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Spent Nuclear Fuel Transportation Casks Evaluation for Water In-Leakage

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1. Abstract

The United States Nuclear Regulatory Commission (USNRC) is responsible for licensing commercial spent fuel storage and transportation systems. To ensure that the regulations are risk-informed, and do not place unnecessary regulatory burden on the industry, the USNRC has been examining its regulations that apply to spent fuel transportation casks for maintaining sub-criticality under hypothetical accident conditions. Code of Federal Regulations, Title 10, Part 71[1] (10 CFR 71), section 71.55(b) requires that, for evaluation of sub-criticality for fissile material packages, water moderation should be assumed to occur to the most reactive credible extent consistent with the chemical and physical form of the contents. This requirement is based on a defense-in-depth policy, and accounts for any possibility of water intrusion into the package. This program is designed to quantify the margins of safety of certified transportation casks to water intrusion following hypothetical accident conditions.

This paper describes the current status of analytical work being performed to evaluate two USNRC-certified spent fuel transportation casks, HI-STAR 100[2] and TN-68[3]. The analytical work is performed using the ANSYS®[4] and LS-DYNA™[5] finite element analysis (FEA) codes. The models are sufficiently detailed in the areas of bolt closure interfaces and containment boundaries to evaluate the likelihood of water in-leakage under free drop hypothetical accident conditions of 10 CFR 71.73.

2. Introduction

To ensure public and environmental safety associated with fissile material packages, such as spent fuel transportation casks, 10 CFR Part 71, section 71.55 regulations require that the casks (or packages) remain sub-critical under normal conditions of transport (10 CFR 71.71), and hypothetical accident conditions (10 CFR 71.73), assuming that the fissile material is in the most reactive credible configuration consistent with the normal or damaged condition of the package and the chemical and physical form of the contents. Additionally, the regulations require sub-criticality if water were to leak into the cask to the most reactive credible configuration consistent with the chemical and physical form of the contents. Current regulatory guidance for addressing the requirements of 10 CFR 71.55(b) for spent fuel casks are included in NUREG-1617, "Standard Review Plan for Transportation Packages for Spent Nuclear Fuel," and NUREG/CR-5661, "Recommendations for Preparing the Criticality Safety Evaluation of Transportation Packages". The requirement of considering water moderation has resulted in the use of neutron poisons for nearly all medium to large capacity spent fuel transport systems utilized in the United States. This requirement is based on a defense-in-depth philosophy that a fissile material package must stay sub-critical if fresh water leaks into the package [10 CFR 71.55(b)]. An assembly of borated aluminum (or boron carbide/aluminum composite) is typically used to form the neutron poison and is incorporated into the cask cavity for this condition. If the requirement of considering water moderation could be removed for spent fuel transportation casks based on the low likelihood of water intrusion into the casks, and if other scenarios, such as human errors and deliberate acts would not require them, the boron plates and flux trap spaces may be removed, allowing for more physical space and greater payload capacity inside the cask.

To improve transport efficiency while maintaining transport safety, the questions of the likelihood of water in-leakage under the regulatory normal and accident conditions are being investigated collectively by staff at the USNRC and Pacific Northwest National Laboratory (PNNL). Detailed finite element models are being built for this purpose. ANSYS®/LS-DYNA™ computer code is being used to create the parameterized three dimensional structural FEA models. LS-DYNA, an explicit finite element code, is being used to compute the structural response of the impact events. Two particular packages are being considered, Holtec International's HI-STAR 100 containing an MPC-24E/EF canister and TransNuclear Incorporated's TN-68.

3. Load Cases

The accident scenario of interest here involves a hypothetical accident condition of a cask 30 ft (9 m) free drop impact onto an essentially unyielding surface, followed by a 40 in (1 m) puncture test, a fully engulfing fire, and then being immersed under 3 ft (0.9 m) of water head, as specified by the regulatory requirements (10 CFR 71.73). In addition, the undamaged containment system of a cask must be designed to withstand an external water pressure of 290 psi (2 MPa) for a period of not less than one hour without collapse, buckling, or in-leakage of water (10 CFR 71.61). Requirements of 10 CFR 71.61 also satisfies 10 CFR 71.73(c)(6) requirements of cask immersion under a 50 ft (15 m) head of water. A major goal of this work is to develop a model that can fully capture the structural effects of impact onto an essentially unyielding surface, with particular emphasis on evaluating the response of the containment boundary. To that end, the bolts, lid, and flange area are modeled in fine detail. Bolt initial tension, cask internal pressure, and non-liner plastic material behavior are all considered.

