The response of a truck package to a radiation fire model is simulated for a range of fire durations using three-dimensional finite element analysis. A model is developed to determine the cumulative seal degradation from its temperature-versus-time history. This model is used to determine the minimum fire duration that causes the seal to lose containment integrity. The fire durations that cause the cladding to reach its long-term creep deformation and burst rupture temperatures are determined and found to be longer than the durations that cause the seal to lose containment integrity. These simulations are repeated for package models without the compliant regions of the impact limiters, and for a package with the impact limiter completely removed. Those simulations quantify the level of thermal protection the impact limiters provide to the seals and cladding during simulated fires.

I. INTRODUCTION

Federal regulations require casks that transport large quantities of radioactive materials (Type B packages) to withstand a test sequence consisting of a 9-m drop onto an unyielding surface; a 1-m drop onto a puncture bar; a 30-min, 800°C fully engulfing fire; and water emersion.1 At the conclusion of this sequence, the confinement, shielding, and criticality functions of the package must be maintained. This regulatory sequence is estimated to be more severe than 99.4% of all transportation accidents.2 However, risk assessment studies must consider the likelihood and consequence of all scenarios that are possible during transport campaigns.3

The thermal performance of packages for regulatory testing and other severe events is evaluated by both testing and analysis. Analyses typically involve construction of finite element thermal models of intact or damaged packages.4,5 First, the steady-state package temperatures are calculated for a normal transport environment. These temperatures are used as initial conditions for a transient calculation that determines the time-dependent package temperatures during a fire. Finally, the package temperatures at the end of the fire are used as initial conditions for a postfire cooldown calculation.

The Code of Federal Regulations (10 CFR 71) evaluation subjects the package, which is damaged during the earlier drop and puncture events, to a 30-min fully engulfing fire.1 The regulations specify a simplified fire heat transfer model that may be used if justified. It consists of a fully engulfing fire with minimum temperature and emissivity of 800°C and 0.9, respectively, and convection heat transfer. The temperatures of the containment seal, gamma shield, fuel cladding, and other important components are monitored during and after the simulated fire. The goal of the regulatory evaluation is to assure that the temperature-versus-time response of these components does not cause the system to lose its confinement, shielding, or criticality function. Since multiple components contribute to each function, failure of a single component may not lead to system failure.

Transportation risk studies2,3 begin by assuming a package satisfies all regulatory requirements. They then consider the likelihood and consequence of all severe events that the package may credibly experience during transport. Since it is not possible to perform simulations for all events, analysts must differentiate events that are of concern from those that are not. “Events of concern” are those that cause one or more cask components to reach a “condition of concern.” These events have potential public health consequence and therefore require further study.

Greiner et al.6,7 simulated the temperature response of intact and damaged versions of truck and rail casks to regulatory format fires. These simulated fires fully engulf the packages with a specified fire temperature and an emissivity of 0.9 (fire convection was not included in that work). The regulator fire has a duration of $D = 0.5\text{ h}$
and a temperature of $T_{\text{fire}} = 800^\circ$C. However, the simulations were performed for a range of effective fire temperatures and durations. The minimum fire durations that cause the package seal or fuel cladding to reach their temperatures of concern were determined. These “durations of concern” were determined for a range of assumed fire temperatures, different assumed component temperatures of concern, and different initial package damage levels. The fire duration of concern helps risk analysts understand how the times and estimates of the durations of concern. Moreover, that the fire is extinguished. The times of concern are useful components continues to increase for a period of time after the fire begins when these components first reach their temperatures of concern. This is because the temperature of interior components increases to increase for a period of time after the fire is extinguished. The times of concern are useful estimates of the durations of concern. Moreover, that work helps risk analysts understand how the times and durations of concern vary with pool shape and package location.

Greiner et al.\textsuperscript{9} again used CAFE to simulate the fire response of the same truck package. However, the bottom of the package body was 1.07 m above a larger 7.2-m-diam ground-level pool. To evaluate the effect of package location, simulations were performed with the package centered over the pool and offset from that location in the direction parallel to the package axis by 1 and 2.5 m. The simulations were repeated for a package whose impact limiters were not present to evaluate the level of thermal protection the limiters provide.

