A STRUCTURAL ASSESSMENT OF
CANDIDATE FUEL BASKET DESIGNS FOR STORAGE
AND TRANSPORT OF SPENT NUCLEAR FUEL

by

K.P. Singh, Ph.D., PE
President, Holtec International
Holtec Center
555 Lincoln Drive West
Marlton, New Jersey 08053

and

Max DeLong, Ph.D.
Executive Engineer, Northern States Power
414 Nicollet Mall (RS-7)
Minneapolis, Minnesota 55401

Holtec International’s quest in the early 90s to identify the most suitable basket design for implementation in the company’s HI-STAR™ and HI-STORM™ systems led to a series of analyses of previously used basket design concepts. Among the analyses carried out were structural evaluations of the old basket designs under typical storage mode and transport mode loads. In this paper, we present results of our findings which revealed some serious weaknesses in the prior-art designs. The structural analyses which led the company to reject both “box and disk” and “plug welded box” design concepts are fully described in this paper. The information presented in this paper should help cask designers of multi-purpose casks avoid the design concepts with intrinsic weaknesses.

For Presentation at the INMM Meeting
L’Enfant Plaza, Washington, DC
January 14-16, 1998
1.0 BACKGROUND

The fuel basket is the heart of a spent fuel storage and transport system. Ensnconced deep inside the cask, surrounded by heavy neutron and gamma shielding, the fuel basket is the part of the cask system which is in direct and extensive contact with the stored spent nuclear fuel (SNF). Because of multiple roles of the fuel basket in a spent nuclear fuel cask system design, the basket functional attributes directly affect the overall soundness of the storage/transport device. The chief functions of the fuel basket may be summarized in five points:

i. Provide a passive means to transport the heat generated by the SNF.

ii. Provide a flat and conformal surface for the fuel to minimize stresses in the fuel cladding.

iii. Maintain the array of spent nuclear fuel in a subcritical configuration, using neutron absorbers, if necessary.

iv. Contribute towards attenuation of gamma radiation emitted by the stored SNF.

v. Possess sufficient structural rigidity to satisfy the regulatory criteria in the aftermath of postulated accident events.

Of the five functions of the fuel basket mentioned above, satisfying the structural integrity criterion is one of the most challenging. The accident events postulated for casks in both storage and transport modes are quite onerous from a structural standpoint. To qualify for certification as a transport package, the package must withstand a free fall from 9 meters (approximately 30 feet) onto an essentially unyielding surface [1]. The orientation of drop should be assumed to inflict maximum damage to the package. Even in well designed casks equipped with well engineered impact limiters at both ends, the maximum deceleration of the cask contents during the impact event is in the range of 50 to 70 g's. In quantitative terms, a deceleration of 60 g's magnifies the weight of a single 1,500 lb PWR assembly to 90,000 lbs or 45 tons! The fuel basket, solely responsible to maintain subcriticality after the so-called 9 meter hypothetical drop event, must not sustain significant permanent deformations lest the provisions of section §71.55(e) (which calls for subcriticality under “most reactive credible configuration under water moderation ...to the most reactive credible extent”) are violated.

The requirements for storage on an ISFSI pad are no less severe. An ISFSI pad, typically built with a 40" (or greater) reinforced concrete slab on soil or engineered fill is a quite rigid surface. The linear Bousinesq stiffness of the concrete pad usually exceeds 10 million
psi/inch, which renders an ISFSI pad a most inhospitable surface for dropped equipment. Among the accident events postulated for a cask on the ISFSI pad is the "tip over" scenario wherein the cask is assumed to overturn non-mechanistically and collide with the pad surface. Since the cask is usually installed without the protection of an impact limiter on an ISFSI pad, the so-called "tip over" event is a high g-load occurrence, contributed in no less measure by the relatively high surface stiffness of most casks.

The rigid body decelerations produced during the impact events interact with the basket structure, and depending on its structural characteristics, produce an even higher g-load within the internals of the basket (the so-called "dynamic amplification" effect).

The designer of the fuel basket must qualify the basket structure under the inertial loads produced by both the cumulative effect of the amplified rigid body deceleration and the local dynamic amplification.

To account for both of these effects, the analyses herein will assume that the maximum g-load sustained by the fuel basket internals is 60g's (typical of current values).

