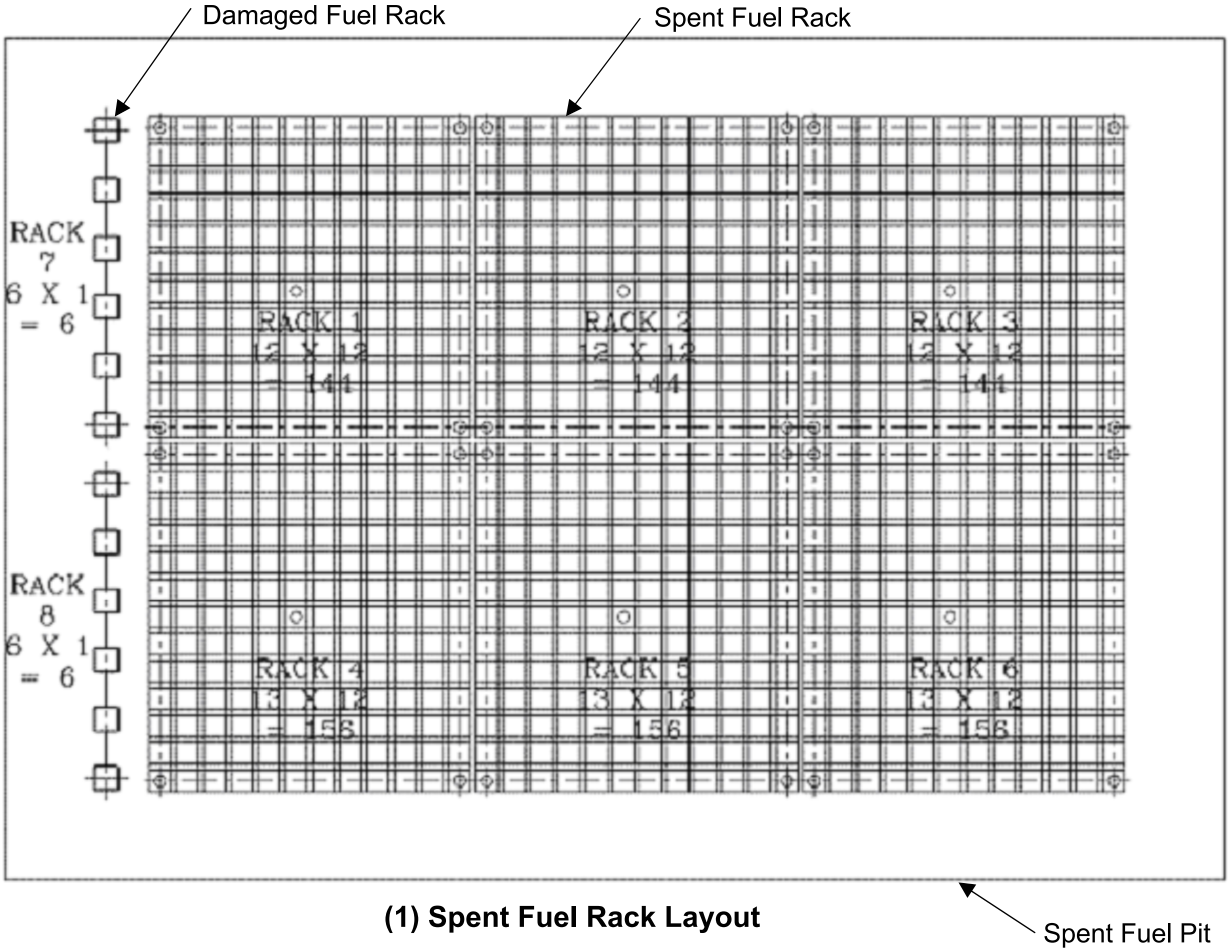
Region	Type	Stress (psi)	Allowable Stress(psi)	Safety Factor (-)
SFR+DFR				
Baseplate-to Rack Cell	Weld	16,184	35,694	2.21
Baseplate-to-Pedestal	Weld	30,270	35,694	1.18
Cell-to-Cell	Weld	12,140	35,694	2.94
	Base Metal Shear	8,584	15,408	1.79
Pedestal Thread	Shear	8,202	15,408	1.88
NFR				
Baseplate-to Rack Cel	Weld	28,922	35,694	1.23
Baseplate-to-Pedestal	Weld	12,716	35,694	2.81
Cell-to-Cell	Weld	16,894	35,694	2.11
	Base Metal Shear	11,946	15,408	1.29
Pedestal Thread	Shear	7,170	15,408	2.15

Table 3-10 Level A Maximum Pedestal Load

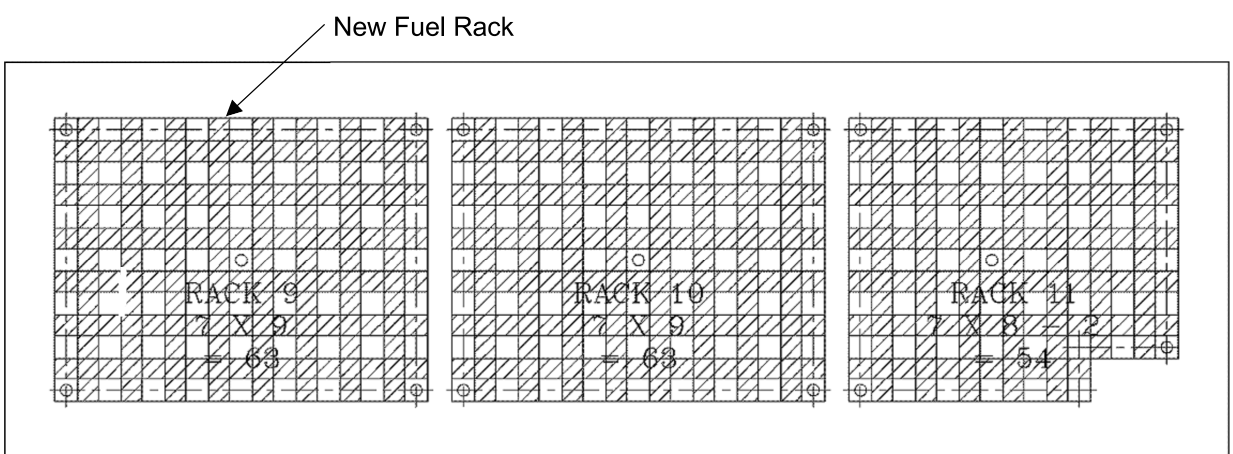
Item	Load (lbf)
Dry Weight of 13x12 Rack	46,800
Dry Weight of 156 Intact Fuel Assemblies	298,272
Total Dry Weight	345,072
Load per Pedestal	69,015

