Structural Design Considerations

Chuck Bullard

Presentation to NRC
January 21, 2009

Overview

- Benchmark Analysis of LS-DYNA Impact Limiter Model
- Fuel Impact Attenuators (FIA)
- Drop Analyses for HI-STAR 180
- Fuel Rod Integrity Analysis

Benchmark Analysis Background

- 1997: HI-STAR 1/4 scale drop tests
- 1998: Analytical 2-D approach to simulate drop conditions, used for HI-STAR 100 approval
- 2007: 3-D transient FEM calculations to benchmark LS-DYNA for Impact Limiter Qualification based on 1/4 scale drop tests
- June 2008: OTIs on HI-STAR 180, including comments on Impact Limiter Benchmarking
- September 2008: Holtec proposes an improved approach on LS-DYNA benchmarking
- Today: Presentation of Final Results

Unresolved HI-STAR 180 OTIs related to Benchmark Analysis

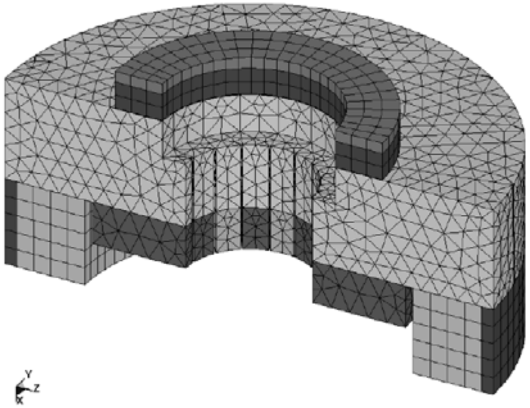
- 2-3 Hexahedron vs. Tetrahedron Elements
- 2-4, 2-5 Material Properties
- 2-6 Mesh Sensitivity
- 2-7 Material Coordinate Systems
- 2-9 Robust Model
- 2-10 Overpack Connection
- 2-11 through 2-14 Bolts

Revised Benchmarking

- Hexahedron vs. Tetrahedron Elements
- Mesh Sensitivity
- Material Properties
- Component Benchmarking
- Material Coordinate Systems

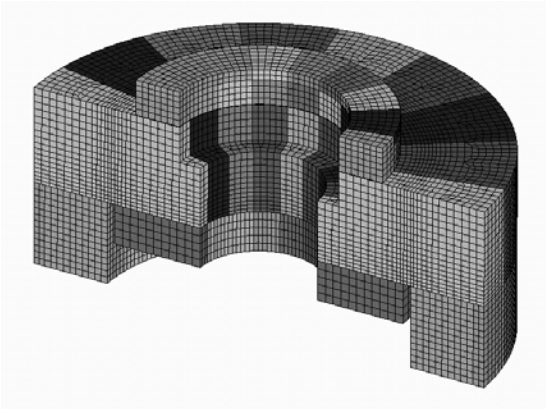
Hex vs. Tet Elements

- Initial Model (Tet Elements)



Hex vs. Tet Elements

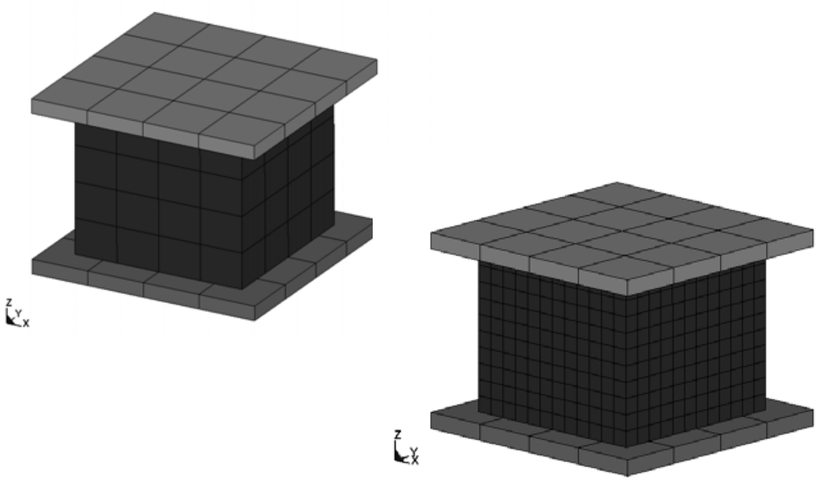
- Revised Model (Hex Elements)



