Legal Weight Truck Cask Response to Regulatory Format Thermal Events

Part 1: Fuel Cladding
(Part 2: Containment Seal)

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OBJECTIVES

Simulate the response of intact and damaged versions of the GA-4 Legal Weight Truck Cask to a range of regulatory format thermal events.

Determine the minimum fire duration which causes the spent fuel cladding temperature to reach a containment-integrity limit for a range of fire temperatures.

Determine the sensitivity of the critical duration versus fire temperature performance envelopes to variations in the modeling assumptions (fuel clad containment-integrity temperature limit, aluminum melt model).
Regulatory Format Fire/Post-Fire Event

Thermal Boundary Conditions
Extension of the Regulatory Fire Test

Normal conditions of transportation
Still air, $38^\circ C$.
Solar Heat Flux, $388 \text{ W/m}^2$.
Steady State

Fire period:
Fully-engulfing thermal radiation environment
Fire emissivity: 0.9.
Cask skin absorptivity: 0.8.
Fire temperature: $T_{\text{fire}} = 600$ to $1600^\circ C$
Fire duration: $D_{\text{fire}}$
(regulatory fire: $T_{\text{fire}} = 800^\circ C$, $D_{\text{fire}} = 0.5 \text{ hr}$)

Post-fire
Normal Conditions of Transportation
GA-4 Legal Weight Truck Cask
Carries 4 Spent PWR Assemblies
27.5 tons

Consider two versions:
Intact
No Neutron Shield
FINITE ELEMENT MODEL
Quarter Section

Intact Model

Polypropylene - 1% Boron Neutron Shield

Aluminum Support Structure

SS Skin

SS Body

DU Gamma Shield

SS Liner

He Gap

SS/B₄C Support Structure

Fuel


Damaged Model

no neutron shield
MATERIAL PROPERTIES

Cask:
Primary:
GA-4 Safety Analysis Report
Effective values designed for 10-CFR.71
evaluation (T_{fire} = 800\degree C, D_{fire} = 0.5 \text{ hr}).

Secondary:
High Temp, Sanga Burnt.
Aluminum melt model. (500\degree C)

Fuel Region:
Effective thermal conductivity:
Manteufel and Todreas (1994, analytical model)
Conduction, convection, radiation.

Zircaloy cladding containment-integrity temp limit:
Not well defined.
Primary: T_{critical} = 740\degree C (Sandoval et al. 1986)
Secondary: T_{critical} = 593\degree C (MPC CDR, 1993)
THERMAL SIMULATIONS
Normal Conditions of Transportation

Color-Filled Temperature Map

Maximum temperature is near fuel region center:
\[ T_{\text{max}} = 142^\circ \text{C}. \]
If aluminum N.S. Support Structures are removed:
\[ T_{\text{max}} = 307^\circ \text{C}. \]

New Req. For Aerial

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Regulatory Fire/Post-Fire Test

\[ T_{\text{fire}} = 800^0\text{C}, \quad D_{\text{fire}} = 0.5 \text{ hr} \]

Center and Corner Fuel Temperature versus Time

Corner responds first.

\[ T_{\text{max}} = 200^0\text{C}, \quad \text{at fuel region center.} \]

7.1 hr after fire is extinguished.

Well below 740^0\text{C}.

Increase fire duration:

Find critical duration which gives \( T_{\text{max}} = 740^0\text{C} \).
Critical Fire Duration

\( T_{\text{fire}} = 800^\circ C \)

\( T_{\text{fuel}, \text{max}} \) versus \( D_{\text{fire}} \)

Max fuel region temperature increases with \( D_{\text{fire}} \), for \( D_{\text{fire}} < 30 \) hr.

Critical duration for \( T_{\text{fire}} = 800^\circ C \) fire: \( D_{\text{critical}} = 10.4 \) hour.

Repeat for other fire temperatures and for damaged cask, find \( D_{\text{critical}} \) versus \( T_{\text{fire}} \).
The fuel will not reach its critical temperature in fires with temperatures below $715^\circ C$, no matter how long they last.

Critical duration for $T_{fire} = 1300^\circ C$
- Intact: 3.0 hr
- Damaged: 17 min

N.S. provides significant cladding protection in high temperature fires.
Variation of Critical Cladding Temperature

$$T_{critical} = 593^\circ C :$$

Reduces asymptotic fire temperature by 155$^\circ$C ($740^\circ$C - 593$^\circ$C = 147$^\circ$C).

Reduces critical duration by a 30% for fire temperatures above 800$^\circ$C.

A margin of safety is observed between the regulatory test and all the calculated performance envelopes.
ALUMINUM MELT MODEL
Thermal Conductivity versus Temperature

![Graph showing thermal conductivity versus temperature with two regions: No-Melt Model and Melt Model.]

This model:
Assume the thermal conductivity halves at 600°C.
Ignores phase change heat of fusion.
Melting decreases the heat flow at high temperatures. Increases the critical fire duration by 40% for $T_{\text{fire}} > 1000^0\text{C}$.

No-Melting Model is more conservative.
CONCLUSIONS

The cladding protection of the GA-4 is significantly affected by the loss of the neutron shield, especially for high temperature fires.

Reducing the critical fuel cladding temperature from $740^\circ C$ to $593^\circ C$ decreases the asymptotic fire temperature by $155^\circ C$, and decreases the critical duration by 30% for fire temperatures above $800^\circ C$.

Neutron shield melting increases the cladding protection compared to the no-melt model.
Performance Envelopes

Serve to address:
1) Margin of safety issues.
2) Sensitivity of results to modeling assumptions.
3) Relative performance of different packages.

Performance envelope evaluation requires knowledge of material behavior for a wider range of conditions than is needed for 10-CFR.71 evaluations.
MPC RAIL PACKAGE

MPC
125-ton, 21 PWR

GA-4
27.5-ton, 4 PWR

We expect larger packages to exhibit:
Higher steady-state fuel temperature.
Slower transient response.
Comparison of MPC and GA-4
Intact Performance Envelopes
(Greiner et al. *PATRAM* 1995)

Critical Duration for $T_{\text{fire}} = 1300^0\text{C}$
GA-4: 3.0 hr
MPC: 8.1 hr (2.7 times slower)

Asymptotic Fire Temperatures:
GA-4: $715^0\text{C}$
MPC: $660^0\text{C}$

GA-4 provides longer lasting protection for fire
temperatures below $730^0\text{C}$. 
Regulatory Format Thermal Conditions

Useful for comparing the performance of intact and damaged packages for a range of modeling assumptions.

The fully-engulfing assumption, as well as the assumed environment emissivity and cask skin absorptivity may be substantially different from actual transportation accidents.

Caution should be exercised before comparing the results of this work to (often incomplete) historical accident data.