Table 4-1 Impact Event Data

Case	Impactor Weight (lb)	Impactor Type	Drop Height (in)	Impact Velocity (in/sec)
Shallow Drop Event	2,450	Fuel Assembly plus Handling Tool	36	151.2
Deep Drop Event (Away from Support Leg)	2,450	Fuel Assembly plus Handling Tool	232 (=36+196)	269.2
Deep Drop Event (Above Support Leg)	2,450	Fuel Assembly plus Handling Tool	232 (=36+196)	116.3



(1) Spent Fuel Rack Layout



(2) New Fuel Rack Layout

Figure 2-1 Layout of US-APWR Fuel Storage

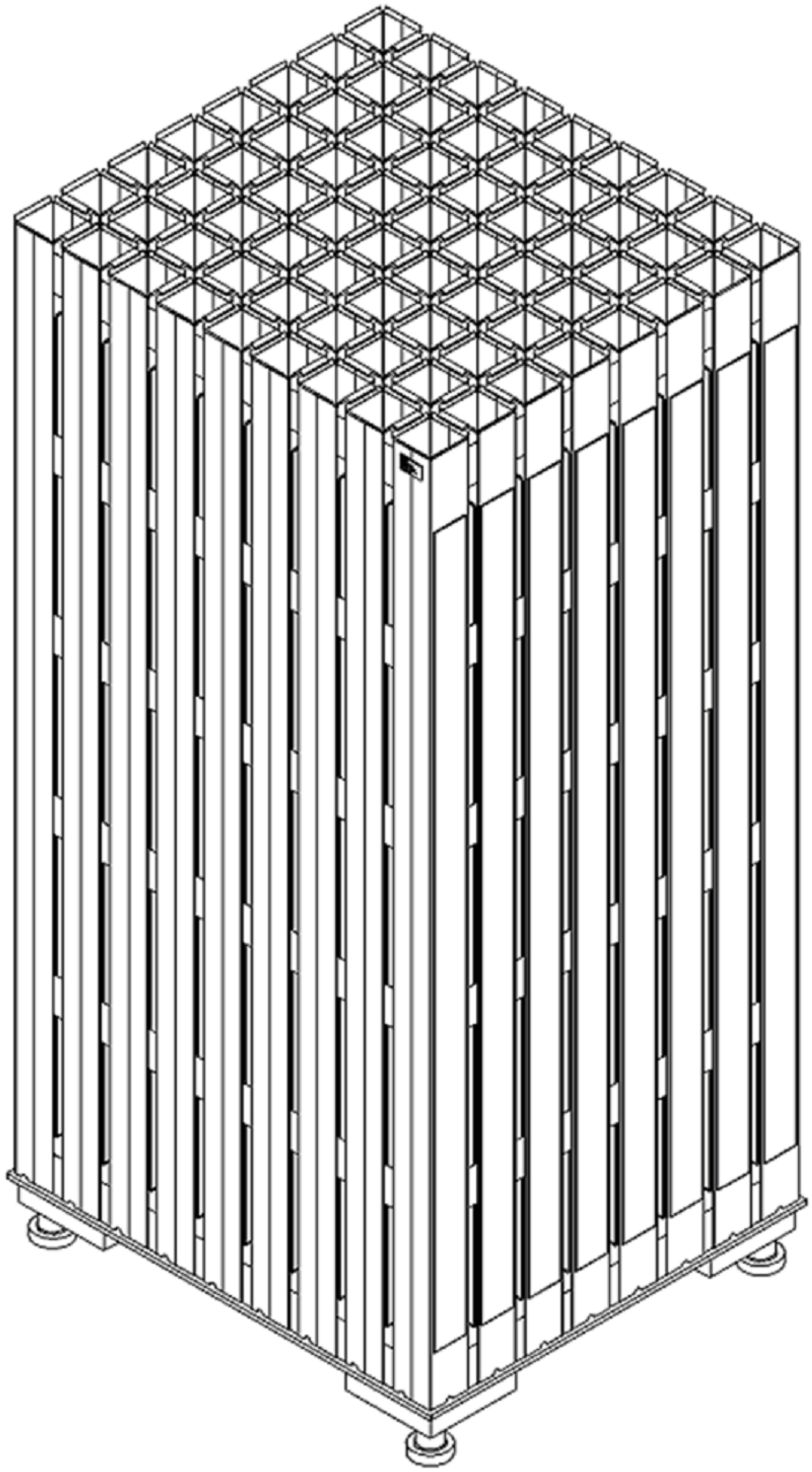


Figure 2-2 Outline of Spent Fuel Rack

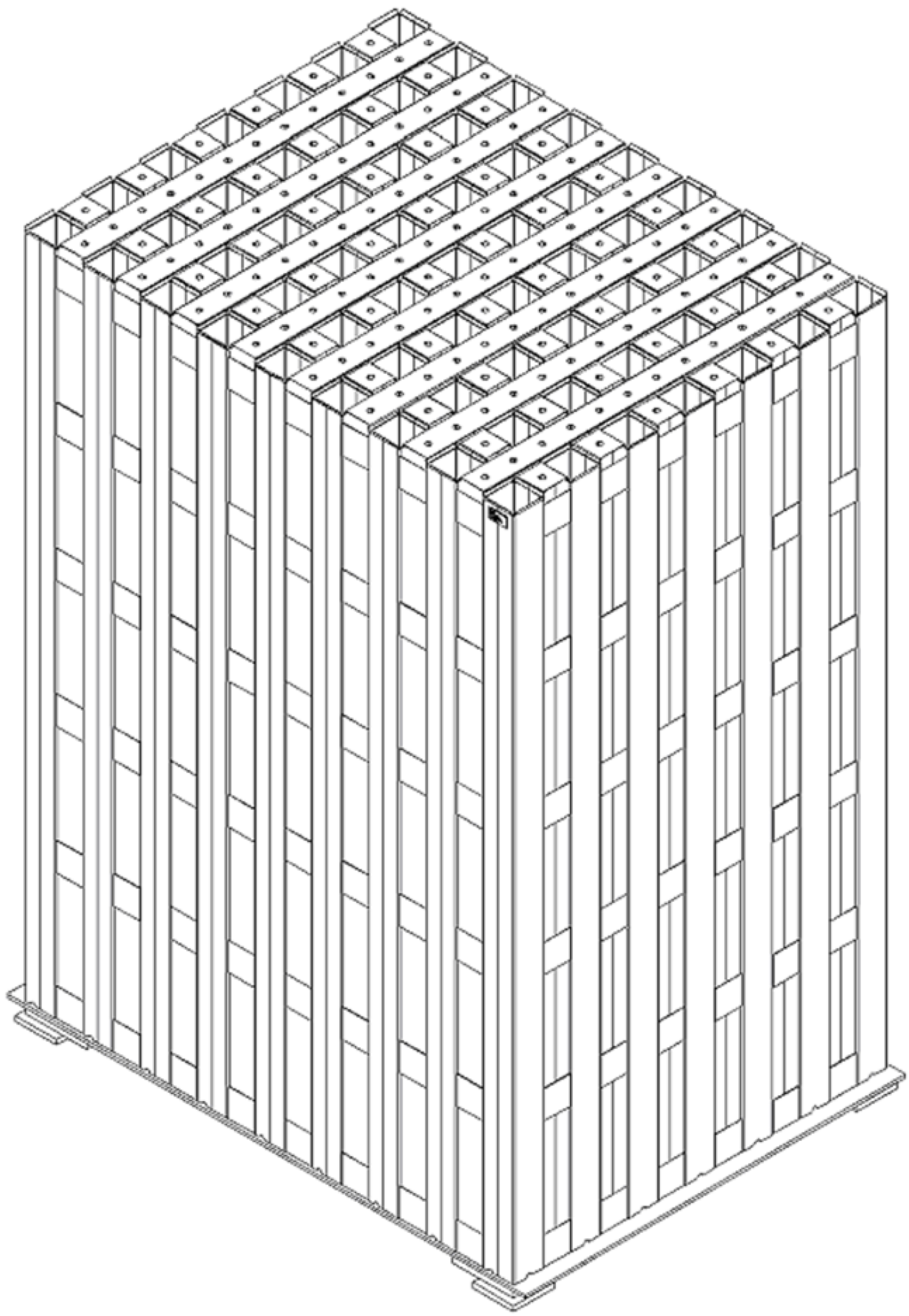
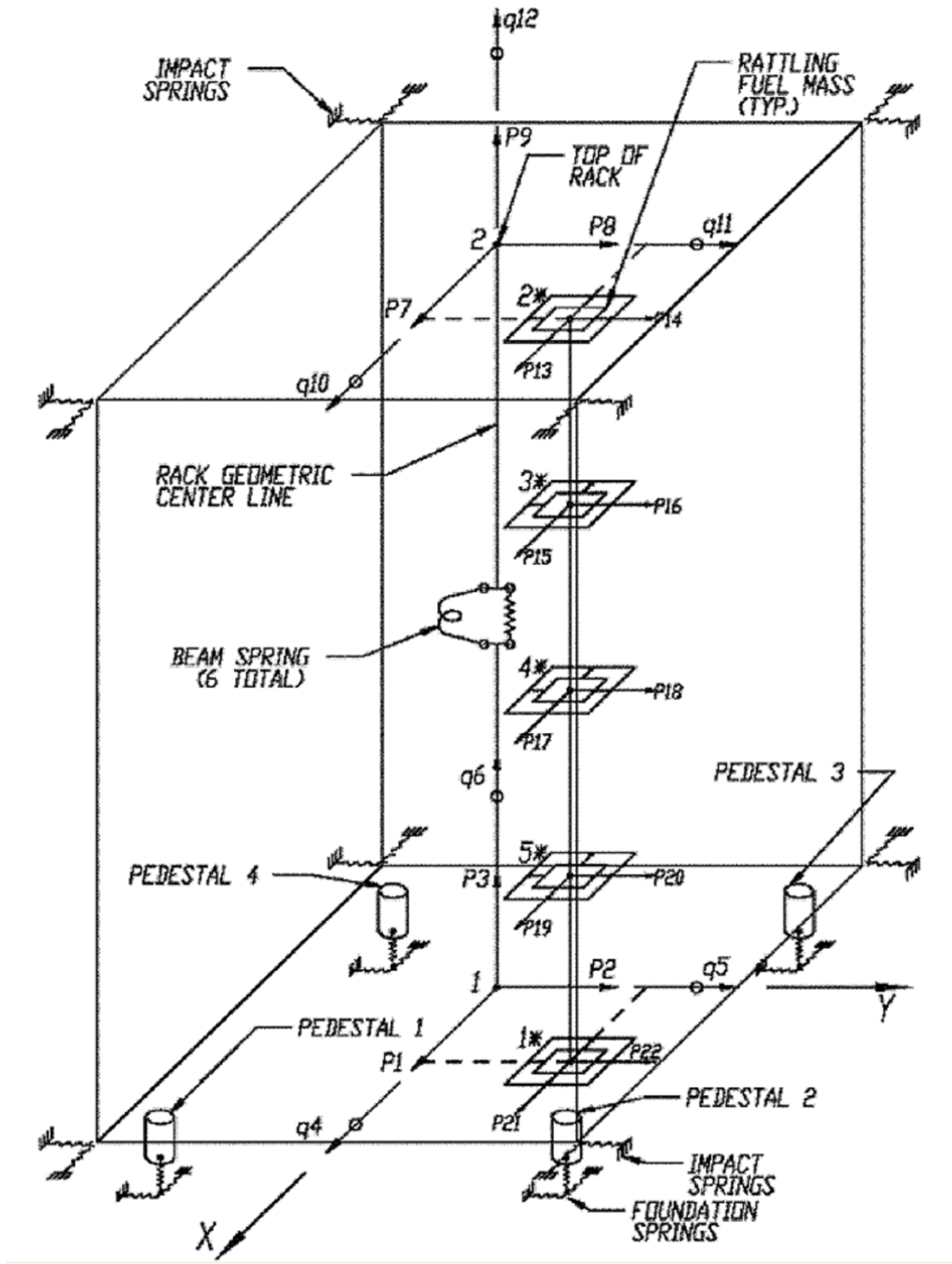


Figure 2-3 Outline of New Fuel Rack



Note: The center pedestal (Pedestal 5) is not shown.