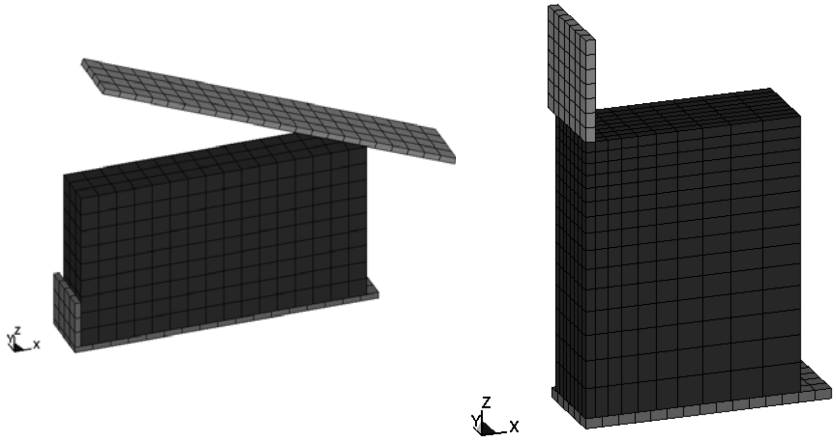
Mesh Sensitivity

- Three simple impact problems, which characterize the various loading conditions of the impact limiter honeycomb
  - Normal Compression
  - Off-Axis Compression
  - Shear Load
- Each problem simulates a honeycomb block impacted by a rigid body dropped from 30 ft.
- Each problem is simulated multiple times, with different element sizes

Mesh Sensitivity
Normal Compression



Mesh Sensitivity
Off-Normal and Shear



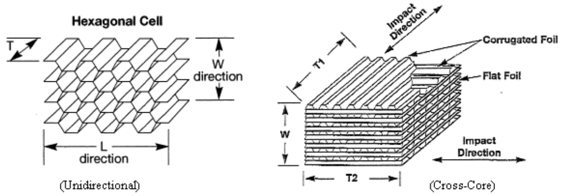
Mesh Sensitivity - Results

- Crush behavior is very insensitive to element size, even for extreme shear deformation
- Lower bound element sizes selected for full impact limiter models
- Using different impact orientations make results applicable to all honeycomb impact limiter – no further mesh sensitivity studies required

---

Material Properties

- Orthotropic material properties are used in the honeycomb LS-DYNA material model.
- Secondary strength properties of honeycomb are derived, or are based on the supplier's estimates.
- The studies with a wide range of parameter variations show that those secondary properties have an insignificant effect on the impact limiter performance.



Material Properties

Required Properties for Honeycomb Material Model	**Unidirectional core**	**Bi-directional core**
LCA- Compressive strength in a-direction	Available	Available
LCB- Compressive strength in b-direction	Estimated by Supplier	Available
LCC- Compressive strength in c-direction	Estimated by Supplier	Available
LCAB- Shear strength in ab-direction	Available	Derived
LCBC- Shear strength in bc-direction	Available	Derived
LCCD- Shear strength in ca-direction	Estimated by Supplier	Derived

Note: The a-, b-, and c-directions in the material model are equal to T-(or T1-), L-(or T2-), and W-directions of the honeycomb, respectively.