Until recently, two types of basket designs were used in the industry. They are:

i. The box-and-disk (B&D) design originally developed in the 1970s [5].

ii. The patented plug welded box (PWB) design [2].

In this paper, we examine the structural response of these two types of basket designs under a 60g impact event. For simplicity we will assume that the maximum deceleration produces a 60g inertia force transverse to the longitudinal axis of the cask which is horizontal (such as due to a 9 meter side drop, illustrated in Figure 1). For continuity of presentation, we provide a brief summary of the structural anatomy of B&D and PWB basket designs before presenting the analysis methodologies and results.

Finally, a brief synopsis of the design concept which eliminates the deficiencies of the B&D and PWB design is presented with supporting stress analysis.

2.0 FUEL BASKET DESIGNS

In essence, a fuel basket is an assemblage of square prismatic cavities arrayed in a square or a rectangular grid. For storage-only baskets, the criticality requirements are somewhat less severe. The stored fuel in the basket is required to maintain the k\text{eff} (reactivity) below 0.95 when submerged in the pool water, but credit for boron in the water (in PWRs) is permitted. While stored at an ISFSI pad, the fuel basket can be assumed to be protected from the intrusion of water (or any other moderator) if the basket enclosure contains a dual seal
system. The assumption of a completely dry basket on the pad, or one flooded with only borated water in the pool, greatly reduces the requirements on the neutron absorber for storage-only baskets. As a result, the storage cells in a fuel basket intended for a storage-only cask can be designed where the neighboring fuel assemblies are separated by a single neutron absorber panel. Holtec's MPC-32 [4] and Transnuclear's TN-32 fuel basket [3], are examples of storage-only baskets engineered with the assumption of boron credit. While Holtec's MPC-32 is structurally designed to be transportable, the TN-32 is designed as a storage-only basket [3]. The latter is also representative of UST&D's patent-based [2] PWB design. A single panel Boral neutron absorber sandwiched between two box walls in the TN-32 provides reactivity control. The boxes are joined to each other through fusion spot welds. In the TN-32 design (Figure 2), two 1/2 inch weld nuggets at approximately 8" axial spacing join contiguous box panels. An array of boxes interconnected in this manner constitutes a PWB basket for PWR fuel. In principle, a PWB basket for BWR applications can be constructed in a similar manner using smaller (= 6 inch) boxes.

For fuel baskets intended for use in transport overpacks, burnup credit is not permitted. In the absence of burnup credit, a single panel of Boral is not sufficient to control reactivity; consequently, transport baskets in PWR applications must have two panels of the neutron absorber separated by a gap (referred to as the "flux trap") between any two fuel assemblies. Holtec's MPC-32 basket which features a single panel of Boral is designed with the expectation that "burnup" credit (disallowed at this time), will be available in the near future. Holtec's HI-STAR 100 [4] and NAC's STC [5], both engineered to be transportable overpacks, feature baskets with two panels of Boral between two facing fuel assemblies. The STC basket is also an example of a Box and Disk (B&D) design (Figures 4 and 5). In the B&D construction, each storage cell is defined by a box with Boral panels contained in sheathings on all sides (Figure 6). Boxes equipped with Boral in this manner are arranged in a rectangular grid using stainless steel disks with square holes cut out in them through which the boxes pass (Figure 3). In the STC basket, the stainless steel disks are 4.37 inches apart, and 0.5 inch thick. A total of 31 disks, arrayed parallel to each other and held in place through a set of tie-rods, comprise the basket's structural support system. The boxes themselves are made from sheet metal stock (0.048" wall), formed and seam-welded to produce a smooth lateral support surface for the contained fuel (Figure 6).