In the current work, a model of an intact legal-weight truck package for four PWR assemblies is constructed. It is representative of modern cask designs that may be used to transport large numbers of spent nuclear fuel assemblies. This model is subjected to the regulatory format fire model (fully engulfing, 800$^\circ$C regulatory fire with a range of fire durations). A cumulative package seal degradation model is developed and used to determine the minimum fire duration that is capable of causing the seal to lose containment integrity. The fire durations that bring the fuel cladding temperature to its initial creep deformation temperature and to its burst rupture temperature are determined. These calculations are repeated for a package that does not have the compliant region of the impact limiters, and again for one with the impact limiters completely removed. These simulations are performed to quantify the level of thermal protection provided by the impact limiters. Details of this work are available in the thesis by Mallidi.\textsuperscript{10}

II. PACKAGE MODEL

II.A. Geometry

Figure 1 shows a three-dimensional finite element model of the intact truck cask. It was constructed using the PATRAN P/thermal finite element code.\textsuperscript{11} The package body has a square cross section with rounded corners. Large impact limiters are bolted to each end. They contain compliant materials that protect the package ends during impact. The impact limiters and a bolted closure on one end of the package are removed when spent fuel is loaded into the package. This generic package transports four spent PWR fuel assemblies. Its dimensions and material properties are similar but not identical to a currently licensed legal-weight truck package.\textsuperscript{4,5}

Figure 2 shows two vertical cross sections of the package. Figure 2a is the plane midway between the package ends. The cross-shaped component at the center of the package is a 1.5-cm-thick stainless steel support structure. Borated carbon (B\textsubscript{4}C) pellets fill 1.1-cm-diam holes that are drilled radially in the legs of the structure. The four squares adjacent to the support structure are the locations where spent fuel is placed.

![Fig. 1. Three-dimensional finite element model of a truck cask that transports four spent PWR fuel assemblies.](image)
sides of these squares are 22.3 cm long. The support structure and fuel are surrounded by a 0.96-cm-thick stainless steel liner. It is part of the package containment boundary. The liner is surrounded by a depleted uranium gamma shield. Its maximum thickness is 6.7 cm, and it has an outer radius of curvature of 11.4 cm at its corners. A 3.8-cm-thick stainless steel cask body surrounds the gamma shield. An external, 12.4-cm-thick neutron shield encircles the package. In this work it is modeled as a single region, but it contains several components. These components are a 12.1-cm-thick layer of polypropylene–1% boron, 24 aluminum radial fins of thickness 0.245 cm, and a 0.27-cm-thick stainless steel outer skin. Mixture thermal conductivity, specific heat, and density properties for this composite structure were developed based on an equivalent conduction and thermal capacity model and employed to model the combined effect of these components.

Figure 2b shows a vertical slice through the package, parallel to its axis. It is slightly displaced from the package center so that it intersects the fuel tube volumes instead of the vertical legs of the support structure. Stainless steel components are on both ends of the package body, and they are surrounded by large impact limiters. In this model, the impact limiters are made up of stainless steel impact limiter support structures that are surrounded by large compliant regions.

The stainless steel portion of the package on the left side of Fig. 2b is permanently attached to the package. On the right side a square stainless steel “ring” with rounded corners is permanently attached to the package body. During transport, a stainless steel closure hatch (shown in Fig. 2b using a different shade) is inserted into the ring and bolted to it. A dotted line shows the location of an ethylene propylene O-ring that seals the closure. The O-ring has the same square shape as the package liner cross section shown in Fig. 2a (with side length of 60 cm).

Spent PWR fuel assemblies are loaded into each of the four fuel tubes. During transport, the containment volume is evacuated and backfilled with helium gas. The outer dimension of the square cross-section assemblies is 21.4 cm, and their axial length is 4.25 m. The current work assumes each fuel assembly “floats” in its tube, so there is a 0.45-cm gap surrounding their sides. The assembly is the same length as the containment volume, so that it touches the package at both ends.

II.B. Thermal Properties

Each of the four assemblies in the package is assumed to generate 700 W. Heat generated within the assemblies is transferred to the tube walls by natural convection through the helium backfill gas, thermal radiation from surface to surface across the nonparticipating gas, and conduction within the fuel rods and spacers of the assemblies. These transport processes are not calculated directly in the current work. Instead, an effective thermal conductivity thermal model of the fuel/backfill gas region is employed. To do this, the fuel assemblies are replaced by solid materials that fill their outer envelopes. The thermal conductivity of the replacement material is based on the volumetric average of the materials in that region; better models are currently under development and will be presented in future work. It increases from 3.0 to 9.53 W/m K as the temperature increases from 200 to 537°C. Its density and specific heat are 2142 kg/m³ and 275 J/kg K, respectively. The thermal properties of the honeycomb impact limiter materials are dependent on their density. The impact limiters are divided into four regions, each with different temperature-dependent properties.4,5 The thermal conductivity is a function of direction. In this work, neither melting nor charring of the honeycomb is modeled.

The material properties for calculating conduction heat transfer within the solid regions of the package are taken from standard sources.4,5,12 Thermal radiation is calculated across the helium-filled gaps between the fuel and the support structure/liner surfaces. The fuel effective thermal emissivity is 0.7, and the emissivity of the stainless steel surfaces is 0.2 (Refs. 4 and 5).