The main load case under consideration is a drop accident, as detailed in 10 CFR 71.73. The doctrine is to assume the most unfavorable set of conditions for this drop event, so the orientation at impact is to be the one that causes the most amount of damage or the greatest amount of seal failure. Since it is not obvious which orientation will be the worst, a series of four analyses will be run with varying impact orientation for each package. These are:

1. An axial top-down drop puts largely axial tension on the lid bolts. This could conceivably stretch the bolts enough to allow a gap between the lid and the flange to open up.

2. A side drop applies mainly a shear load on the lid bolts and a bearing load on the bottom facing portion of the cask, potentially providing even greater complex loading of the lid/mating flange components.

3. A center of gravity (CG)-over-top corner drop case is expected to cause the most localized deformation to the closure, with the highest chance of causing seal failure due internal hammering of the lid and potential plastic deformation of the bolts.

4. The slap-down to the top (where the secondary impact is subjected to the top closure) case adds an additional rotational velocity component to a side drop event. This occurs when the impact angle between the cask axis and the horizontal impact surface is small.

Other loads included in the models were initial bolt tension and initial internal pressure. Torque specifications from the vendor were used to calculate initial bolt cross-section stresses. From the Hi-Star 100 Safety Analysis Report (SAR)[2] issued by the applicant, the least favorable set of hypothetical accident conditions has an MPC internal pressure of 100 psig (689 kPa) and an overpack internal pressure of 100 psig (689 kPa).

4. Finite Element Model

A diagram of the HI-STAR 100 cask system (including MPC) is provided in Figure 1. The HI-STAR 100 design utilizes a welded multi-purpose canister (MPC) to contain the spent fuel. HOLTEC has a variety of MPC configurations designed to accommodate either 24 or 32 Pressurized Water Reactor (PWR) or 68 Boiling Water Reactor (BWR) spent fuel assemblies. The MPC is placed into the transportation cask for shipment after it has been loaded with spent nuclear fuel and the closure lid is welded shut. The overall outer diameter of the cask is 96 in (244 cm), and the length including the impact limiters is approximately 316 in (803 cm). The stainless steel cask inner shell is 2.5 in (6.35 cm) thick. The gamma shield is comprised of 5 layers of carbon steel plates a total of 6 in (15.24 cm) thick. The next layer is a neutron shield, approximately 4.5 in (11.43 cm) thick, strengthened by a network of carbon steel stiffening fins. The outer enclosure shell of the cask is fabricated of 0.5 in (1.27 cm) thick carbon steel, and is painted.

Impact limiters, made of aluminum honeycomb material with a stainless steel skin, are installed on the cask at the ends prior to shipping. Impact limiters serve to prevent damage to the cask, specifically protecting its closure lid, MPC basket, and payload in the event of a cask drop/impact accident. This cask weighs approximately 277,300 lbs (125,781 kg) when loaded for transport.

