SAND2007-4615P

Package Designs and Performance

KHNP Training Program
Module 5: Packaging and Transportation

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SAND 2007-

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Package Design

Inventory of existing packages

- Packages have been designed to fulfill many of the needs of the nuclear industry.
- These packages cover the spectrum from industrial packages, Type A, and Type B and range in size from a few inches on a side to many feet.
- When a need for transportation arises, the first step is always to look for an existing package that can be used.

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Some examples of packages

Information about existing packages

- The US NRC updates a publication containing all the certificates of compliance they issue on a periodic basis (NUREG-0383).
- An electronic database of US packages is available at www.rampac.com.
- A detailed listing of spent fuel transportation and storage casks is published by the JAI corporation, “Shipping and Storage Cask Data for Commercial Spent Nuclear Fuel”, March, 2005.

Spent fuel truck casks

Name	Weight (pounds)	Wall Thickness (inches)	Cavity Diameter (inches)	Impact Limiter	Design Heat Rejection (kW)	C of C
NAC-LWT	52,000	0.75,5.75,1.2	13.375	honeycomb	2.5	71-9225
NAC-1	49,000	0.31,6.63,1.25	13.5	balsa	11.5	71-9183
NLI-1/2*	49,250	0.5,2.125Pb, 2.75DU,0.875	13.375	balsa	10.6	71-9010
TN-FSV	47,000	1.12,3.44,1.5	18.0	wood	0.36	71-9253
FSV-1	47,600	0.67,3.5,0.91	17.7	yes	4.1	71-6346
GA-4	53,610	0.375,2.64,1.5	18.16 sq.	honeycomb	2.47	71-9226

Spent fuel rail casks – directly loaded

Name	Weight (pounds)	Wall Thickness (inches)	Cavity Diameter (inches)	Impact limiter	Design Heat Rejection (kW)	C of C
NAC-STC	250,000	1.5,3.7,2.65	71.0	wood	22.3	71-9235
125B	181,500	1.0,3.88,2.0	51.25	foam	0.7	71-9200
Excellox-6	194,000	N.A.	32.8	yes	N.A.	-
NLI-10/24	194,000	.75,6,2	45.0	balsa	70	71-9023
TN-24**	224,000	9.5	57.25	none	24	72-1005
REG	225,000	9.25	71.25	redwood	2.7	71-9206
BRP	215,000	9.62	64	redwood	3.1	71-9202
Castor-V/21**	234,000	15.0	60.1	none	28	72-1000

Spent fuel rail casks – canister

Name	Weight (pounds)	Wall Thickness (inches)	Cavity Diameter (inches)	Impact limiter	Design Heat Rejection (kW)	C of C
HI-STAR 100	278,000	9.5	68.75	honeycomb	20	71-9261
MP-187	271,000	1.0,4,2.0	68	foam	14	71-9255
TS-125	278,000	1.0,3.88,2.0	67	honeycomb	22.	71-9276
NAC UMS	255,000	2,2.75,2.8	67.6	wood	20	71-9270
MP-197	265,000	1.0,3.88,2.0	68	foam	16	71-9302

NUREG/CR-6672

- **This report, prepared by Sandia, is a generic risk assessment of the transportation of spent fuel.**
- **It examined the response of four types of spent fuel casks to a variety of accidents.**

Generic casks were used to represent all casks in this study.

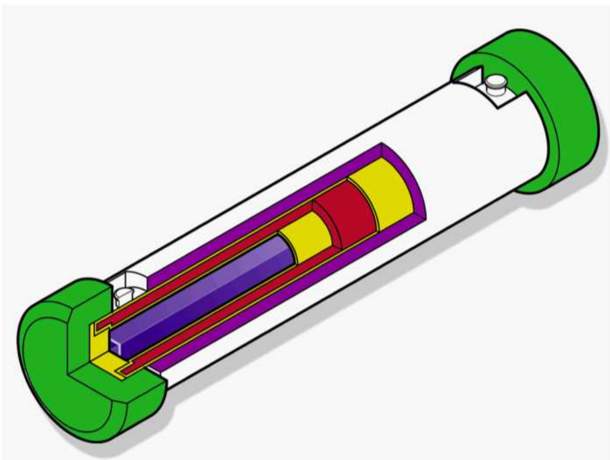
- **Generic casks are used to investigate the behavior of a broad packaging type.**
- **At least two casks of the type must be available to develop a generic model.**
- **No attempt is made to optimize the generic design for fuel capacity. It may not be physically possible to fit the number of assemblies used in the source term calculations within the cask cavity.**
- **There is no attempt to design the basket.**

Generic casks used in this study.

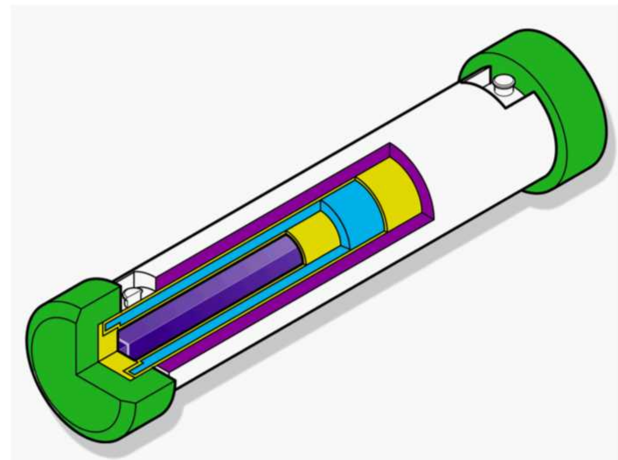
Name	Weight (pounds)	# of Assemblies PWR/BWR	Closure Bolts (no./size)	Wall Thickness (inches)	Outside Diameter (inches)	Cavity Diameter (inches)	Length (inches)
Steel-Lead-Steel-Truck	50,000	1/2	12/1”	0.5, 5.5, 1.0	27.5	13.5	205
Steel-DU-Steel Truck	50,000	3/7	12/1”	0.5, 3.5, 0.9	28	18	200
Steel-Lead-Steel Rail	225,000	24/52	24/1.75”	1.0, 4.5, 2.0	80	65	200
Monolithic Rail	224,000	24/52	24/1.75”	10	85	65	190

All casks were made of stainless steel, had impact limiters, and a 4.5” thick neutron shielding layer.

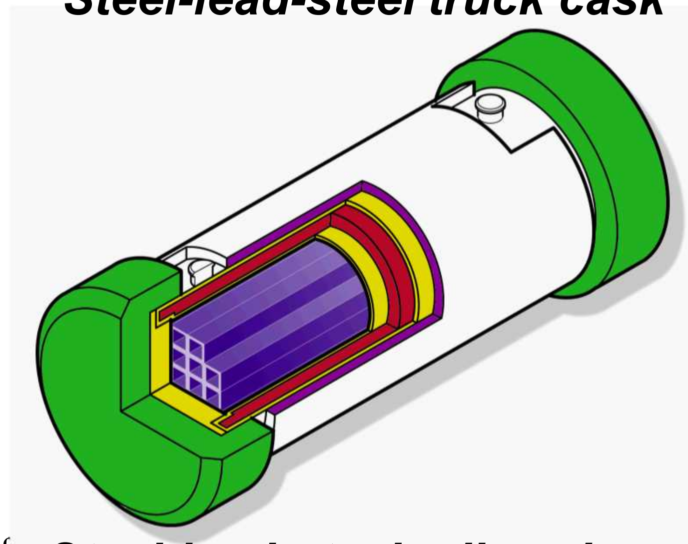
Generic casks used in this study.