Figure 3-1 Schematic of the Dynamic Model for Dynarack

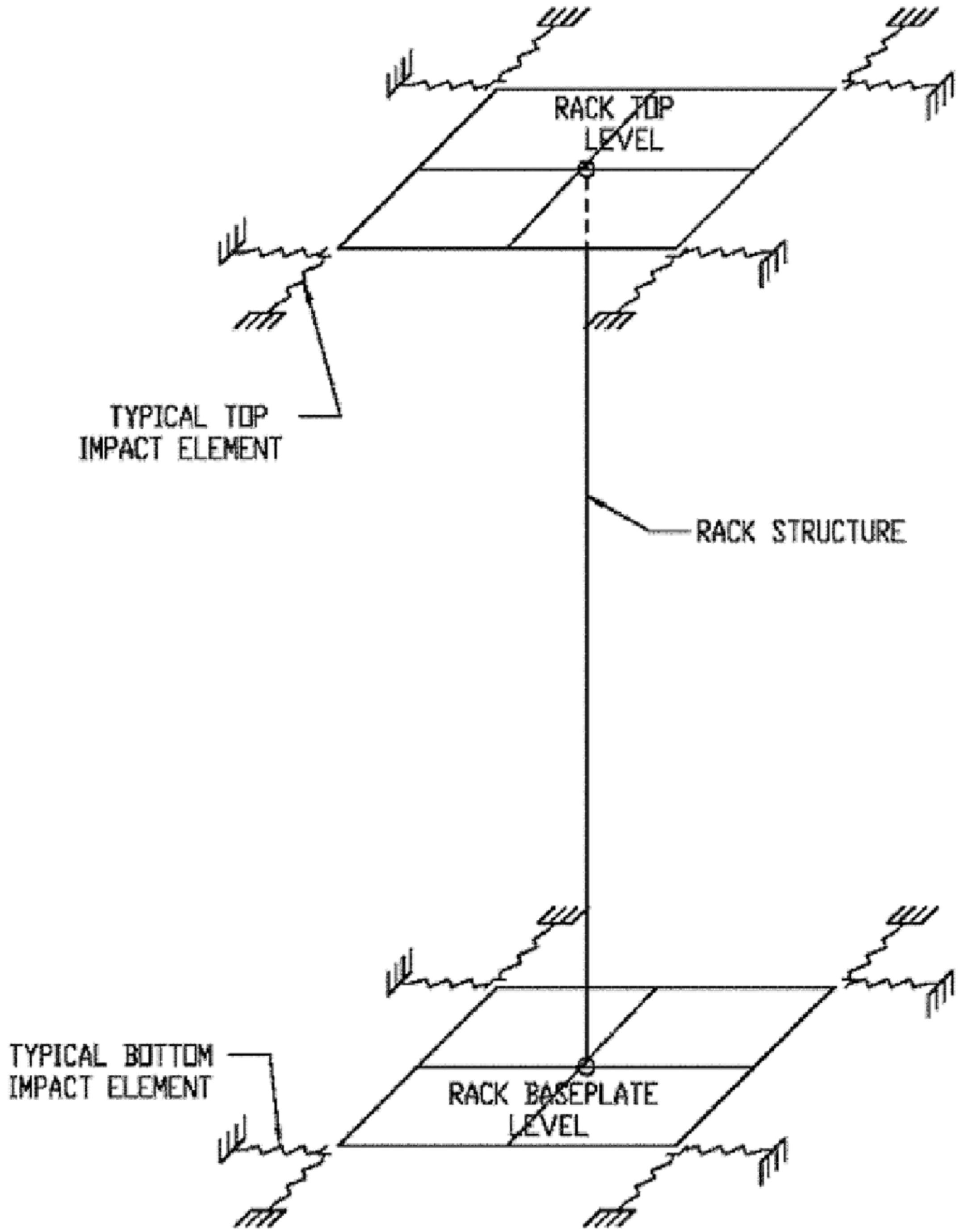


Figure 3-2 Rack–to–Rack Impact Springs