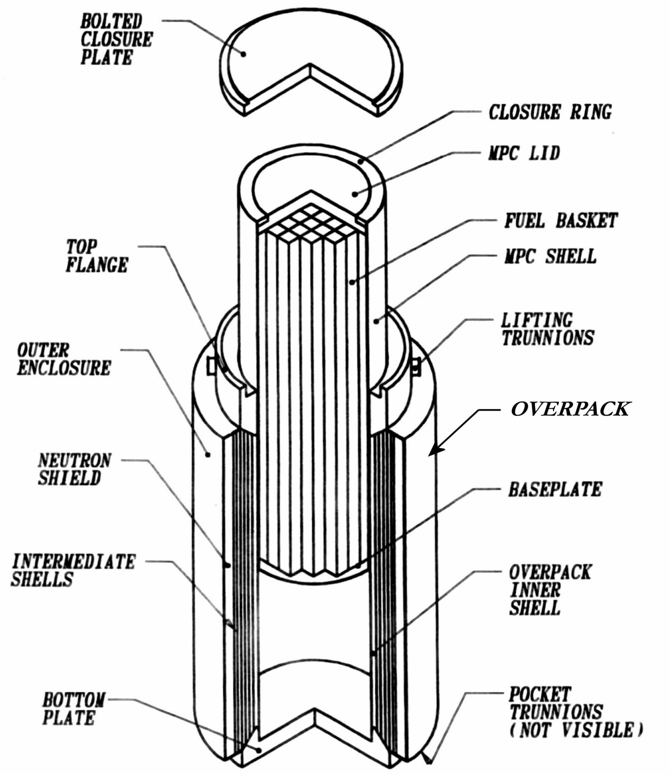

Figure 1. HOLTEC HI-STAR 100 Spent Fuel Transportation Cask

The models are built in ANSYS and written to LS-DYNA input file format. One structural model for each package is being constructed, with an angular orientation parameter to define the particular load case. Figure 2 shows the FEA representation of the geometry of the HI-STAR 100.

The main solid structural element used throughout the model is an 8-noded hexahedral element with full integration. Most of the structures are represented by these elements; the exceptions are discussed below. The lid bolts of both casks are modeled with a dense mesh of these elements to ensure proper response under the complex loads experienced during impact. In the Hi-Star 100, the long bolts connecting the bottom impact limiter to the cask also use these elements since significant bending and contact with the impact limiter plates are expected along their lengths.

Bolts with less complicated loads and surroundings have correspondingly simpler representations. Tiebreak contact definitions, point-to-point constraints that uncouple when a certain separation force is reached, are used in the buttress plate to cask flange interface. Each bolt has its own tiebreak set to allow for individual failure. Beam elements are used to represent bolts connecting the upper impact limiter of the Hi-Star 100 to the outside of the flange. A plastic material curve is implemented along with a maximum allowable plastic strain failure criterion. Both of these sets of bolts have a sufficiently simple stress state of tension and shear. As such, a more complicated representation is not warranted.

Four-node fully-integrated shell elements are used to model thin plates wherever applicable, as they are less computationally expensive than hexahedral elements. These are used in the Hi-Star 100 gamma shield, which is comprised of layers of 1.0 to 1.25 in (2.54 to 3.18 cm) plates, and the 0.5 in (1.27 cm) steel that surrounds the neutron shield. Shell elements are also used in the impact limiters to represent the skin, honeycomb septums, disks, and stiffening cylinders. The joining of shells to solids is accomplished via tied shell edge to surface contact definitions. Shell thicknesses were reduced slightly (by less than a percent) at select locations to avoid contact surface penetrations.

Mesh density is established at a reasonable level for the problem size to maintain solution tractability. Degenerate elements were also avoided as much as possible. The smallest element size occurs in and around the lid bolts, the region of the greatest interest because of the importance of containment and the role the lid seal plays. Bolts were modeled as three concentric cylinders representing the bolt head, the unthreaded bolt shank, and the threaded bolt shank. The minimum thread diameter was used for the threaded shank. Washers were included at each lid bolt. Figure 3 shows the mesh density of the area around the lid bolts.