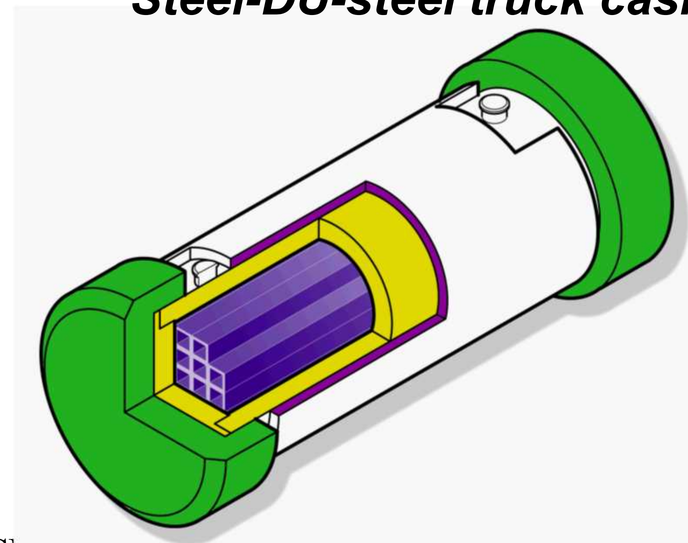
Steel-lead-steel truck cask



Steel-DU-steel truck cask



Steel-lead-steel rail cask



Monolithic steel rail cask

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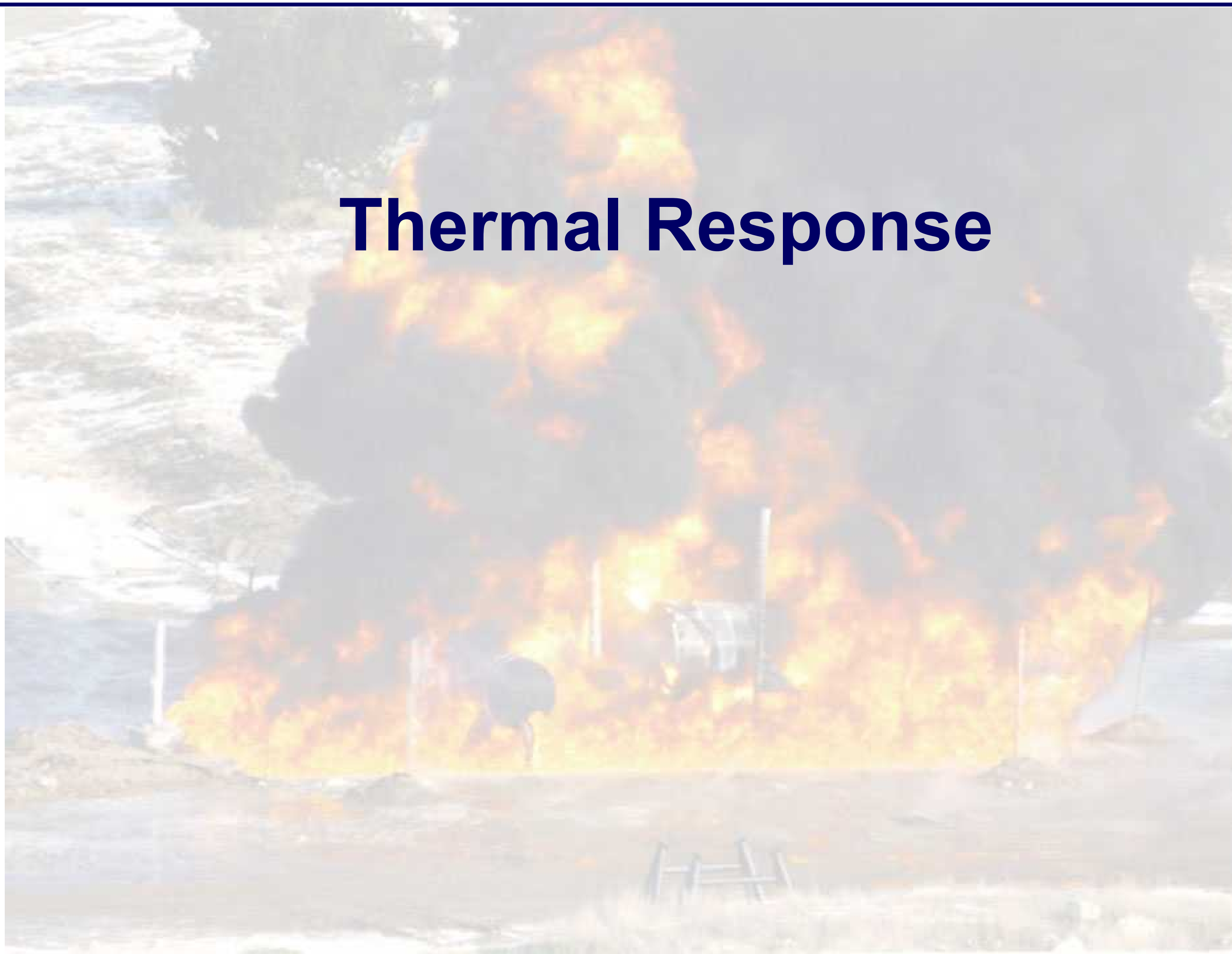
Assumptions for the closure bolts and seals.

- All of the generic casks are assumed to have a single closure lid with elastomeric o-ring seals inboard of the bolt location.
- Development of source terms with metallic seals would be possible using results from the impact and thermal analyses.
- Seals are in a face-seal configuration.
- The closure is recessed into the cask body.

Conservatism in generic cask selections.

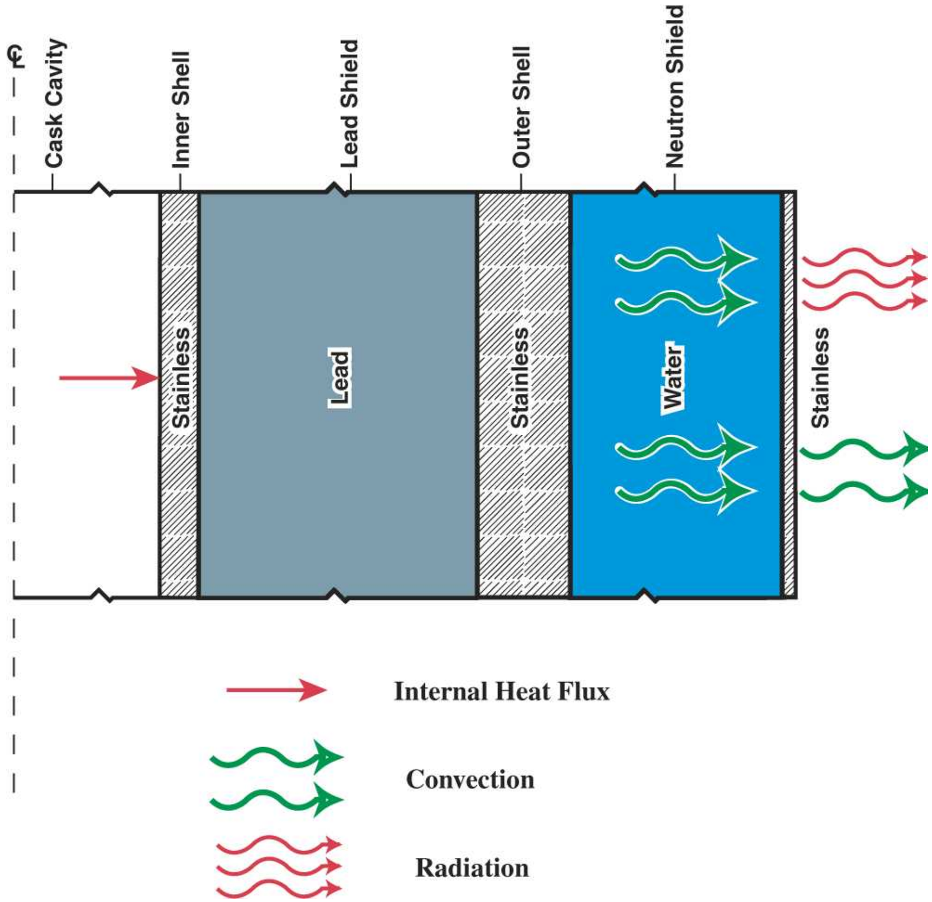
- All of the sandwich wall casks have shell thicknesses that are less than those of modern designs.
- Thicker shells result in smaller deformations, lower probabilities of puncture, and reduced lead slump.
- The generic rail casks have fewer bolts than modern designs.
- Increasing the number of bolts decreases the closure deformations.
- Generic cask designs were meant to be conservative, but that does not imply that casks with similar dimensions could not be approved for transportation.