Material Properties

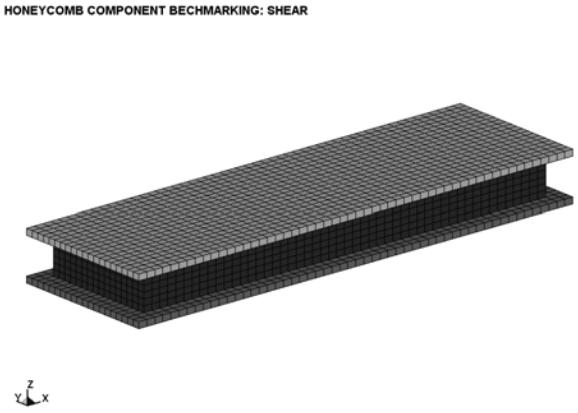
Effects of Secondary Strength Properties on ¼-Scale HI-STAR 100 Drop Simulation Results (C.G.Over Corner)

Item	Lower-Bound Properties	Upper-Bound Properties	Measured
Maximum Deceleration (g's)	165.45	168.14	155
Crush Depth (in)	4.00	3.94	4.19

Component Benchmarking

- Standard honeycomb compressive and plate shear tests are simulated for the honeycomb material model component benchmarking. Load is applied slow enough to avoid significant inertial loads
- Component benchmarking is performed for various LS-DYNA Material Model/Element Form combinations and the best combination for HI-STAR 100 Benchmarking is identified.

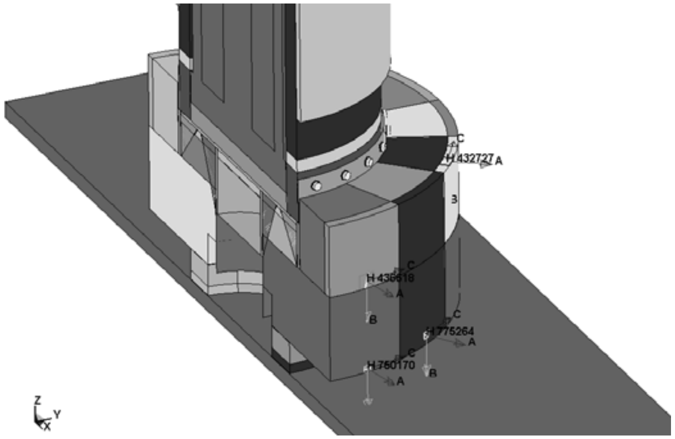
Component Benchmarking



Material Coordinate Systems

- The improved benchmarking model specifies the material coordinate system for each honeycomb block based on the orientation of the block.
- Results show an effect of a few percent difference in peak deceleration compared with the single material coordinate system approach used in the old benchmarking model.

Material Coordinate Systems



Benchmark Analysis Results

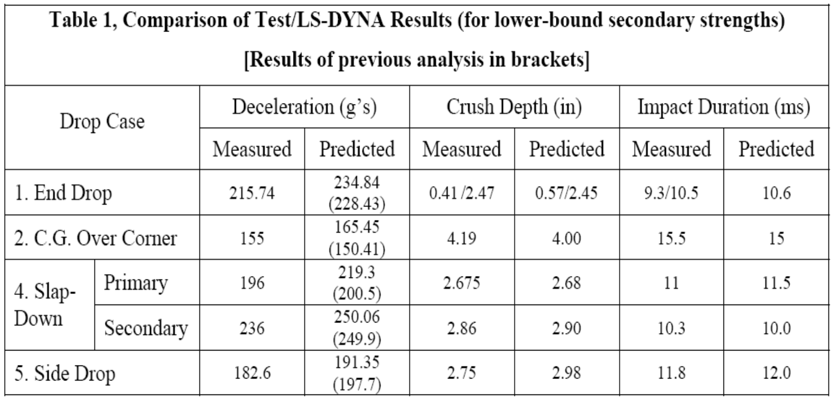


Table 1, Comparison of Test/LS-DYNA Results (for lower-bound secondary strengths)
[Results of previous analysis in brackets]

Drop Case		Deceleration (g's)		Crush Depth (in)		Impact Duration (ms)	
		Measured	Predicted	Measured	Predicted	Measured	Predicted
1. End Drop		215.74	234.84 (228.43)	0.41/2.47	0.57/2.45	9.3/10.5	10.6
2. C.G. Over Corner		155	165.45 (150.41)	4.19	4.00	15.5	15
4. Slap-Down	Primary	196	219.3 (200.5)	2.675	2.68	11	11.5
	Secondary	236	250.06 (249.9)	2.86	2.90	10.3	10.0
5. Side Drop		182.6	191.35 (197.7)	2.75	2.98	11.8	12.0

Benchmark Analysis Conclusions

- LS-DYNA Benchmarking calculations completed successfully using the improved approach.
- No significant changes in results compared to earlier approach
- Benchmarks qualify LS-DYNA for determination of Rigid Body Deceleration and Impact Limiter Deformation.