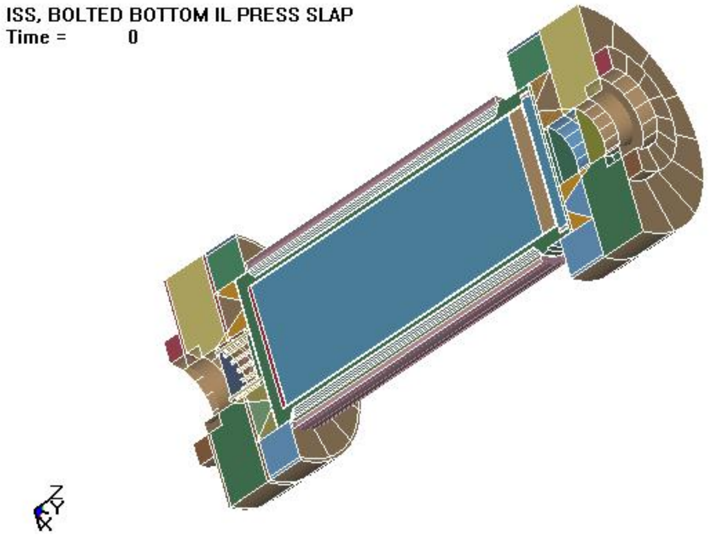

Figure 2. FEA Model Geometry

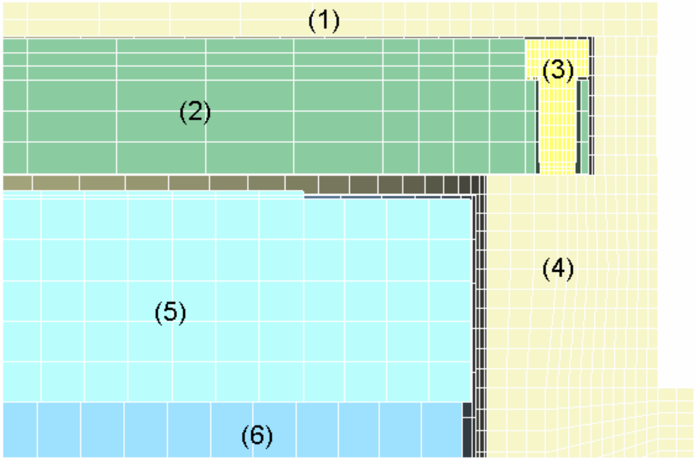

Figure 3. Finite Element Analysis Mesh

(1) Impact Limiter Buttress Plate (2) Bolted Closure Plate (Lid) (3) Lid Bolt

(4) Top Flange (5) MPC Lid (6) Fuel Basket

5. Material Properties

The Hi-Star 100 includes many types of steel, nickel alloy lid bolts, and aluminum honeycomb impact limiter material. “Alloy X” is a term used for stainless steel that can be any one of a few different grades – 316, 316LN, 304, or 304LN. Standard analytical practice is to select the most unfavorable set of properties from within the group. Table 1 lists material strength data being used in the Hi-Star analyses [2]. Temperature zones were based on prior thermal analyses and represent typical Normal Conditions of Transport (NCT) per 10 CFR 71.71.

Table 1: Hi-Star 100 Material Strengths

	Temperature (F) (K)	Yield Strength (ksi) (MPa)	Ultimate Strength (ksi) (MPa)	Location
Alloy X	150 (339)	27.5 (189.6)	73.0 (503.3)	Impact Limiters
Alloy X	300 (422)	22.5 (155.1)	66.0 (455.1)	Top and Side Canister
Alloy X	450 (505)	20.0 (137.9)	64.0 (441.3)	Bottom Canister
SA350-LF	300 (422)	33.2 (228.9)	66.7 (459.9)	Cask Forging and Lid
SA515/516	225 (380)	34.4 (237.2)	70.0 (482.6)	Outer Cask
SA193-B8S	200 (366)	50.0 (344.7)	95.0 (655.0)	Bottom Impact Limiter Bolts
SB-637-N07718	225 (380)	150.0 (1034.2)	185.0 (1275.5)	Lid Bolts

LS-DYNA’s piecewise linear plastic material (LS-DYNA Type 24) is used in each of the steels. True stress/true strain curves were constructed using temperature-dependant material data from handbook sources [6,7]. The nickel alloy lid bolts are represented as a plastic bilinear material with kinematic hardening (LS-DYNA Type 3). The tangent modulus after yielding is based on handbook sources [8]. The aluminum impact limiter uses LS-DYNA’s honeycomb material model (LS-DYNA Type 26), with material parameters derived from manufacturer’s data and engineering judgment. An example of crush strength versus volumetric strain is shown in Figure 4. The basket and fuel assembly were modeled as a simple cylinder of homogenized elastic material with representative density and modulus.