Thermal Response



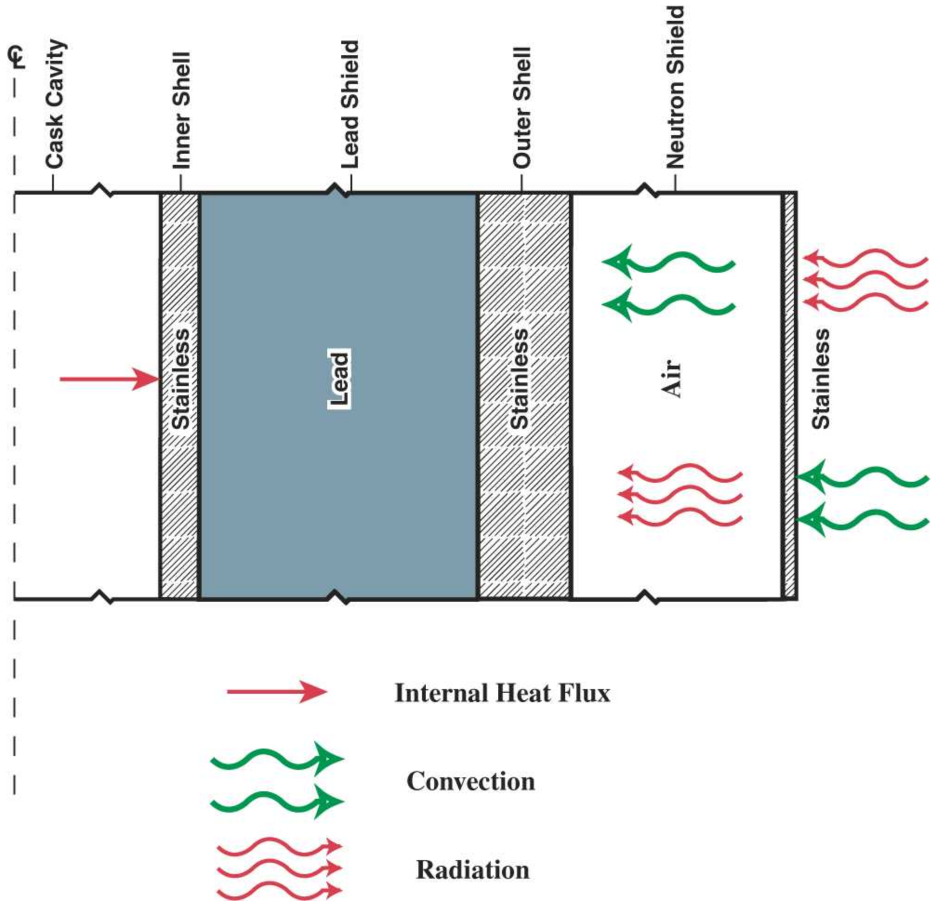
Thermal response was determined by 1-D axi-symmetric analyses.

Initial conditions are calculated using a steady state analysis.



Decay Heat Flux (W/m^2) For High Burnup 3-Yr Cooled Spent Fuel		
Cask	Fuel	
	PWR	BWR
Truck		
S-L-S	482	312
S-DU-S	1100	828
Rail		
S-L-S	2190	1532
Mono S	2289	1600

The fire response was determined with air in the neutron shield.



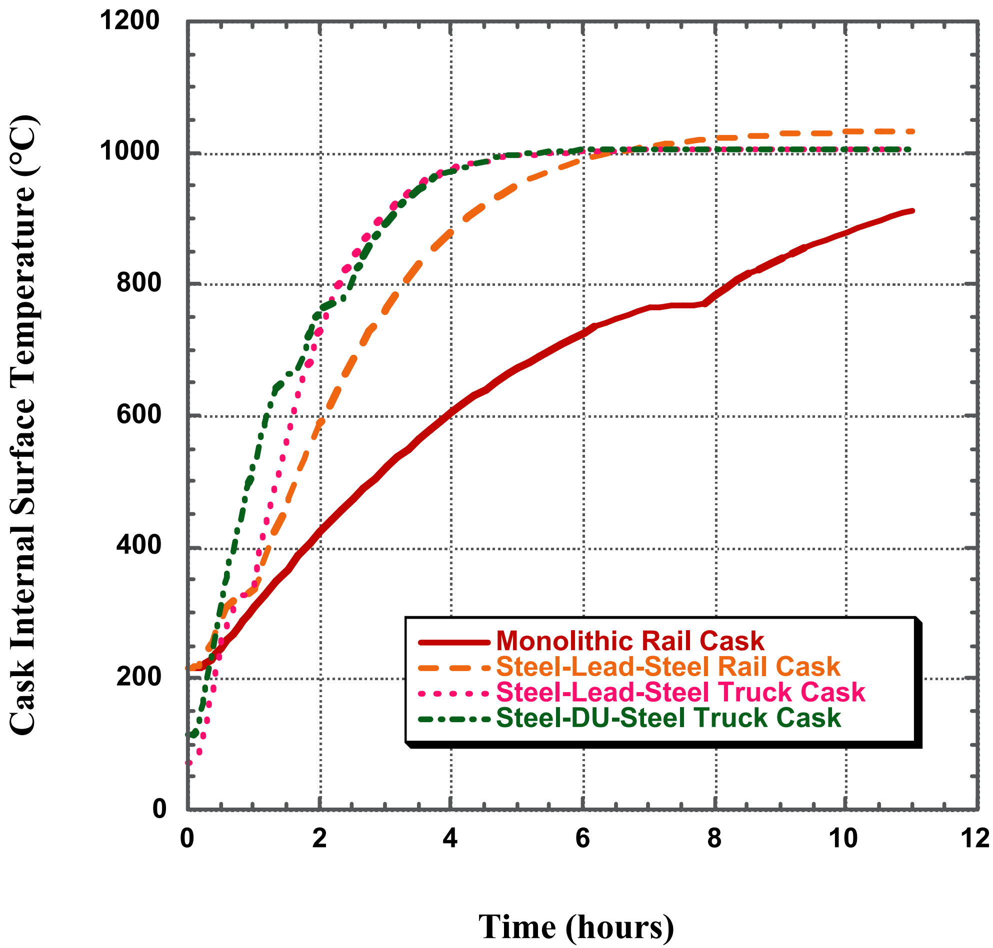
Water or organic moderator will drain, boil, or burn away soon after fire starts

There are characteristic temperatures and times in a risk analysis.

- **Characteristic Temperatures**
  - Elastomer seal failure — 350°C
  - Fuel rod burst rupture — 750°C
  - Average temperature pool fire — 1000°C

- **Characteristic Times**
  - Automobile fire — 10 minutes
  - Regulatory fire duration — 30 minutes
  - Truck tanker fire duration — 60 minutes
  - Rail tank car fire duration — 400 minutes

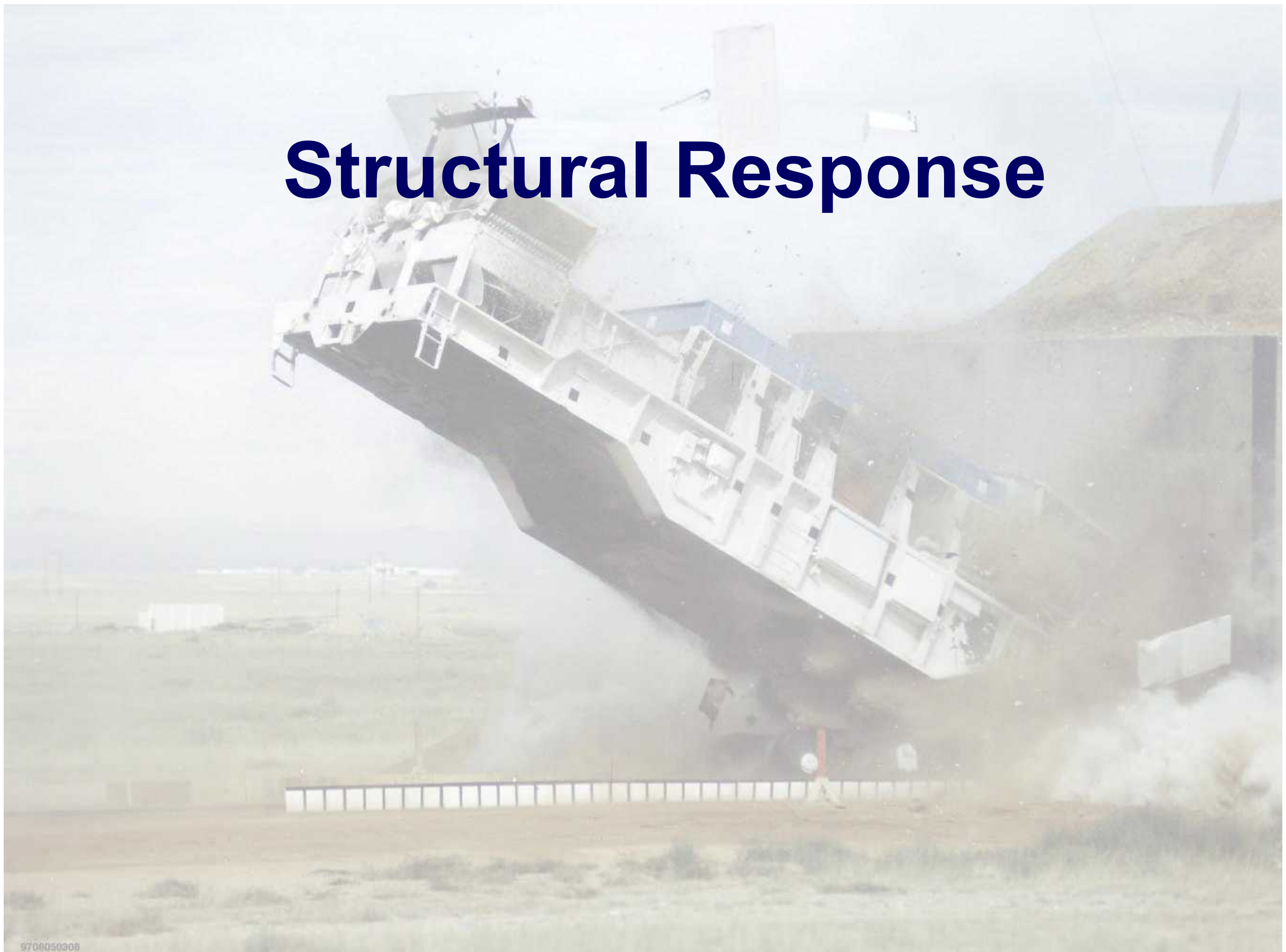
Internal surface temperature histories for generic casks in a 1000ºC fire.