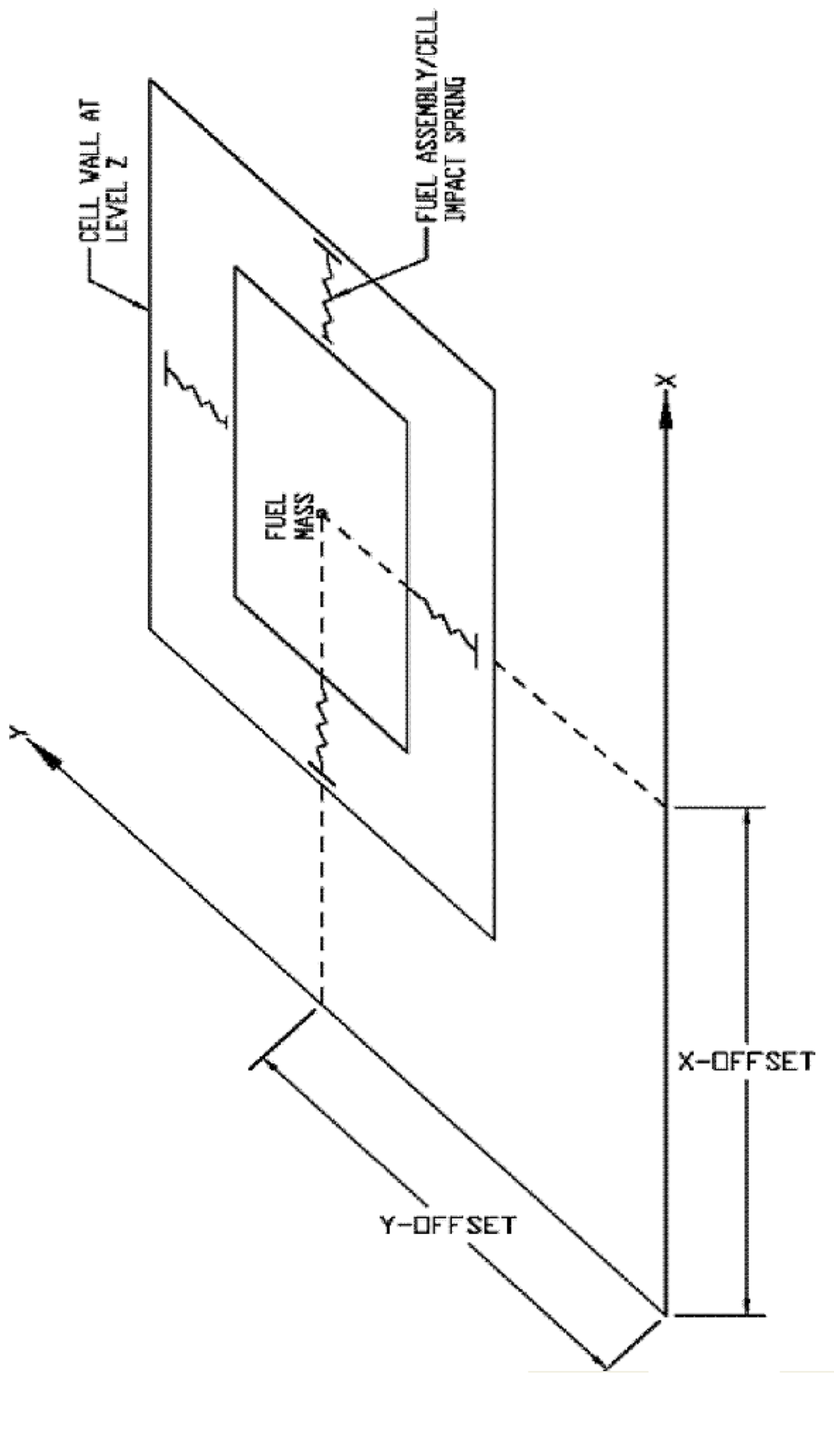


Figure 3-3 Fuel-to-Rack Impact Springs at Level of Rattling Mass