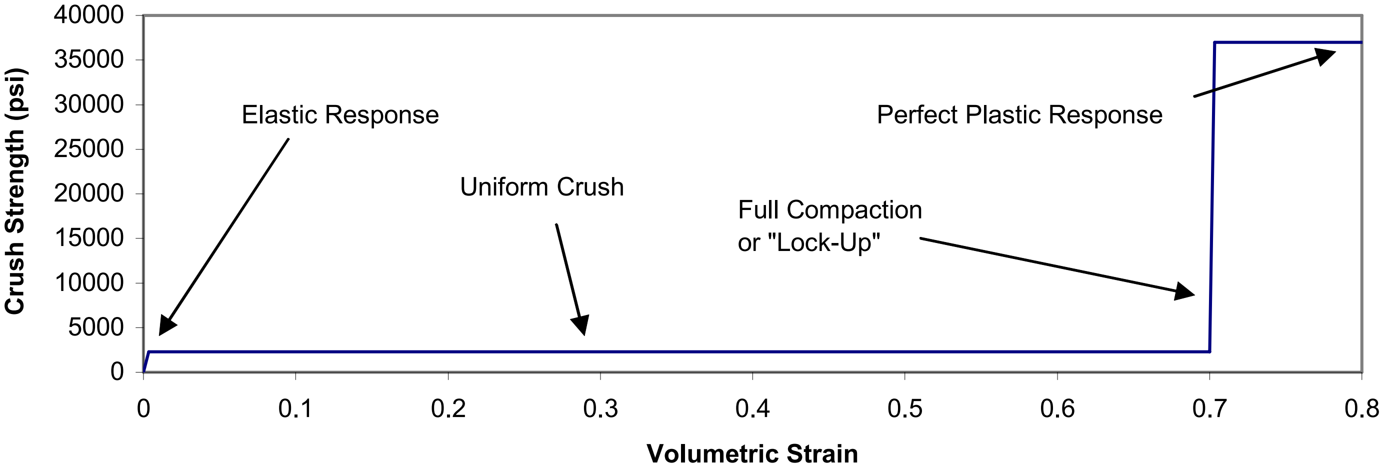

Figure 4. Example of Crush Strength vs. Volumetric Strain for Aluminum Honeycomb

1 psi = 6.894753 kPa

6. Analysis

The solution consists of many phases. First phase is a period of dynamic relaxation. This is a structural load initialization step that occurs in pseudo-time before the starting point of the analysis. This is used to apply the internal pressure in a time-invariant fashion, which will not affect the dynamic solution. Second phase is a small window of free fall (.003 sec) during which time the bolt preload is applied. This is accomplished with a pre-release feature of LS-DYNA version 971, *INITIAL_STRESS_SECTION, which puts an initial stress state through elements along a plane. This will be available to the general public with the next official release from Livermore Software Technology Corporation (LSTC). The bolt preload is ramped up over 0.002 seconds, while the whole package is in a state of free fall. A further 0.001 second passes before impact, to allow any unrealistic transient effects to die out.

During impact, the total kinetic energy of the falling package is transferred into internal energy. The solution time extends until the kinetic energy of the system is nearly dissipated. The package tends to bounce back off the ground, so the kinetic energy picks back up slightly beyond a certain point (around 0.04 sec). An example of the kinetic and internal energy history of the system is shown in Figure 5. In this example, the final version of the solution will only need to be run to 0.04 sec.