Time to reach characteristic temperatures.

Times (hrs) Required To Heat Generic Cask Internal Surfaces to Characteristic Temperatures in a Long Duration Engulfing, Optically Dense, 1000°C Fire				
Temperature	Steel-Lead-Steel Truck	Steel-DU-Steel Truck	Steel-Lead-Steel Rail	Monolithic Steel Rail
350 °C	1.1	0.7	1.4	2.4
750°C	2.1	2.1	3.4	6.7
1000°C	6.4	7.1	8.6	>11

Structural Response



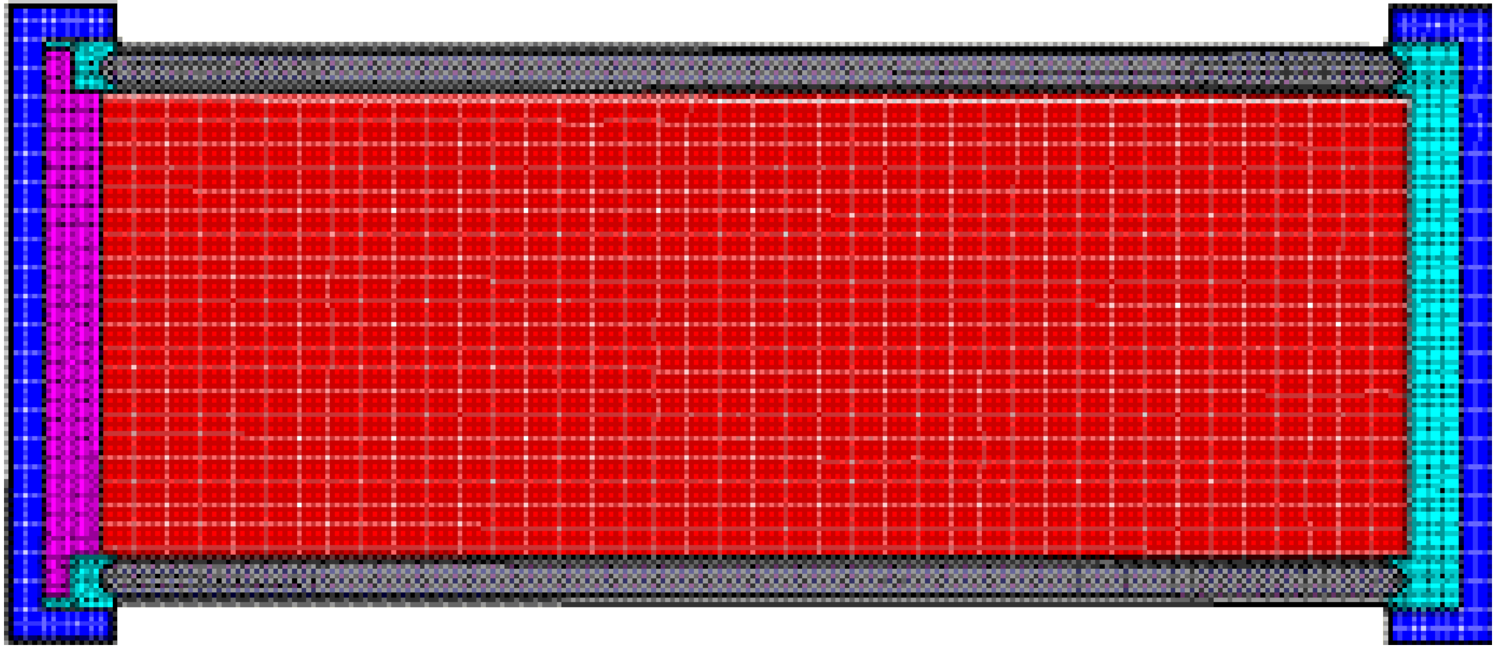
Response to impacts was determined by 3D finite element analyses.

- **All analyses are for impacts onto rigid targets.**
- **The impact limiter was assumed to be crushed to lock-up before the analyses start. (The actual energy absorbed in the collision is higher than the analysis predicts.)**
- **Impact limiters were held in place only by inertia.**
- **Sandwich wall casks were modeled with zero-thickness shell elements (incorrect contact location).**
- **Basket and spent-fuel were treated as homogenized, no attempts is made to model fuel response.**

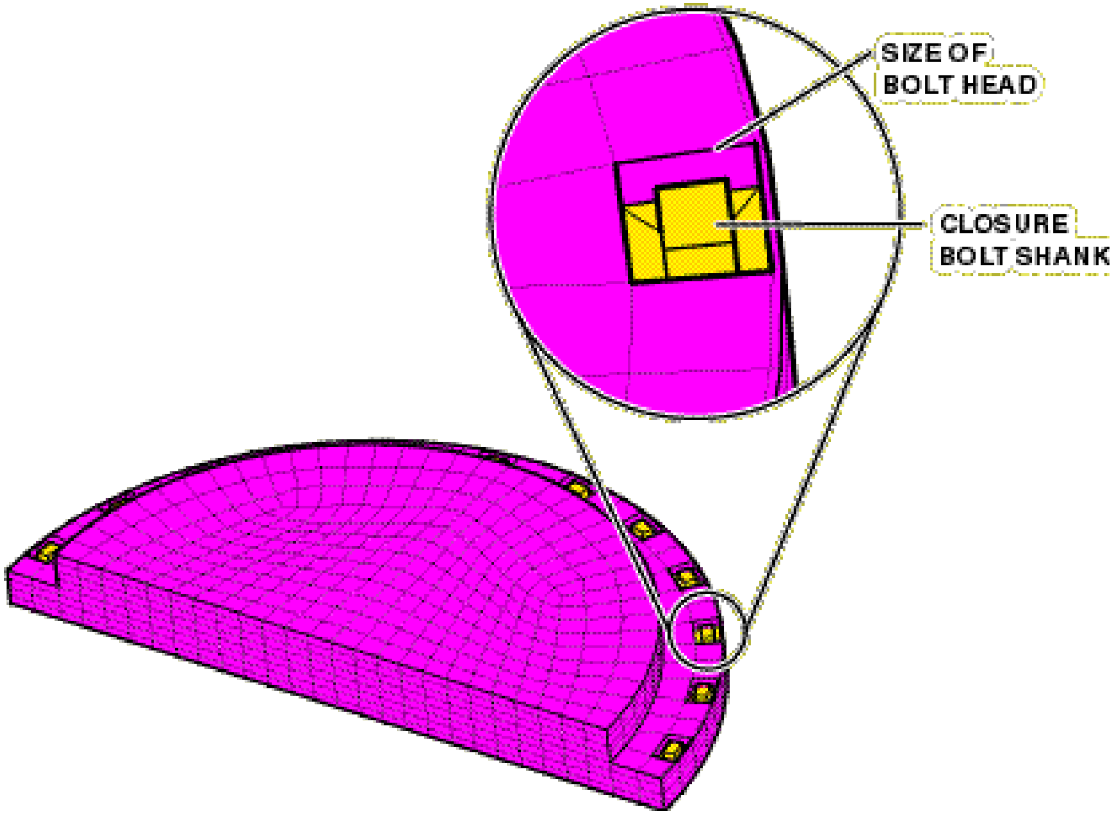
Assumptions for finite element analyses.