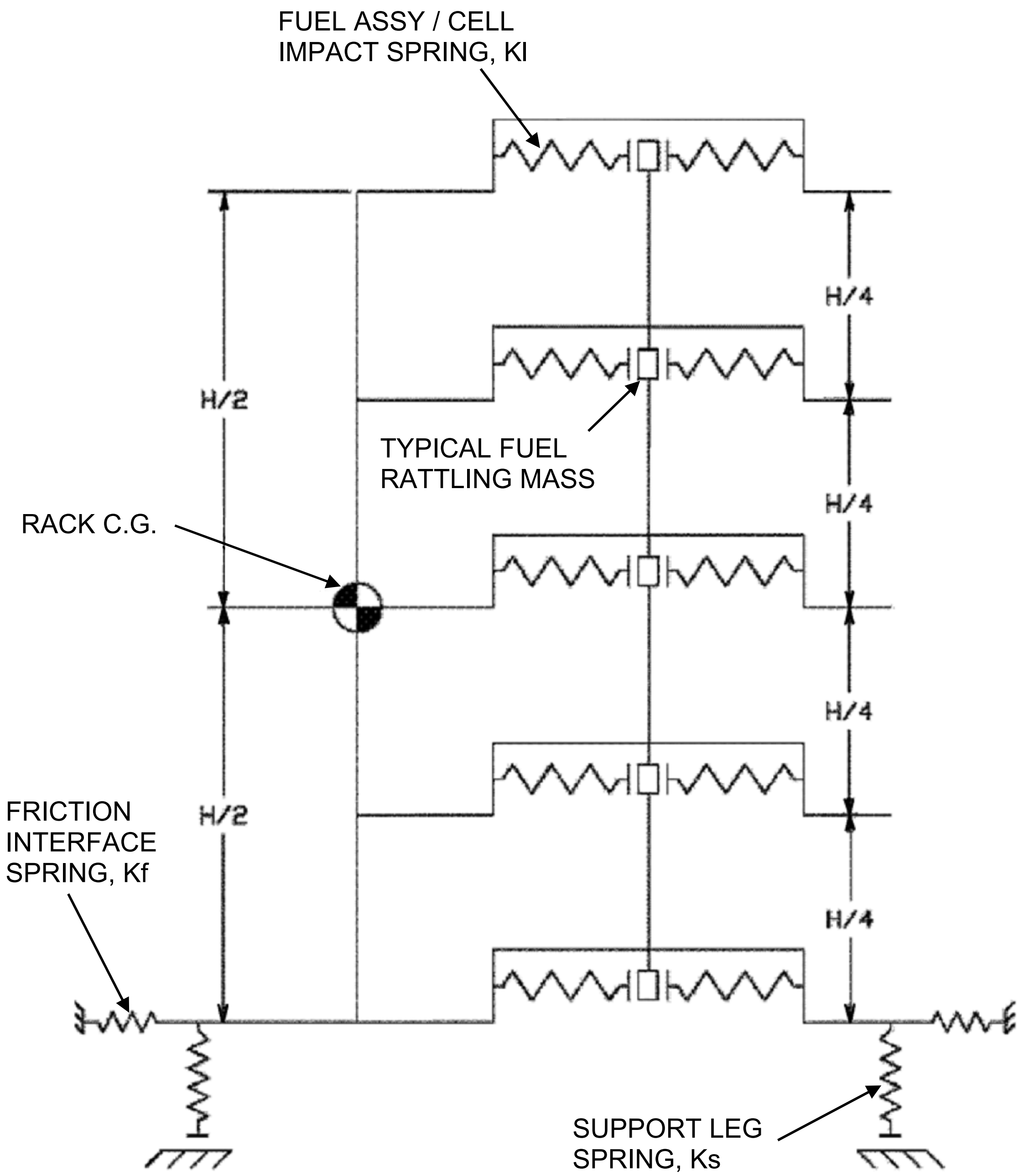
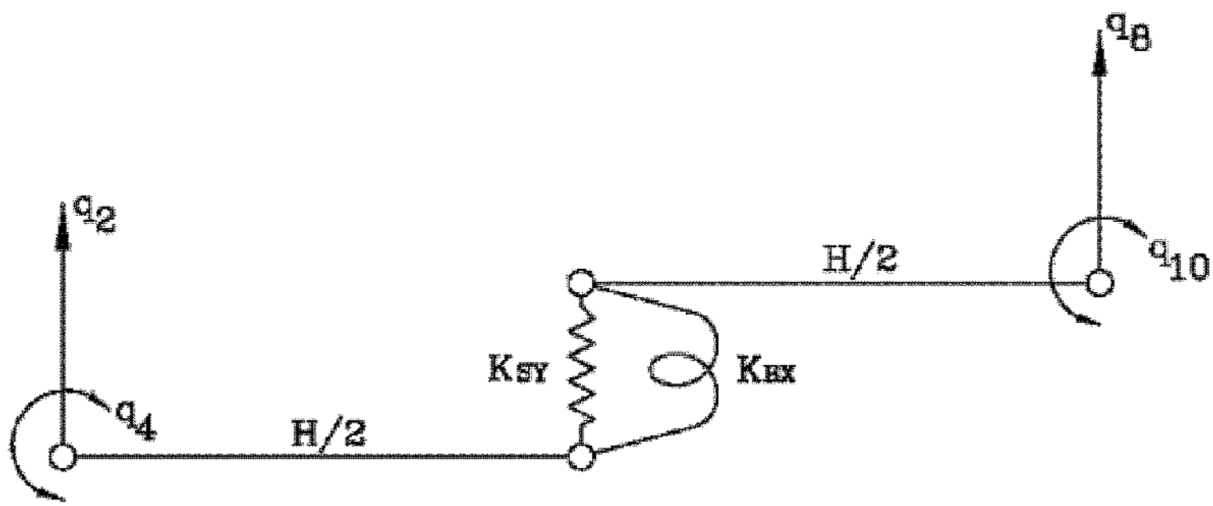
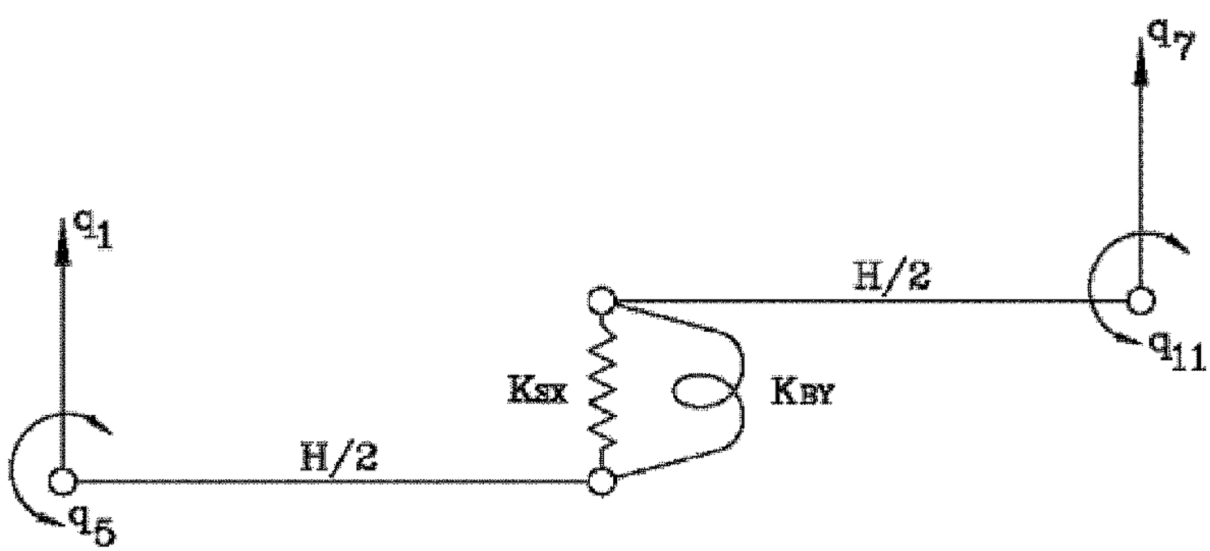


