Response of a

Spent Nuclear Fuel Transportation

Package to

Regulatory Format Thermal Events

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OBJECTIVES

Simulate the response of intact and damaged versions of the 125-ton MPC rail package conceptual design to a range of regulatory format thermal events.

Determine the minimum fire duration which causes the spent fuel cladding temperature to a reach 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 fuel region effective thermal conductivity and containment-integrity temperature limits.
125-ton MPC Rail Package

Multi-Purpose Canister

Transportation Cask
Regulatory Format Fire/Post-Fire Event

Thermal Boundary Conditions
Extension of the Regulatory Fire Test

Normal conditions of transportation
Still air, $38^0\text{C}$.
Solar Heat Flux, 388 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 $1600^0\text{C}$
Fire duration: $D_{\text{fire}}$
(regulatory fire: $T_{\text{fire}} = 800^0\text{C}$, $D_{\text{fire}} = 0.5$ hr)

Post-fire
Normal Conditions of Transportation
FINITE ELEMENT MODEL
Two Models

Intact

Damaged (no neutron shield)

Fuel Region Model:
Temperature dependent thermal conductivity.
Containment integrity temperature limit.
MODELING ASSUMPTIONS
Most cask material properties are well defined.

Define the baseline modeling assumptions used in this paper.
Define alternate assumptions used to determine the sensitivity of the results to different assumptions.

Zircaloy cladding containment integrity temperature limit:

\[ T_{\text{critical}} = 740^\circ \text{C} \ (\text{Sandoval et al. 1986}) \]
\[ T_{\text{critical}} = 593^\circ \text{C} \ (\text{MPC CDR, 1993}) \]
MODELING ASSUMPTIONS

Fuel region effective thermal conductivity:
Manteufel and Todreas
(1995, analytical model)

E-MAD
(1987, dry storage data)

\[
\begin{align*}
\text{Factor of } & \textbf{four} \text{ variation.} \\
(k_{\text{aluminum}} = 200 \text{ W/mK})
\end{align*}
\]

Is the fuel/fuel basket region mixture conductivity effected by fuel conductivity?
THERMAL SIMULATIONS
Normal Conditions of Transportation

Color-Filled Temperature Map

Line A-B
three fuel regions
Helium gap
MPC and Cask body
Neutron Shield.
THERMAL SIMULATIONS
Normal Conditions of Transportation

Temperature Profile
Both fuel region conductivity models.

$k_{\text{fuel}}$ variation has little effect on maximum temperature (and fuel/fuel basket mixture conductivity).
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

\[ \text{Fire Duration} \]
\[ \text{Center} \]
\[ \text{Corner} \]

No Response during fire.

\[ T_{\text{max}} = 304^0 \text{C}, \]
\[ 17.8 \text{ hr after fire is extinguished.} \]
\[ \text{At fuel region center.} \]
\[ \text{Well below } 740^0 \text{C.} \]

Increase fire duration

Find duration which gives \[ T_{\text{max}} = 740^0 \text{C} \].
Critical Fire Duration

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

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

Maximum (steady state) fuel temperature: \( 870^{\circ}C \).

\( D_{\text{critical}} = 22.1 \) hour.

Repeat for other fire temperatures and for the damaged cask.
The fuel will not reach its critical temperature in low fire temperature fires.

Asymptotic Fire Temperature

Intact: $657^\circ C$

Damaged: $675^\circ C$

Critical duration for $T_{\text{fire}} = 1600^\circ C$

Intact: 4.8 hr

Damaged: 0.74 hr (6 times faster)
Variation of Modeling Assumptions

E-MAD fuel model
Increases critical duration by less than 15%.
Not shown..

\[ T_{\text{critical}} = 593^\circ C: \]

![Graph showing critical fire duration vs. fire temperature for different temperatures.](image)

Reduces asymptotic fire temperature by 180\(^\circ\)C
(740\(^\circ\)C - 593\(^\circ\)C = 147\(^\circ\)C).
Reduces critical duration by a factor of 2/3 for fire temperatures above 800\(^\circ\)C.

A wide margin of safety is observed between the regulatory test and all the performance envelopes.
CONCLUSIONS

The performance envelope is significantly effected by the presence of the neutron shield, especially for high temperature fires.

The cask performance is essentially unaffected by the fuel region thermal conductivity model.

Reducing the critical fuel cladding temperature from $740^\circ C$ to $593^\circ C$ decreases the asymptotic fire temperature by $180^\circ C$ and decreases the critical duration by $2/3$ for fire temperatures above $800^\circ C$.

The 125-ton MPC adequately protects the fuel cladding under regulatory fire conditions, for all of the modeling assumptions employed by this work.
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.
Asymptotic Fire Temperature
Steady State

Intact
\[ T_{\text{fuel}} = 740^0\text{C} \]

Damaged
\[ T_{\text{fuel}} = 722^0\text{C} \]

\[ T_{\text{fire}} = 657^0\text{C} \]

Under steady state conditions, the fuel temperature is greater in the intact cask than in the damaged package.

Transient, high temperature fire conditions
NS keeps heat out

Steady state, low temperature fire conditions:
NS keeps heat in.