- Neutron shielding and shell were not included.
- Density of contents was adjusted to achieve the desired total weight.
- Seals were not modeled.
- Bolts were explicitly included in the model.
- All impacts were assumed to be normal to the unyielding target.
- Impact velocities of 30, 60, 90, and 120 MPH were modeled (equivalent velocities of 42, 67, 95, and 124 MPH).

Finite element model for the generic monolithic steel rail cask.



Modeling of the closure bolts.



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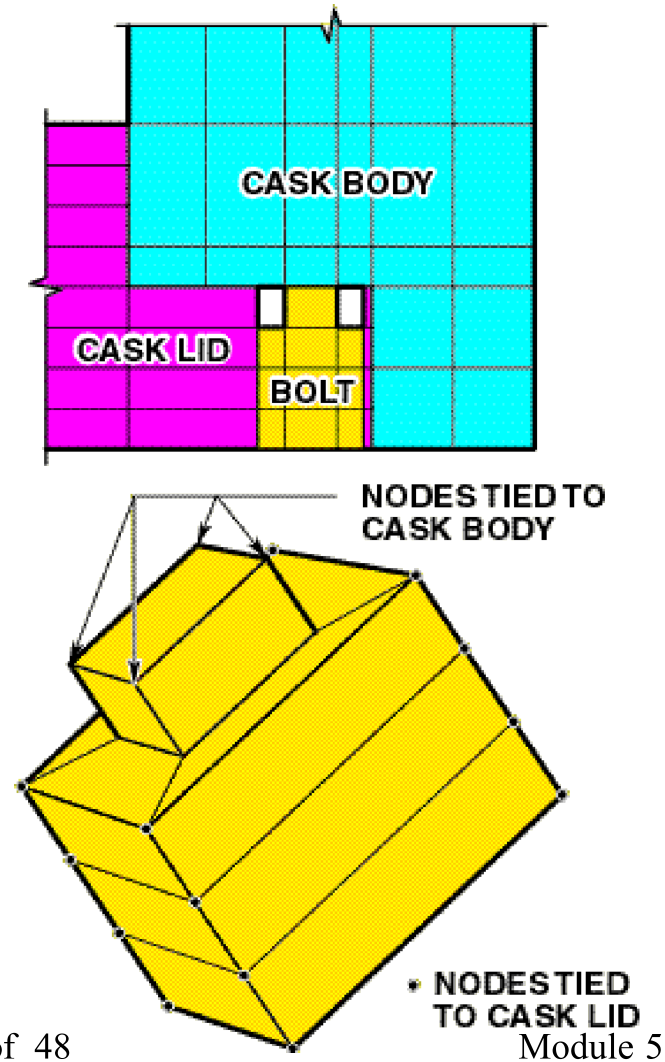
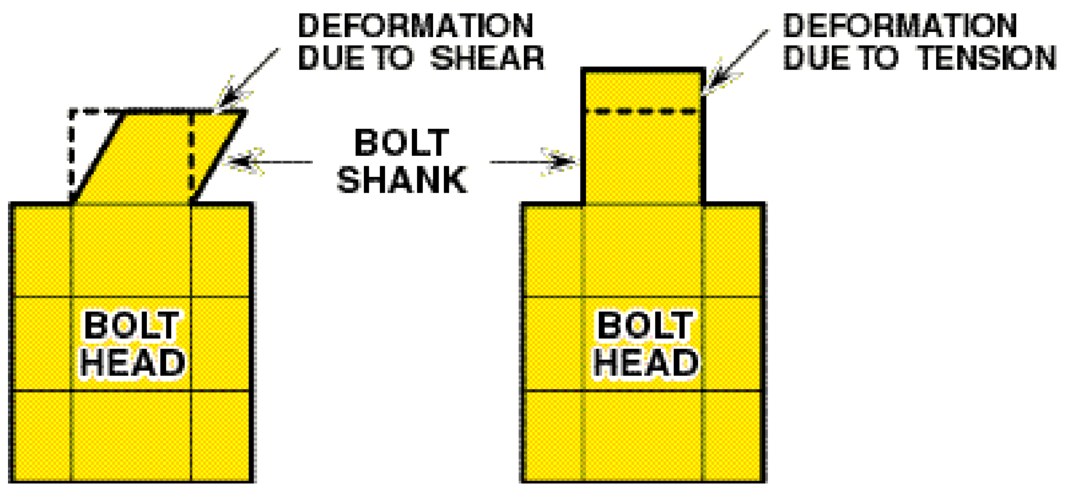
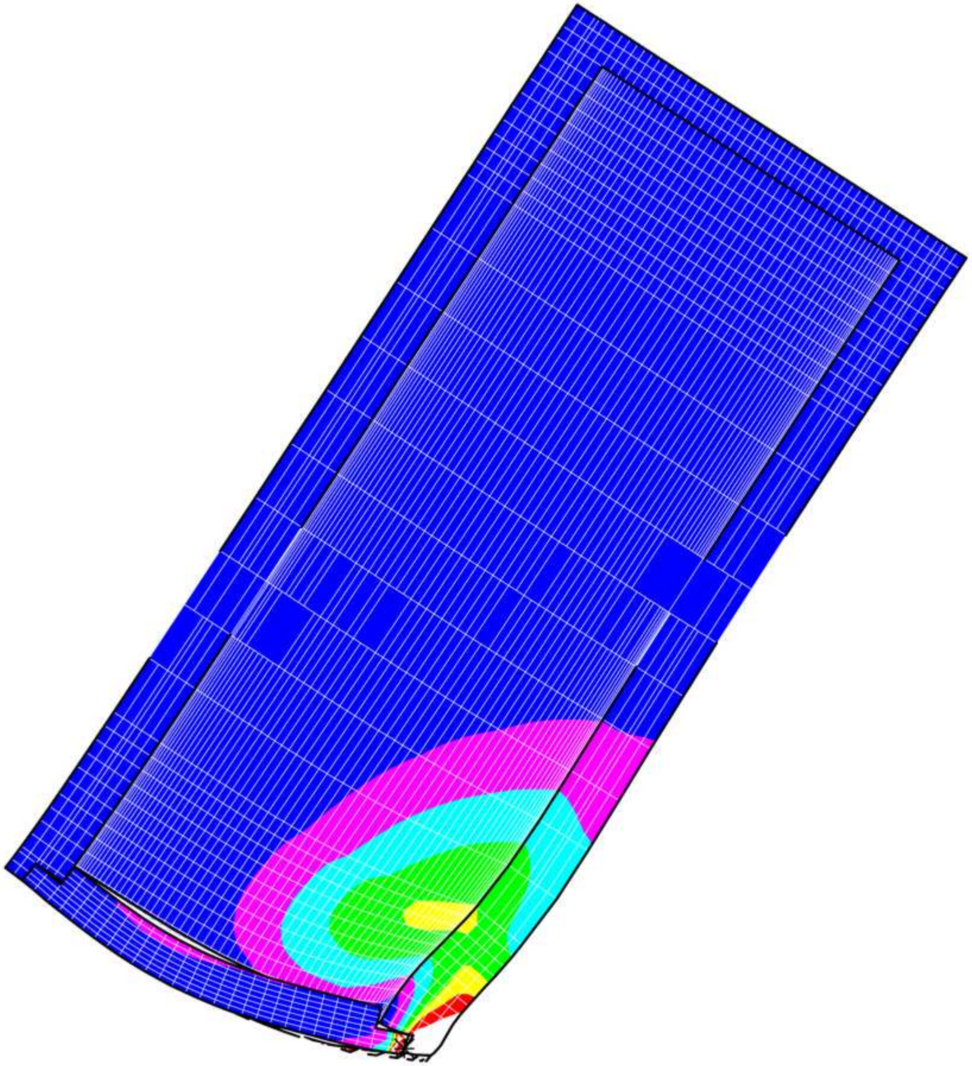
Mechanics of bolt response.





Monolithic steel rail cask following a 120 MPH corner impact.



Loss of containment can occur if the body strains are too high.

Maximum plastic strain on the inside of the monolithic steel rail cask.