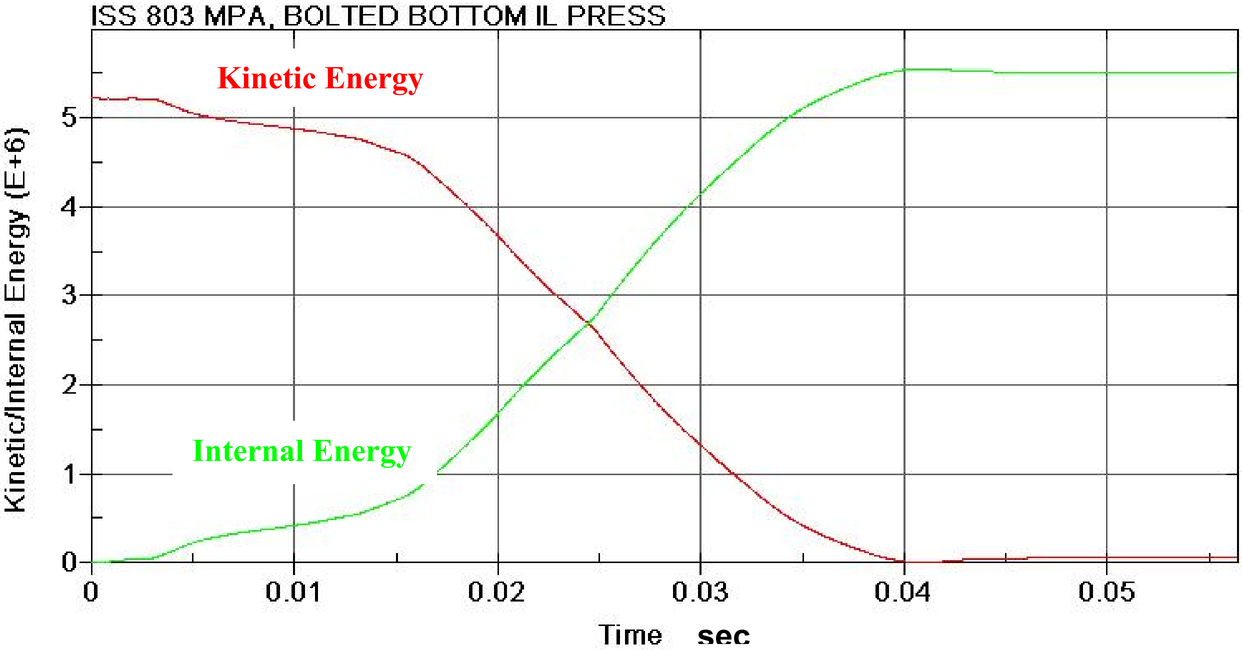

Figure 5. Kinetic and Internal Energy (Joules) History

1 Joule = 0.7376 ft-lbf

7. Preliminary Results

At the current state of completion, axial drop analyses of the HI-STAR 100 show the model is behaving as expected in terms of maximum deceleration. As part of the SAR, testing of the impact limiter showed a 60 g (acceleration due to gravity) deceleration under similar conditions. Figure 6 shows the acceleration of the center of mass over time for the HI-STAR 100. Excluding the 80 g spike at 0.025 sec, the peak deceleration is approximately 60 g, which matches the experimental drop tests well. The timing of the nearly instantaneous deceleration spike coincides with the canister striking the cask lid, due to an initial gap between the top of the canister and the underside of the lid. This gap represents the most-unfavorable condition. In a realistic drop accident, the canister could slide into close contact with the lid before impact, eliminating the spike.