It is evident from the foregoing that the B&D and the PWB baskets are entirely different design constructs. Both design concepts have seen some application and NRC review a few years ago. In this paper, we present some of our structural findings which led Holtec International to introduce an alternate design in the Company's HI-STAR and HI-STORM systems to overcome apparent design inadequacies of the prior art B&D and PWB storage-only design concepts. The analyses also helped Holtec International converge on a design which eliminates the deficiencies discovered in the PWB and B&D design concepts. The emphasis in our numerical analyses was to examine the robustness of the concept rather than a specific design in a specific cask. While the input data is taken, to the extent possible, from
public domain information on the representative B&D and PWB designs, we do not mean to present the analyses as rigorous QA validated evaluations of specific cask systems. Inasmuch as the objective of the analyses is to explore the innate strengths and weaknesses of the design concepts, the numerical data should be considered representative values for a typical, rather than a specific, design. A complete exposition of all evaluations would be too lengthy for the space of this paper. We will, therefore, confine our assessment to the response of the basket to only one of the several drop events evaluated for storage/transport certifications. In particular, we will consider the case where the impact between the cask and the ISFSI pad is lateral (such as in a 9 meter side drop event, or "tip over" on an ISFSI pad). Furthermore, to simplify our analysis, we will assume that the basket is built with machinery-like precision such that the boxes are perfectly square and straight and all external supports to the basket are perfectly aligned.

Under a 60g lateral impact event, the two basket designs transfer the fuel inertia load (approximately 45 tons each) in a different manner. Figure 7 shows the load transfer mechanism during side impact event across a column of boxes in the PWB design. The load from the fuel assembly transfers down through the vertical walls of the box. If the inertia load from one fuel assembly is $F$, then the vertical walls in the second box from the top have vertical load of $0.5F$ each. Figure 7 shows the progressive increase in the box wall load. The walls in the lowest box in the vertical stack have five times the load of the second box from the top. We will evaluate the stresses and deformation in this stack of boxes using a finite element formulation.

In the "Box and Disk" design, each box is subject to equal load, $F$. The transfer of the loading to the overpack surface occurs through the transverse disks, which, as stated earlier, are spaced fairly close to each other. The boxes, however, play a crucial safety function; they must not permanently sag or bow from the fuel inertia load such that the inter-box spacing (the flux trap gap) is preserved. Any measurable reduction in the flux trap gap has a direct, adverse effect on the system reactivity.

To protect against excessive deformation of fuel baskets, the USNRC has traditionally required the basket designer to comply with the stress limits of ASME Section III, Subsection NG [6]. Under the so-called "faulted condition", to which the 9 meter drop and tip over events belong, the maximum allowable stress intensity (membrane plus bending) is limited to $3.6S_m$. For stainless steel (SA240-304) at 725°F, this amounts to a limit of 55,400 psi. The same material of construction has been assumed for both B&D and PWB test problems to ensure uniformity in the assessment process.

In the following sections, a summary of the input data and associated stress analyses to evaluate the structural integrity of the two classical design geometries (B&D and PWB) is presented.
3.0 KEY INPUT DATA AND PROBLEM FORMULATIONS

For purposes of the analyses, the material of construction is assumed to be austenitic stainless steel. The following elastic properties are assumed:

Young's Modulus: 25.8E+06 psi
Yield Strength: 19,400 psi
Tangent Modulus: 158.75 ksi

In customary stress analysis to satisfy the ASME Code [5], the material is assumed to remain elastic even when the stress exceeds the elastic limit. The stress limits are also set outside the elastic range for limiting events (formally termed as “faulted condition”, or level D condition). Demonstration of structural compliance with the stress limits of the code requires that the model be linearly elastic. Therefore, the first set of analyses are carried out assuming linear elasticity.

The linear elastic solution, however, does not provide an accurate answer for the deformation of the structure. To obtain an accurate and correct solution for the displacement it is necessary to perform an elastic-plastic large deformation solution. The large deformation solution is henceforth referred to as the "LD" solution (in contrast to the linear elastic "LE" solution).

The following data is used in the analysis.

<table>
<thead>
<tr>
<th></th>
<th>B&amp;D Design</th>
<th>PWB Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell I.D. (inch)</td>
<td>8.78</td>
<td>8.78</td>
</tr>
<tr>
<td>Cell Wall Thickness, t (inch)</td>
<td>0.048</td>
<td>0.1</td>
</tr>
<tr>
<td>Disk-to-Disk Center-to-Center Spacing, inch</td>
<td>4.87</td>
<td>N/A</td>
</tr>
<tr>
<td>Box inner corner radius</td>
<td>t</td>
<td>t</td>
</tr>
<tr>
<td>Disk web thickness, inch</td>
<td>1.77</td>
<td>N/A</td>
</tr>
<tr>
<td>Weight of SNF</td>
<td>1,525 lbs</td>
<td>1,525 lbs.</td>
</tr>
<tr>
<td>Assembly box length, inch</td>
<td>155.5</td>
<td>155.5</td>
</tr>
</tbody>
</table>
4.0 RESPONSE OF THE BOX & DISK FUEL BASKET