Corner Impact		End Impact		Side Impact	
Speed	**Strain**	**Speed**	**Strain**	**Speed**	**Strain**
30 mph	<10 %	30 mph	<2 %	30 mph	<10 %
60 mph	<20 %	60 mph	<5 %	60 mph	<30 %
90 mph	<30 %	90 mph	<10 %	90 mph	<50 %
120 mph	<50 %	120 mph	<17 %	120 mph	<60 %

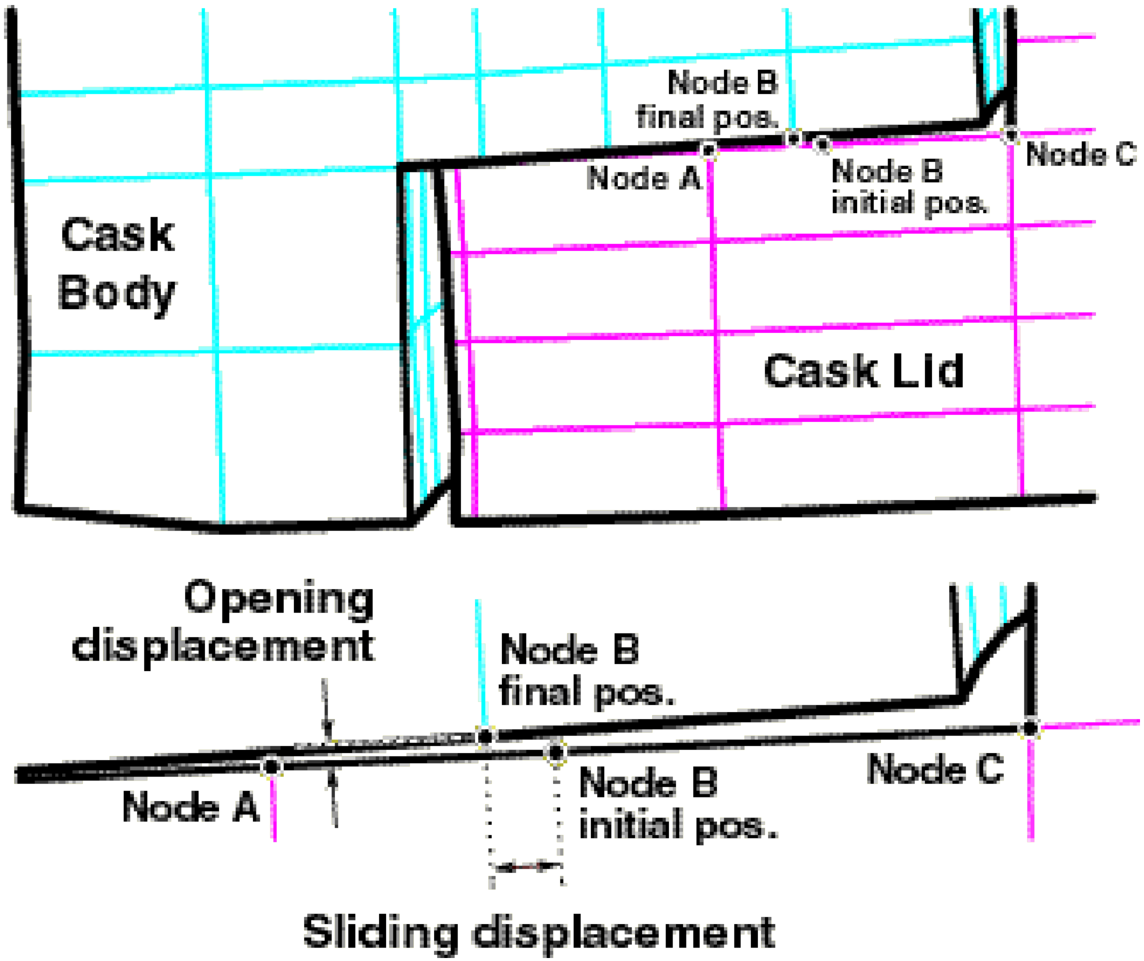
True strain at failure for stainless steel is larger than 60%, so there will be no failure of the body.

Loss of containment can occur if the bolts fail.

Maximum true strain in the closure bolts for the monolithic steel rail cask.

Corner Impact		End Impact		Side Impact	
Speed	**Strain**	**Speed**	**Strain**	**Speed**	**Strain**
30 mph	14 %	30 mph	4 %	30 mph	15 %
60 mph	*40 %*	60 mph	14 %	*60 mph*	*32 %*
90 mph	**67 %**	*90 mph*	*35 %*	**90 mph**	**104 %**
120 mph	**80 %**	**120 mph**	**58 %**	**120 mph**	**170 %**

Seal region displacements for the 90-mph end impact of the monolithic steel rail cask.



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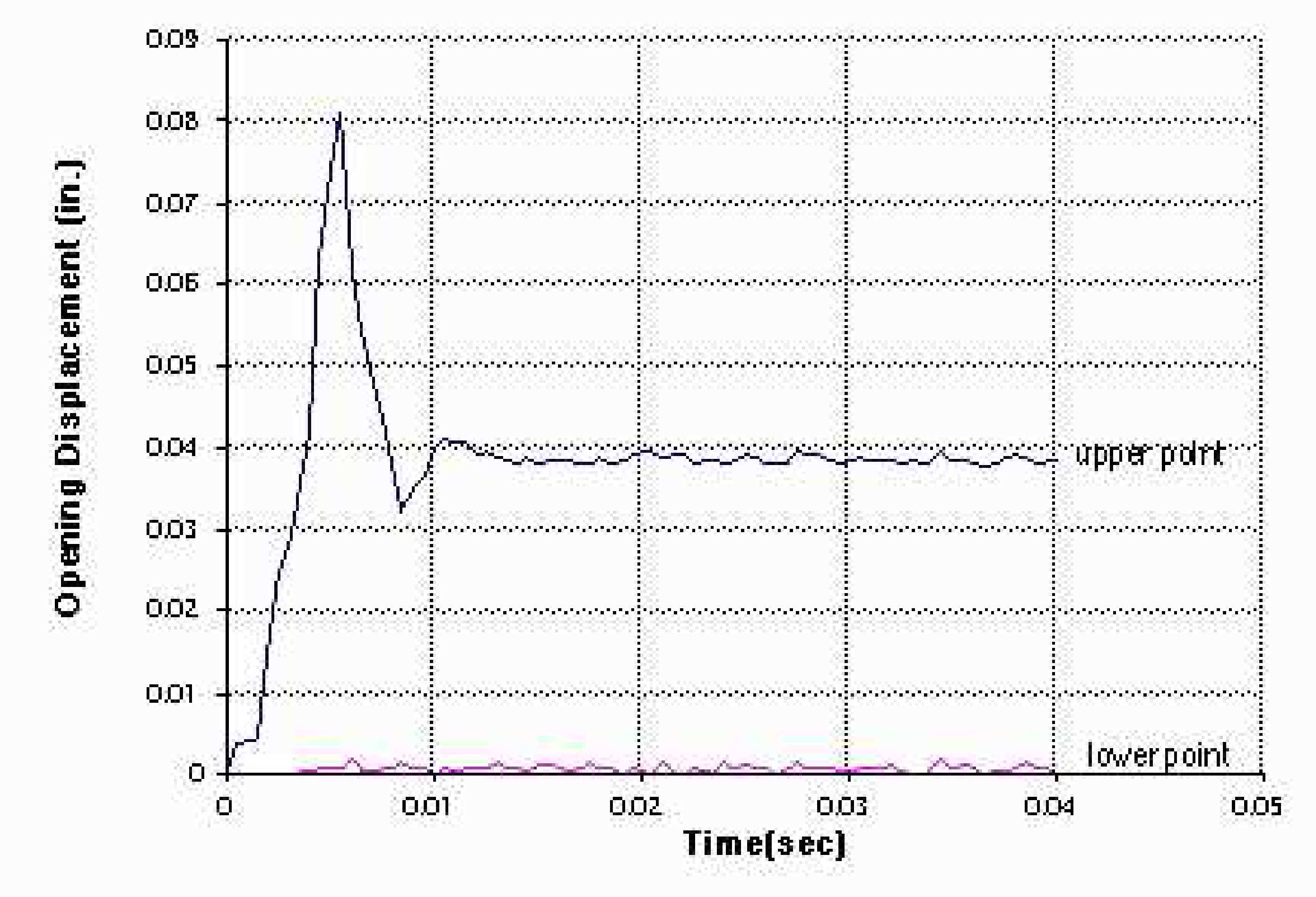
Loss of containment can occur if the closure displacements are too large.

Closure displacements (in inches) at the seal location at the end of the analysis for the monolithic steel rail cask.