Figure 3-4 Two Dimensional View of the Spring–Mass Simulation



(1) Y-Z Plane Bending with Shear and Bending Spring



(2) X-Z Plane Bending with Shear and Bending Spring

Figure 3-5 Rack Degrees-of- Freedom

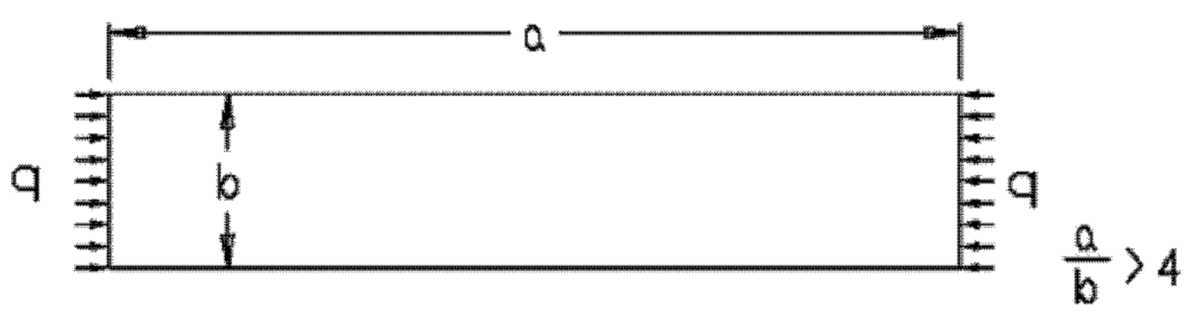


Figure 3-6 Loading on Rack Wall

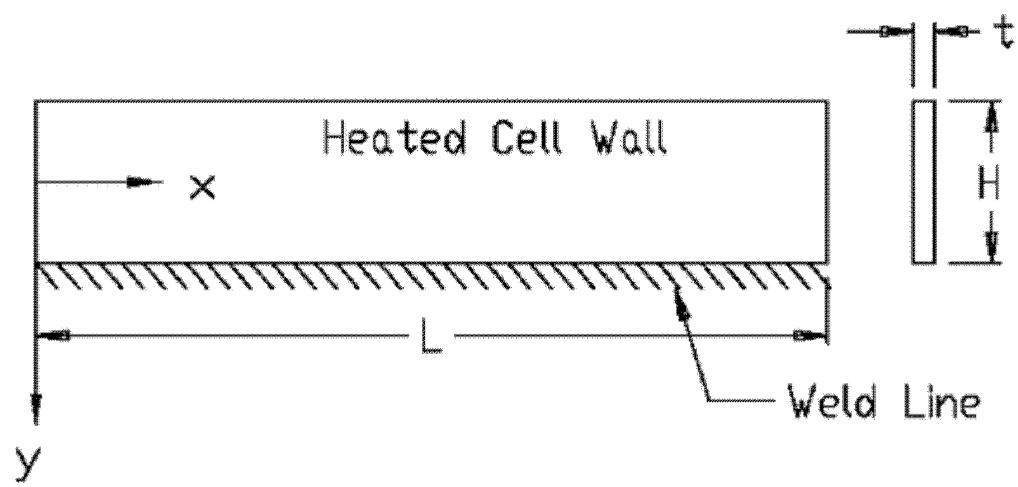


Figure 3-7 Welded Joint in Rack