Fuel Impact Attenuator (FIA)

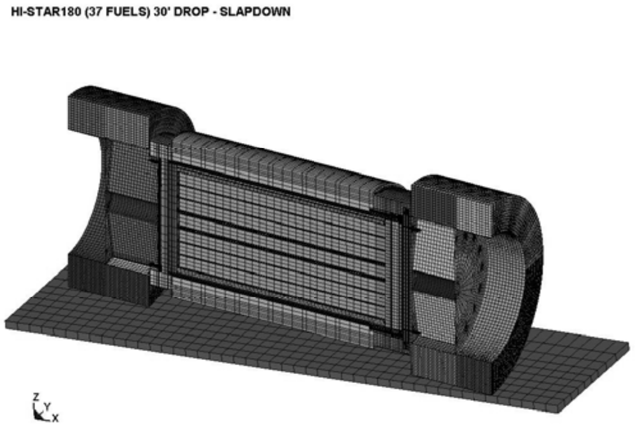
- Installed inside the HI-STAR 180 containment cavity
- Principal design functions are:
  - To ensure zero gap between fuel assembly and inner closure lid in a top end drop
  - To control the maximum gap between the fuel assembly and the containment baseplate
  - To attenuate the impact force on the containment baseplate during a bottom end drop

---

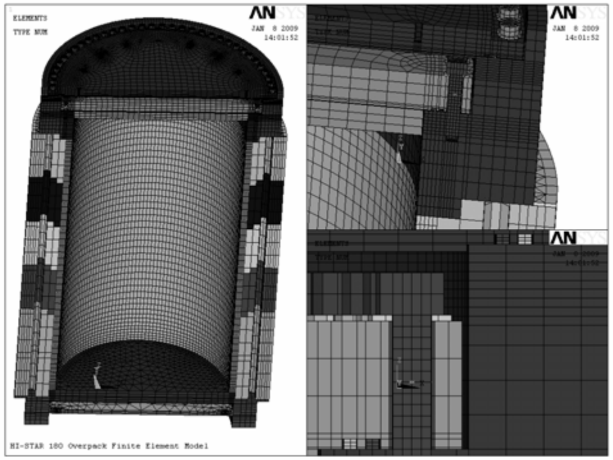
Drop Analyses for HI-STAR 180 Overview

- Peak rigid body decelerations for the HI-STAR 180 Package are calculated using LS-DYNA
  - LS-DYNA model of HI-STAR 180 impact limiters is consistent with the benchmark model
- LS-DYNA drop simulations conservatively assume maximum feasible internal gaps in both the axial and radial directions at the moment of impact
- Cask and Fuel Basket are qualified using bounding decelerations and static calculations performed in ANSYS