In the B&D design, each box is autonomous from all others in the structural sense. The disks provide a common support system. Therefore, to study the response of the loaded boxes it is adequate to model one typical box with the undergirding disk ribs representing the support structure. Further, the fuel assembly is simulated as a uniformly distributed load, a reasonable assumption considering the relative flexibility of the grid spacers which bind the assemblage of rods in a fixed grid in a fuel bundle. Figure 8 illustrates the loading on a typical box. The pressure \( p \) on the box is computed simply by dividing the inertia load by the panel surface area.

\[
p = \frac{(1,525)(60)}{(155.5)(8.78)} = 67 \text{ psi}
\]

An ANSYS finite element model of the box and four consecutive support ribs is shown in Figure 9.

The stress field using the linear elastic model, implemented on the finite element Code ANSYS yields a maximum calculated stress intensity equal to 308,896 psi.

It is clear from the above that a 18-gage box (0.048" wall) is grossly inadequate to meet level D ASME stress limits of 55,000 psi. Figures 10 and 11 show the lateral deformation contours. The maximum deflection is computed to be 0.3542 inches.

To determine the effect of the overload on the 0.048" basket, an elastic-plastic large deformation analysis was also performed. For this purpose, a close approximation of the stress-strain curve for austenitic stainless steel at 500°F reference temperature was used (Figure 12). Figure 13 shows the deformed profile of the loaded box. The plastic sag of the box panel is over 0.21 inch, which means that approximately 12% of the flux trap space in the assumed B&D basket configuration would be lost in a typical 9 meter drop event. The concomitant increase in reactivity would not be inconsiderable. In summary, the structural deficiency in the fuel basket directly translates to a nuclear safety concern.

5.0 RESPONSE OF THE PLUG WELDED BOX (PWB) BASKET

As discussed earlier, a PWB basket is a honeycomb construction wherein boxes are attached to each other through a number of tungsten fusion welds. The Boral neutron absorber and aluminum sheet (to promote heat transfer) are sandwiched between facing walls of the boxes. In order to make the fusion (plug) welds, round cut-outs in the Boral/aluminum panels are made and a cylindrical stainless stub is placed in the circular slot. A patented fusion welder process connects the cylindrical stainless stub to the box panels at its two extremities. This
process is said to produce typically 1/2 inch diameter "nuggets" with shear strength on the order of 3,000 psi. A review of previous topical safety analysis reports available in the public domain indicates that in PWR baskets two plug welds, traverse to the box, are made of approximately 5 inch spacing. The pair of plug welds is made every 8 to 10 inches along the box length. The resulting honeycomb structure has the appearance of a set of stacks of boxes arranged in the manner of Figures 2 and 3.

Certain structural features of this honeycomb are readily evident from Figures 2 and 3, namely:

i. The Boral/aluminum insert between the box walls transfers the vertical load from the box above to the box below.

ii. The corners of the boxes cannot be supported by the aluminum filler, and therefore, must transfer the load from the box above through cantilever action. The greater the box corner radius, the greater is the cantilever arm and the associated bending moment.

iii. The plug welds must withstand lateral shear and bending as the adjacent box walls tend to bend under the fuel loading.

A finite element model of the stack of boxes illustrated in Figure 7 is prepared on the computer code ANSYS. A representative box length containing one set of plug welds is modelled. The pressure loading corresponding to 60g's (67 psi) is applied at the bottom surface of each box. Recognizing that the adjacent column of boxes will provide lateral restraint to the box walls, the plug weld locations in the box welds are assumed to be fixed against lateral movement.

As discussed earlier, the bottom box in the stack is most heavily loaded. The maximum computed primary stress is 247,769 psi compared to the allowable limit of 55,400. Figures 14 through 17 provide detailed results in a graphical format extracted from ANSYS outputs.

The maximum lateral force on each of the plug weld locations is computed to be 23,566 lbs. This would lead to a nominal stress of 120,020 psi on the weld, which is an order of magnitude greater than the "strength" of welds of this genre.