Impact velocity (mph)	Corner Impact		End Impact		Side Impact	
	Opening	Sliding	Opening	Sliding	Opening	Sliding
30	0.004	0.20	0.01-0.05	0.04-0.05	0.01	0.01
60	0.10	0.36	0.04-0.12	0.09-0.10	0.04	0.01
90	0.22	0.48	0.03-0.13	0.38-0.39	0.08	0.09
120	0.44	0.59	0.09-0.16	0.668	0.12	-

O-ring will not fail unless the opening is greater than 0.10 inches.

Lid opening displacement for the 60-mph side impact of the monolithic steel rail cask.



Upper point is at the top of the cask, lower point at the bottom.

Calculated monolithic steel rail cask leak path cross-sectional areas.

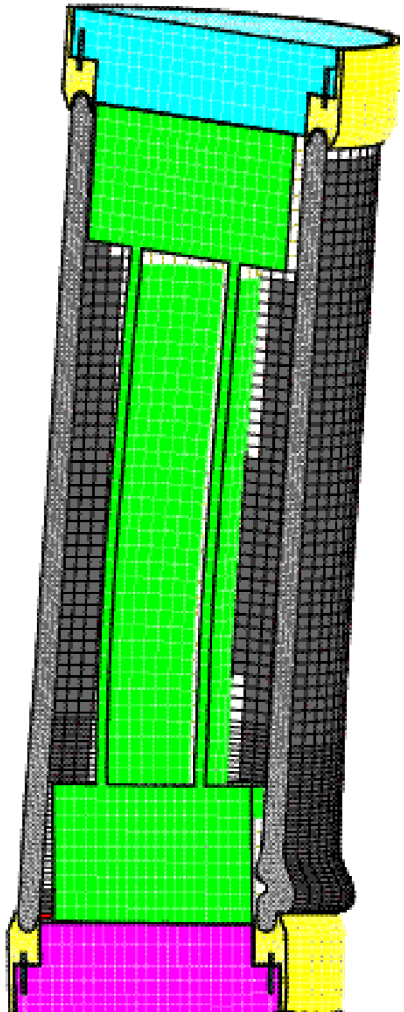
Velocity (mph)	Orientation	Opening Displacement (inches)	Opening Width (inches)	Leak Path Area (in^2)
60	Corner	0.103	6.38	0.00028
90	Corner	0.216	12.76	0.40
120	Corner	0.439	19.14	2.5
120	Side	0.123	6.38	0.014

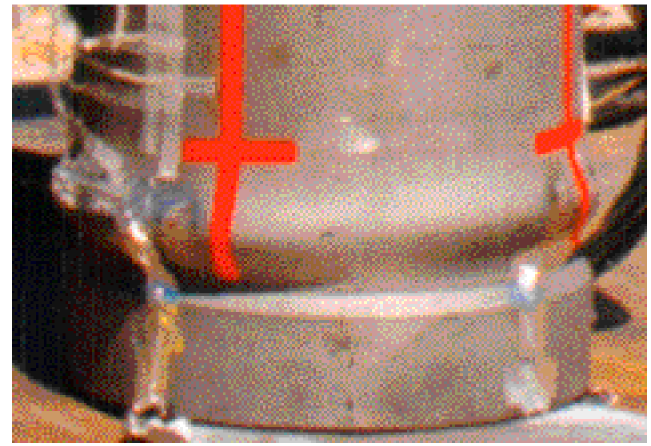
- O-ring compliance is assumed to be 0.100 inches.
- Leak-path cross sections are assumed to be a triangle with height and width from the table. The area from the lower 0.100 inches of the triangle are truncated by o-ring compliance

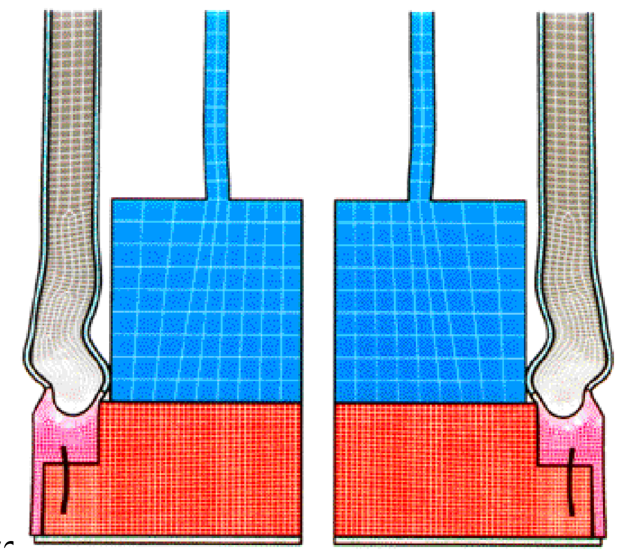
Benchmarking of finite element calculations.

- **The accuracy of the results of the finite element analyses was validated by comparison with test results.**
- **During the early 1990s Sandia performed a series of tests and finite element analyses with a test unit that closely approximated a 1/3-scale steel-lead-steel rail cask.**
- **The finite element models used in these analyses were similar to those used in that program.**

Comparison of analysis and test results.







Impacts onto yielding targets.

- To use the results of the finite element analyses in a risk assessment, there must be a method of correlating the calculated results from impacts onto rigid targets to impacts onto yielding targets that represent surfaces likely to be impacted by the cask.
- Three types of real targets were examined: soil, concrete, and hard rock.
- The soil was assumed to be hard desert soil like that found around Albuquerque, NM.
- Concrete was assumed to be a 9-inch thick concrete roadway.
- Hard rock was assumed to be unfractured granite.

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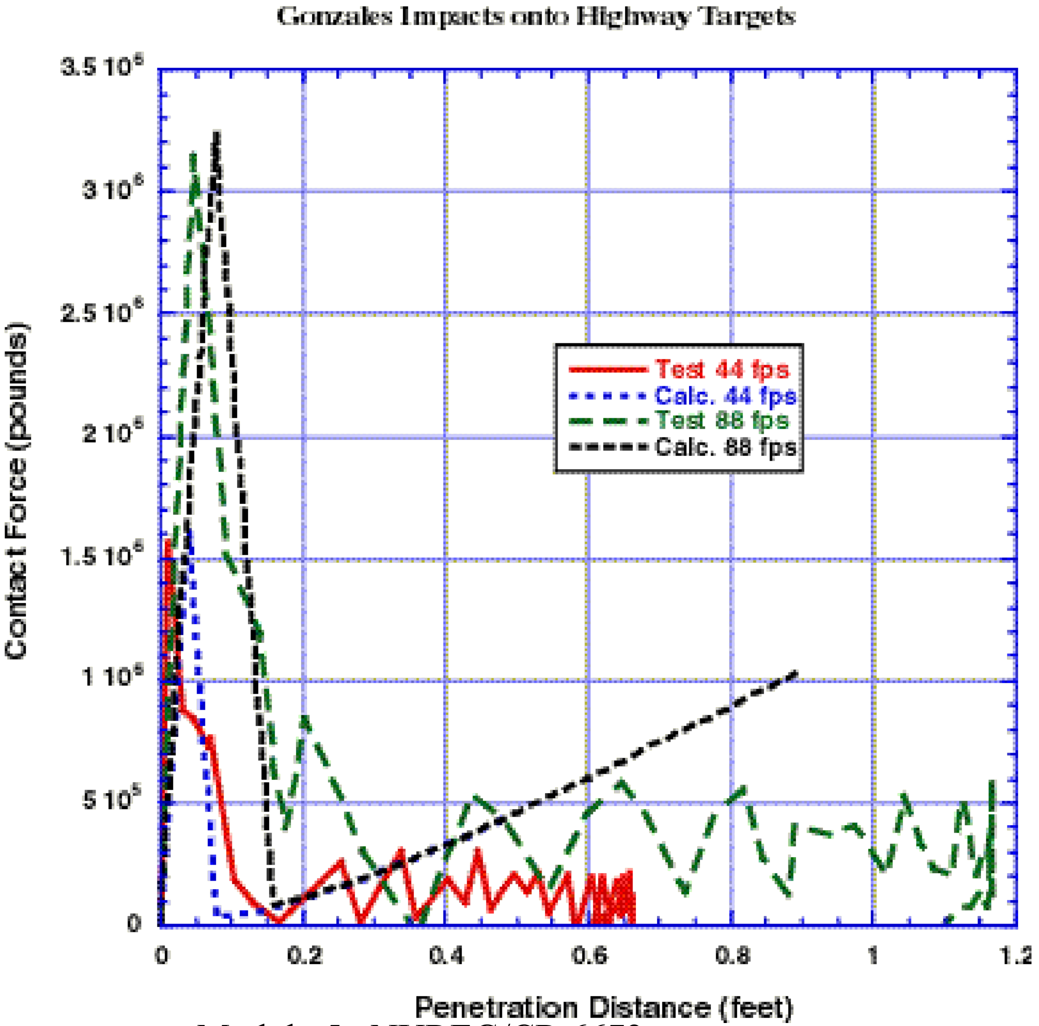
Method used for deriving equivalent velocities.