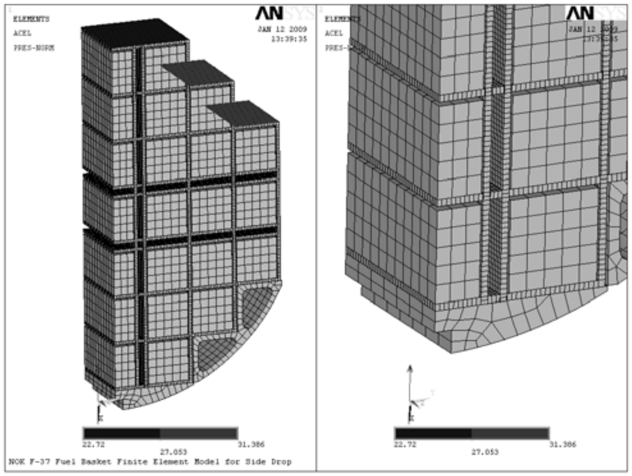
LS-DYNA Model of HI-STAR 180



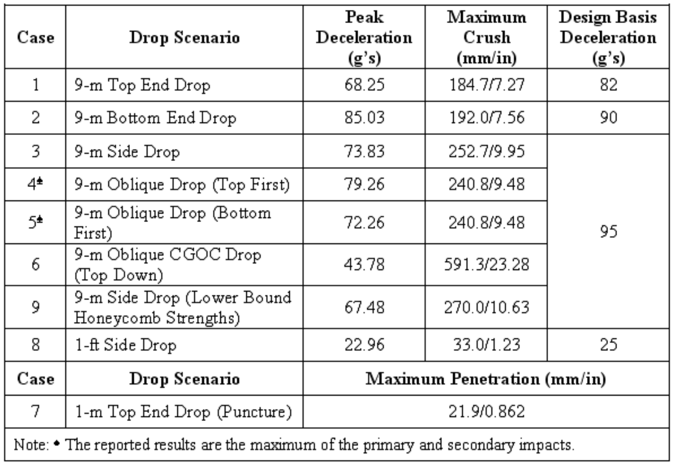
ANSYS Model of HI-STAR 180 Cask



ANSYS Model of F-37 Fuel Basket



LS-DYNA Analysis Results

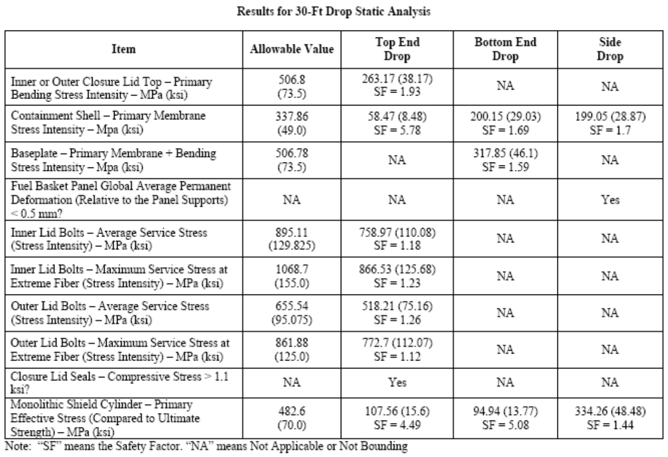


Case	Drop Scenario	Peak Deceleration (g's)	Maximum Crush (mm/in)	Design Basis Deceleration (g's)
1	9-m Top End Drop	68.25	184.7/7.27	82
2	9-m Bottom End Drop	85.03	192.0/7.56	90
3	9-m Side Drop	73.83	252.7/9.95	95
4♦	9-m Oblique Drop (Top First)	79.26	240.8/9.48	
5♦	9-m Oblique Drop (Bottom First)	72.26	240.8/9.48	
6	9-m Oblique CGOC Drop (Top Down)	43.78	591.3/23.28	
9	9-m Side Drop (Lower Bound Honeycomb Strengths)	67.48	270.0/10.63	
8	1-ft Side Drop	22.96	33.0/1.23	25

Case	Drop Scenario	Maximum Penetration (mm/in)
7	1-m Top End Drop (Puncture)	21.9/0.862

Note: ♦ The reported results are the maximum of the primary and secondary impacts.