6.0 THE COPLANAR CELL WALL HONEYCOMB BASKET

The structural deficiencies revealed by the stress analysis of the B&D and PWB fuel basket designs prompted the development of an entirely new basket design in 1993. This design is illustrated for a 32 assembly fuel basket used in Holtec's HI-STAR [4] and HI-STORM [8] systems in Figures 18 and 19. The key features of this basket design are:
i. The storage cells are connected to adjacent cells at all common corners.

ii. The cells' walls are completely coplanar, i.e., there is no offset between the walls of the successive cells.

iii. There is no "corner radius" at cell corners. This feature in the PWB design, as we stated earlier, is the central cause for high stresses under lateral impact events.

iv. The cell wall is considerably thicker (0.2813 inch) compared to the prior art designs (viz. 0.048 inch used in NAC's STC [5]).

v. Since all "boxes" are connected to each other, no disks are necessary which, as a secondary benefit, eliminates the potential of concentrated loading of the overpack due to lack of perfect alignment among the disks.

vi. The neutron absorber (Boral) is removed from the load path, eliminating the potential of damage to the neutron absorber during lateral impact events.

A finite element model of a column of boxes in the manner of the PWB model on the ANSYS finite element code was prepared for Holtec's MPC-32 basket with box I.D. adjusted to 8.78 inch to coincide with the B&D and PWB models analyzed earlier. All other input data, such as the applied loading and basket material properties, are set equal to the previously discussed models. Figure 20 shows a pictorial view of the model.

Figure 21 shows the stress field in the basket structure. The maximum stress intensity in the structure is 28,583 psi, which is well below the previously stated allowable limit of 55,400 psi. The maximum deformation of the cell panels is bounded by 0.034 inch (Figure 22). The coplanar cell honeycomb design, therefore, complies with the stress limit criterion; it also satisfies the regulatory criterion that the deformations remain infinitesimal.

Other aspects of this basket design, such as its thermal-hydraulic characteristics, are discussed in another paper [7] and, therefore, do not warrant repetition here.

In summary, the coplanar cell wall honeycomb basket design concept deployed in Holtec International's HI-STAR and HI-STORM systems was analyzed under identical loadings. The results showed that all ASME Code and regulatory limits are satisfied.

7.0 CONCLUSION

Two different "prior art" fuel basket designs were subjected to a simplified finite element static stress analysis to establish their structural response in the horizontal orientation when
the fuel inertia load is magnified by a factor of 60. The Box and Disk design which is perhaps the forerunner of all modern basket designs, was analyzed assuming the box wall thickness to be 0.048" and the disk separation at 4.37 inches. The focus of the analysis was to ascertain the behavior of one loaded box; the finite element model was not large enough to evaluate the response of the disks. The results showed that the liner elastic stress level in the box reaches excessive levels and the maximum deflection is over 0.35 inches. An elastic-plastic large deformation solution indicates somewhat smaller sag; however, even with credit for large deformation the maximum sag is over 0.2 inches. This may be an unacceptable level of deformation from the standpoint of nuclear criticality.

The other design analyzed was the plug welded box (PWB) constructed and patented by UST&D some years ago and adopted by Transnuclear, Inc. in its family of cask designs. The box wall thickness is set at 0.1 inch. A simplified linear-elastic model of a portion of the 32-cell PWR fuel basket was prepared. The stress analysis showed that stresses in the boxes located at the bottom of the stack (with the basket in the horizontal orientation) are well above the ASME Code limits. The stresses in the plug weld locations are likewise substantially in excess of their strength limit.

In conclusion, while both PWB and B&D basket designs can theoretically be strengthened to meet the current regulatory and ASME Code criteria; prior art designs are intrinsically ill-configured to withstand drop event loads. The inherent weakness in these designs is due to the fact that criticality and gross weight considerations restrict the increase in the box wall thickness. From a purely structural standpoint, the chief vulnerability in the PWB design is the presence of corner radii in the boxes which creates a cantilever situation leading to high bending stresses. Increasing the box thickness unfortunately causes a proportional increase in the corner radius and, consequently, the bending moment. Thus, as the box thickness is increased so is the bending moment at the box corners which produces the box bending stresses. Eliminating the corner radius, unfortunately, is not possible. The only solution for this design conundrum is to increase the box wall thickness until the stress limits are satisfied. However, this would lead to a loss in storage capacity.