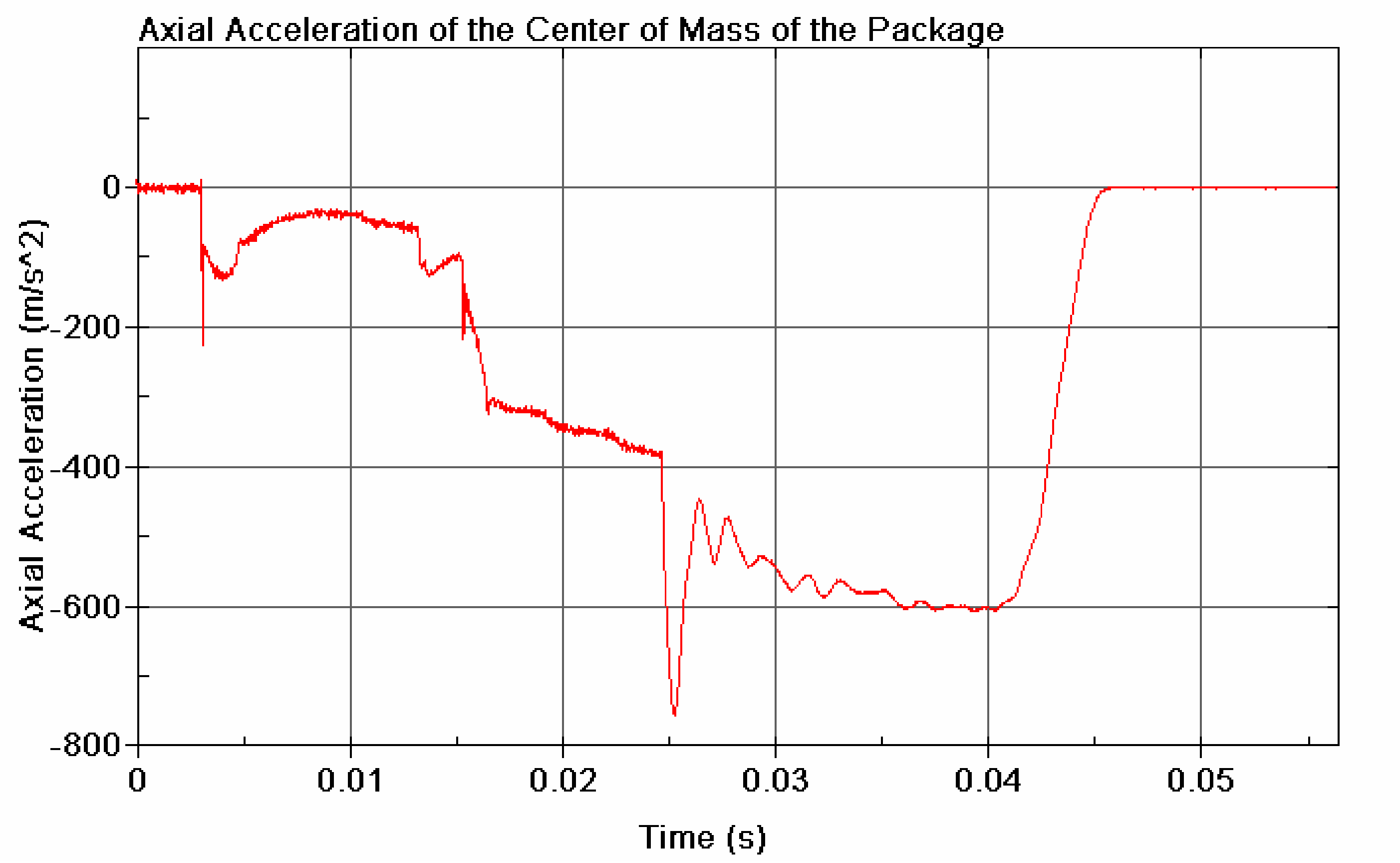

Figure 6. Preliminary Acceleration Data

1 $m/s^2 = 39.4$ in/s^2

8. Current Status

Currently, the HI-STAR 100 analyses are in their final stages. The basic underlying model has evolved from a simple structural representation to one of high detail. Using mass-scaling, a way of speeding up explicit FE analyses at the cost of some inaccuracy, preliminary runs show contact surfaces, materials, and preloads are behaving satisfactorily. Final accurate results require longer-running analyses. Predictions place run time to be between three to seven days for each of the four load cases.

The TN-68 model is largely finished, and is following the same build-up pattern as the HI-STAR 100. Final details such as the implementation of bolt preloads, internal pressure, and wood impact limiter material properties remain. A series of mass-scaled runs will be used to confirm all the model features are working properly, then it will be submitted for long-term batch runs including all drop orientations cited above.

9. Conclusions

An assurance of seal integrity during regulatory drop scenarios could lead to increased spent nuclear fuel transport efficiency. This paper describes the analytical approach to addressing this important question. Initial results indicate the model features are working correctly, and acceleration results compare well with experimental data, but final structural results and evaluation are still forthcoming.

10. References

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