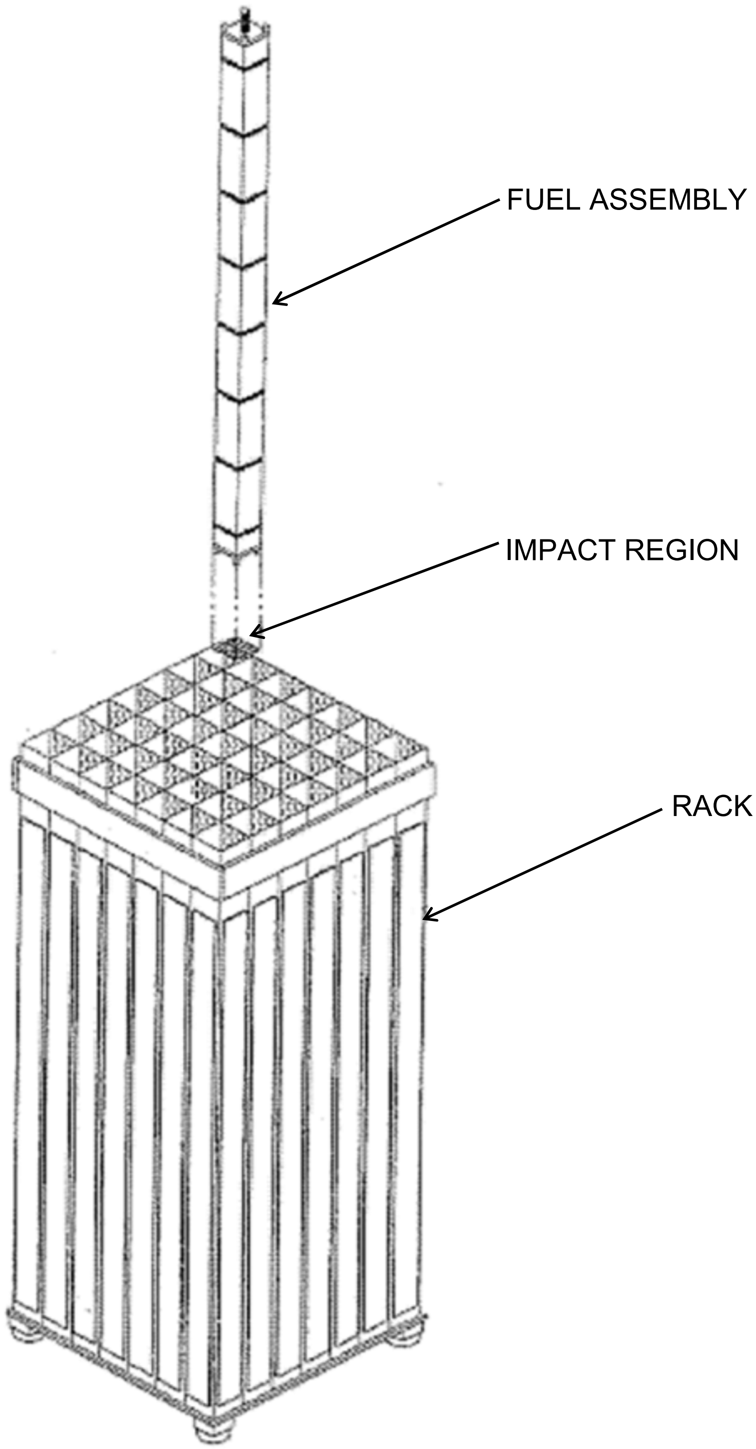


Figure 4-1 Schematic of the Straight Shallow Drop on a Rack Cell

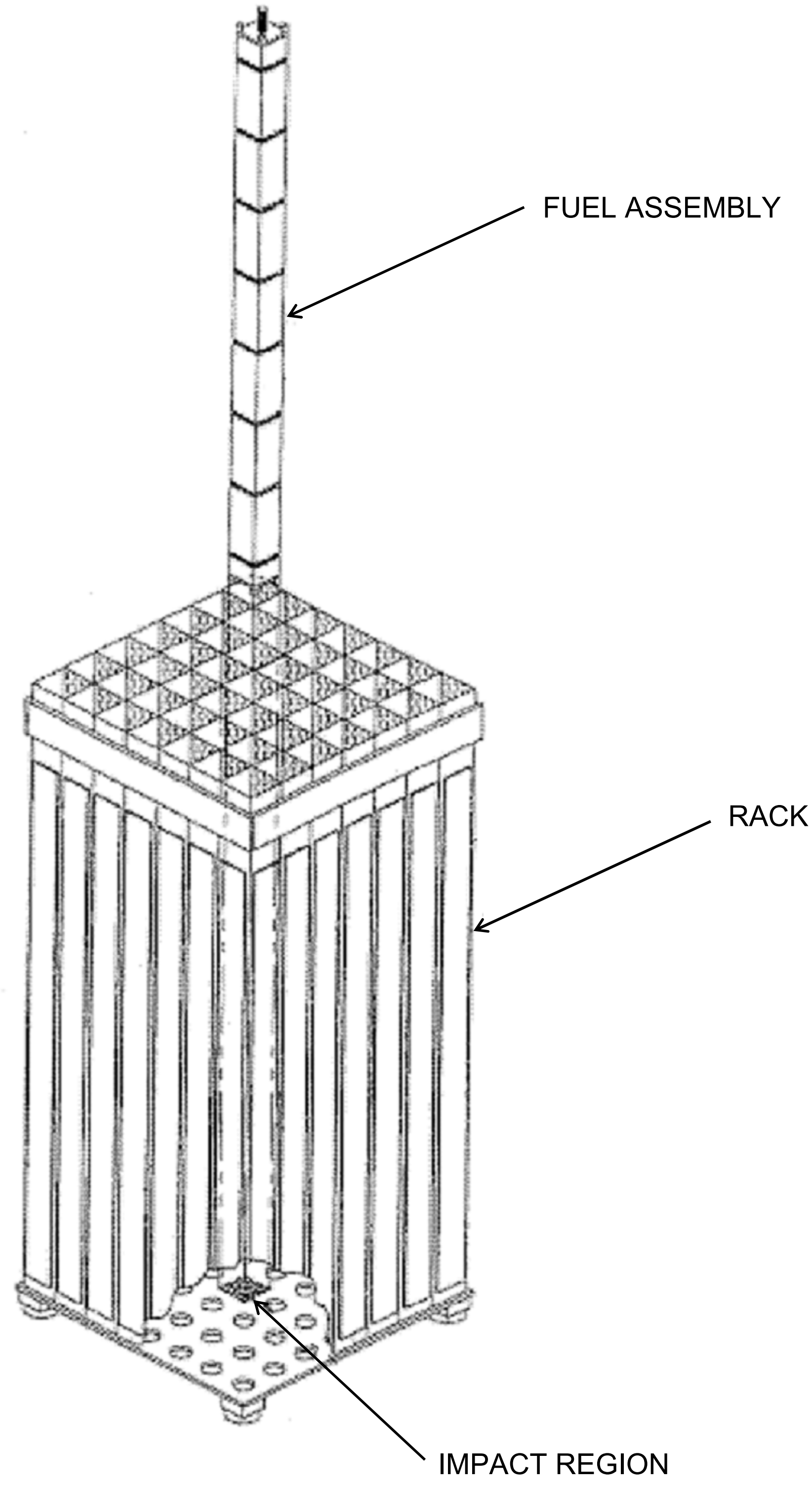


Figure 4-2 Schematic of the Deep Drop Scenario 1 on a Center Cell Location

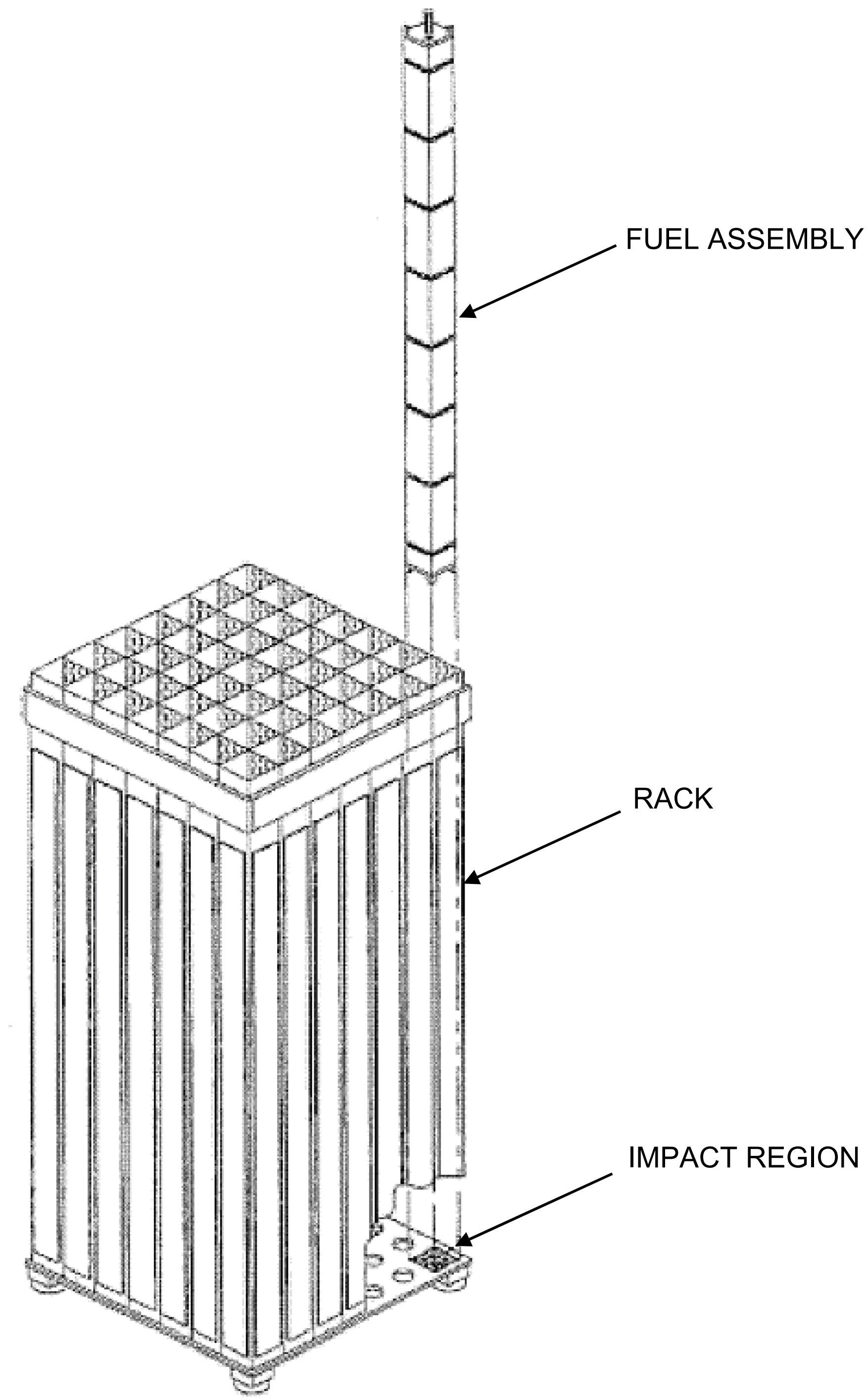


Figure 4-3 Schematic of the Deep Drop Scenario 2 on a Support Pedestal Location