The design inadequacies in the Box & Disk construction and in the PWB construction were demonstrated herein by considering only one loading scenario. Increasing regulatory emphasis on stern compliance makes it inevitable that the old design embodiments will have to be fully reassessed and improved to eliminate their inherent weaknesses for future applications.

To be sure, in contrast to the transport (Subpart 71) requirements, which have a direct consequence to public health and safety, the Subpart 72 (storage-only) requirement of non-mechanistic tipover is an artificial regulatory construct. The systems utilizing the prior art technology in storage-only applications, therefore, are not a matter of safety concern. It can be reasonably asserted that storage-only systems licensed for ISFSI deployment in the past do not need to be retroactively evaluated. Licensed transport systems, on the other hand,
being free to traverse the nation’s railroads, should be subject to retrospective review, if technical information so warrants.

While the analyses in this paper have been carried out using PWR baskets, it is quite reasonable to expect that similar analysis on equivalent BWR baskets would lead to similar results.

In closing, it should be emphasized that the structural weaknesses revealed by the analyses presented in this paper do not disqualify the B&D and PWB designs from possible use in MPC canisters. By thickening the box walls, for example, the cell wall stress levels can be reduced and brought within acceptable limits. The numerical analyses nevertheless show that, from a structural standpoint, the B&D and PWB design concepts make inefficient use of the available metal.

8.0 POSTSCRIPT

This paper attempts to provide the answer to a persistently asked question about Holtec's fuel basket design. Over the past three years, the company was repeatedly asked by utility personnel to explain the reason why it elected to develop a wholly new design concept for the HI-STAR™ HI-STORM™ fuel baskets when "licensed" design concepts have existed for over a decade. This paper, based on the exploratory research conducted in the 1992-93 period, provides a key reason which compelled the company to a new, albeit far more labor intensive and expensive, basket design technology. Holtec International recognizes that the NRC's "Demand for Information" and "Confirmatory Action Letter" issued to cask vendors have thus far dealt with deficiencies discovered in the course of cask operations and NRC audits. The natural progression of the increasing NRC vigilance is destined to escalate into in-depth scrutiny of design analyses. In view of the rising rigor in regulatory reviews, Holtec's thorough and detailed approach to basket design may have been a most prudent approach. Holtec's basket design which essentially produces a multi-flange beam-like structure to minimize internal stresses during drop events, is also presented in a previous industry paper [7].

9.0 REFERENCES


FIGURE 1: ACCIDENTAL DROP FROM 9 METERS ON TO AN ESSENTIALLY UNYIELDING SURFACE
FIGURE 2: 32 ASSEMBLY "PLUG WELDED BOX" FUEL BASKET
FIGURE 3: TYPICAL "PLUG WELDED BOX" FUEL BASKET CONSTRUCTION
FIGURE 4; CLASSICAL BOX-AND-DISK FUEL BASKET DESIGN
FIGURE 5: SUPPORT DISK IN THE 26 ASSEMBLY STC BASKET
FIGURE 6; COMPOSITE BOX ELEMENT FOR THE STC BASKET
Figure 8: A typical box panel supported by disks under pressure loading from a lateral impact event.
FIGURE 12: STRESS-STRAIN CURVE FOR THE PANEL MATERIAL (304 SS) AT DESIGN TEMPERATURE (500°F)
FIGURE 15: TN-32 FINITE ELEMENT MODEL (BOTTOM FUEL COMPARTMENT)
FIGURE 16: TN-32 DEFORMATION PROFILE (INCHES)
FIGURE 17: TN-32 TOP SURFACE STRESS INTENSITY (PSI)
FIGURE 18: CROSS SECTION OF THE NPC-32 FUEL BASKET AND THE ENCLOSURE SHELL
FIGURE 19: PICTORIAL VIEW OF MPC-32 FUEL BASKET

FEATURES:
- HONEY COMB CONSTRUCTION
- CONTINUOUS WELD
- BASKET EXTREMELY RIGID - RESEMBLES A MULTI FLANGE BEAM
- NO CONCENTRATED LOADINGS - NO SUPPORT DISKS
FIGURE 21: 60G SIDE IMPACT STRESS INTENSITY (psi) FOR MPC-32