- An impact onto a yielding target was equivalent to the impact onto a rigid target if the contact force between the cask and the target were equal.
- Force-deflection curves were generated for each cask analysis from the output of the finite element calculations.
- Force-deflection curves were generated for each target based upon empirical data, engineering principles, and target properties.

Comparison between test data and empirical representation.



Peak contact forces from impacts onto rigid targets for the monolithic steel cask.

Corner Impact		End Impact		Side Impact	
Speed	**Force (pounds)**	**Speed**	**Force (pounds)**	**Speed**	**Force (pounds)**
30 mph	21E6	30 mph	38E6	30 mph	22E6
60 mph	39E6	60 mph	95E6	60 mph	54E6
90 mph	58E6	90 mph	110E6	90 mph	95E6
120 mph	75E6	120 mph	130E6	120 mph	110E6

Real target equivalent velocities (mph) for the monolithic steel rail cask.

Target/Orientation		Rigid Target Velocity			
		30 mph w/o limiter	60 mph w/o limiter	90 mph w/o limiter	120 mph w/o limiter
Soil	End	>150	>>150	>>150	>>150
	Side	92	>150	>>150	>>150
	Corner	111	>150	>>150	>>150
Concrete Slab	End	>150	>>150	>>150	>>150
	Side	104	>>150	>>150	>>150
	Corner	>>150	>>150	>>150	>>150

Response of fuel rods to regulatory impacts.

- **The response of the fuel rods to regulatory impacts will be a function of the strains in the rod and the strain required to cause the rod to fail.**
- **The strain required to cause rod failure is a strong function of the amount of burn-up for the assembly.**
- **For a generic risk assessment, a method of determining an average fuel rod response is needed.**

Peak strains in fuel rods from a 100 G side impact.

Fraction of PWR Rods	Peak Strain %	Fraction of BWR Rods	Peak Strain %
1/15	3.3	1/7	1.1
2/15	2.9	2/7	1.0
3/15	2.2	3/7	0.85
4/15	2.0	4/7	0.83
5/15	1.7	5/7	0.78
6/15	1.5	6/7	0.66
7/15	1.4	7/7	0.62
8/15	1.4		
9/15	1.4		
10/15	1.3		
11/15	1.3		
12/15	1.2		
13/15	1.2		
14/15	1.1		
15/15	1.1		

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Peak accelerations from rigid target impacts for the monolithic steel rail cask.

Orientation	30 mph	60 mph	90 mph	120 mph
Corner	93.8	174.2	259.1	335.1
End	169.8	424.4	513.8	580.8
Side	98.3	241.3	424.4	491.5

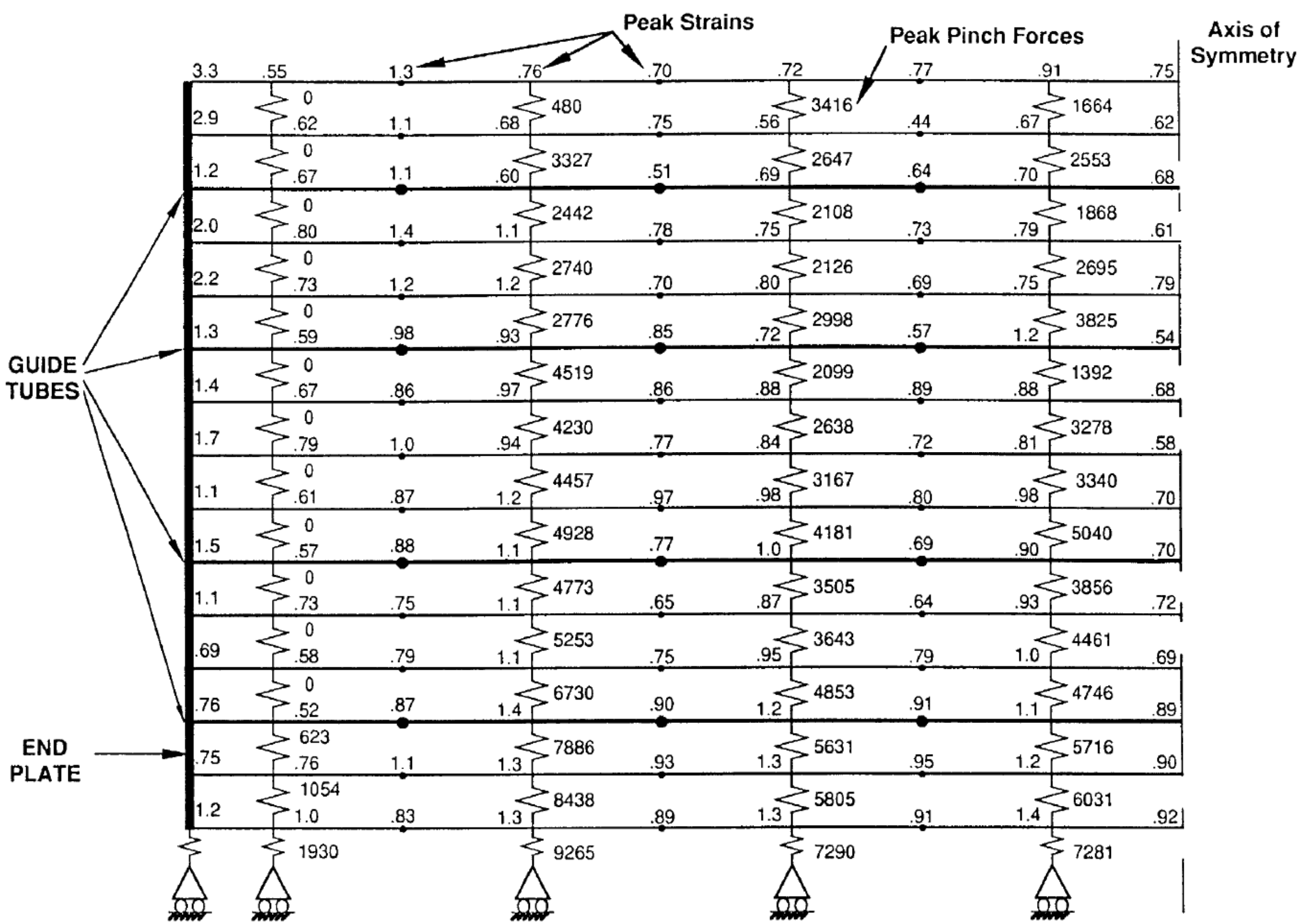
Average burn-up of current and future spent fuel.

- **1994 spent fuel inventory contained 49% low burnup (0-20 GWDt/MTU), 49% intermediate burnup (30-45 GWDt/MTU), 2% intermediate to high burnup (45-50 GWDt/MTU), and only 0.2% high burnup (50-60 GWDt/MTU) spent fuel.**
- **1998 data suggests that about 25% of PWRs and 20% of BWRs are producing high burnup spent fuel and thus about 50% of all reactors will be producing high burnup fuel by 2002.**
- **Assume all reactors operate for 40 yrs; all produce average burnup spent fuel from 1995 through 2001 and high burnup fuel thereafter.**

Mass weighted sum of burnup dependent strain failure levels.

GWDt/MTU	MTU	Strain Failure Criterion	
		Range	Weighted
0-25	8437	8	0.88
25-30	6177	7	0.56
30-35	6815	6	0.53
35-40	5149	5	0.34
40-45	2570	4	0.13
45-50	636	3	0.02
50-55	44	2	0.00
55-60	5	1	0.00
Future Avg. Burnup	13,181	4	0.69
Future High Burnup	33,600	1	0.44
Total	76,614	Sum	3.60

Strains in PWR assembly from 100G impact



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Failure of rods

- **The strains from the 100G impact were scaled by the acceleration level (assumed that strain in rods was linear with acceleration).**
- **The number of rods with strains above the failure level were counted.**
- **The fuel failure fraction was the number of failed rods/number of rods.**
- **Source term for release also depends on the response of the fuel ceramic.**
- **Release fraction depends on the hole size in the cask.**

Summary

- **There are a large number of existing packages.**
- **The response of these packages to accident events can be determined by finite element analysis.**
- **Most packages have a large safety margin, so they will not fail even in many extra-regulatory accidents.**