ANSYS Static Analysis Results



Results for 30-Ft Drop Static Analysis

Item	Allowable Value	Top End Drop	Bottom End Drop	Side Drop
Inner or Outer Closure Lid Top – Primary Bending Stress Intensity – MPa (ksi)	506.8 (73.5)	263.17 (38.17) SF = 1.93	NA	NA
Containment Shell – Primary Membrane Stress Intensity – Mpa (ksi)	337.86 (49.0)	58.47 (8.48) SF = 5.78	200.15 (29.03) SF = 1.69	199.05 (28.87) SF = 1.7
Baseplate – Primary Membrane + Bending Stress Intensity – Mpa (ksi)	506.78 (73.5)	NA	317.85 (46.1) SF = 1.59	NA
Fuel Basket Panel Global Average Permanent Deformation (Relative to the Panel Supports) < 0.5 mm?	NA	NA	NA	Yes
Inner Lid Bolts – Average Service Stress (Stress Intensity) – MPa (ksi)	895.11 (129.825)	758.97 (110.08) SF = 1.18	NA	NA
Inner Lid Bolts – Maximum Service Stress at Extreme Fiber (Stress Intensity) – MPa (ksi)	1068.7 (155.0)	866.53 (125.68) SF = 1.23	NA	NA
Outer Lid Bolts – Average Service Stress (Stress Intensity) – MPa (ksi)	655.54 (95.075)	518.21 (75.16) SF = 1.26	NA	NA
Outer Lid Bolts – Maximum Service Stress at Extreme Fiber (Stress Intensity) – MPa (ksi)	861.88 (125.0)	772.7 (112.07) SF = 1.12	NA	NA
Closure Lid Seals – Compressive Stress > 1.1 ksi?	NA	Yes	NA	NA
Monolithic Shield Cylinder – Primary Effective Stress (Compared to Ultimate Strength) – MPa (ksi)	482.6 (70.0)	107.56 (15.6) SF = 4.49	94.94 (13.77) SF = 5.08	334.26 (48.48) SF = 1.44

Note: "SF" means the Safety Factor. "NA" means Not Applicable or Not Bounding

---

Drop Analyses for HI-STAR 180 Conclusions

- Primary stress intensities in the containment boundary components are below the ASME NB limits for Level D conditions.
- Closure lid bolts remain in the elastic stress range and the closure lid seals remain in a compressed state during the drop simulations.
- Monolithic shield surrounding the containment shell remains intact.
- Global average permanent deformation in Fuel Basket is less than the design basis limit of 0.5 mm.

HOLTEC
INTERNATIONAL

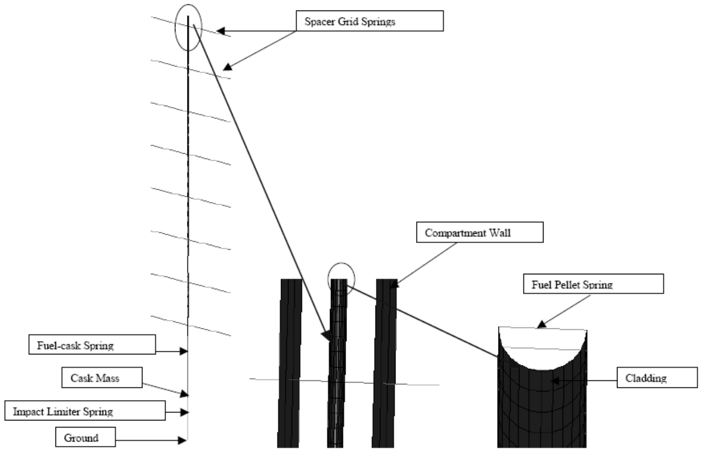
Fuel Rod Integrity Analysis

- Based on the methodology in NUREG-1864 Appendix C to calculate fuel rod strains during a cask end drop event
- Holtec model is benchmarked against results in Reference C.3 of NUREG-1864 Appendix C
  - Results agree within 5%
- Benchmarked model is modified to reflect HI-STAR 180 Design Basis Fuel and impact limiter performance

---

HOLTEC
INTERNATIONAL

Fuel Rod Integrity Analysis



HOLTEC
INTERNATIONAL

Fuel Rod Integrity Analysis

- The failure strain limit for high-burnup fuel is expected to range from 1.7% to 3.0% (per Reference C.3 of NUREG-1864 Appendix C)
- For the HI-STAR 180, the maximum calculated principal strain in the fuel rod due to a 9-meter end drop is 1.4%