Two intact package models were constructed for this work. The nominal model had 16 096 finite elements and 17 497 nodes. The refined model had 35 960 elements and
39 483 nodes. Results from both these models are presented in this work to demonstrate mesh independence. A set of simulations is also performed for a package without the compliant portions of the impact limiters. These simulations are referred to as the no compliant region (NCR) simulations. Another set was performed for a package with the entire impact limiter (the compliant region and stainless steel support structure) removed. These simulations are referred to as the no impact limiter (NIL) simulations. The nominal finite element model was used for both these simulation sets. The number of finite elements for the NCR and NIL models are 11 552 and 10 208, respectively. These simulations results are compared to the intact package results to quantify the level of thermal protection provided by the impact limiters. We acknowledge that transport events capable of completely removing large portions of an impact limiter are highly unlikely.

III. NORMAL TRANSPORT SIMULATIONS

The Code of Federal Regulations (10 CFR 71) specifies normal hot day conditions for a package during transport. They are still air at an environment temperature of $T_E = 38\,^\circ\text{C}$, with a constant, solar heat flux of 388 W/m² absorbed by the entire exterior package surface. In this work, the solar absorptivity is 1, and the package radiates to the environment with a surface emissivity of 0.2 (Refs. 4 and 5). The natural convection heat flux at each surface location is calculated as $q = h(T - T_E)$. In this expression $T$ is the local surface temperature, and $h$ is the heat transfer coefficient between the package surface and its surroundings. It is determined based on a Nusselt number correlation for a horizontal cylinder in stagnant air, as follows:

$$h = \frac{k}{d} \left(0.6 + \frac{0.387 \cdot \text{Ra}^{1/6}}{\left[1 + \left(\frac{0.559}{\text{Pr}}\right)^{9/16}\right]^{8/27}}\right)^2,$$

where

- $d$ = package diameter = 2.42 m
- $k$ = thermal conductivity of air
- $\text{Pr} = \nu/\alpha = \text{air Prandtl number}$

The kinematic viscosity of air is $\nu$ and its thermal diffusivity is $\alpha$. The Rayleigh number is

$$\text{Ra} = \frac{g \beta (T - T_E) d^3}{\nu \alpha},$$

where $g$ is the acceleration of gravity and $\beta$ is the isobaric expansion coefficient of air.

Figure 3 shows normal conditions of transport temperature contours for cross sections through an intact package, as well as ones with NCR and NIL. All three cross sections are vertical planes parallel to the package axis. They are offset from the package centerline and cut through the fuel location that exhibits its maximum temperature. The letter “A” in Fig. 2b refers to the inner corners of each fuel assembly midway, between the two package ends. These locations exhibit the highest temperature during normal transport for all three packages. For the nominal intact model, the highest-temperature model is $151\,^\circ\text{C}$. It is $2\,^\circ\text{C}$ lower using the refined model. For both the NCR and the NIL versions, the maximum fuel temperature is $0.6\,^\circ\text{C}$ lower than for the intact version. Removing the impact limiters, which are at the ends of the package, has little effect on the maximum fuel clad temperature, which is located midway between the ends. All of these temperatures are below the allowed limit for normal transport of $400\,^\circ\text{C}$ (Ref. 14).

As described earlier, the package seal has a square shape, and its axial location is shown in Fig. 2b. The maximum seal temperature is at the midpoints of the four sides. For the intact package, the maximum temperature is $108\,^\circ\text{C}$. It is $\sim4\,^\circ\text{C}$ lower for both the NCR package and NIL packages. The impact limiters have a larger effect on the normal transport seal temperature than on the fuel.

IV. FIRE/POSTFIRE SIMULATIONS

The normal conditions of transport temperatures described in the last section are used as initial conditions (time $t = 0$) for the transient fire simulations. The Code of Federal Regulations (10 CFR 71) specifies a fire heat transfer model that consists of a fully engulfing fire temperature and emissivity of at least 800°C and 0.9, respectively, and appropriate convection. For the current fire simulations, these lower limits are used along with a package surface emissivity of 0.8. For simplicity, convection heat transfer between the fire and package is not included (the sensitivity of the results to convection can be considered in future work). The 10 CFR 71 regulations specify a fire duration of $D = 0.5\,\text{h}$. In the current work, we calculate the package response for a range of fire durations.

The package temperatures at the end of the fire (time $t = D$) are used as the initial condition for a transient postfire calculation. In this work, the postfire environment is identical to the normal hot day transport conditions. These simulations calculate the temperatures throughout the package after the fire.

V. SEAL PERFORMANCE

This section presents the maximum closure seal temperature versus time during and after different fires. A method to predict if a seal temperature-versus-time
history causes the seal to lose containment integrity is also developed. The Parker O-Ring Handbook\(^{15}\) describes the allowed exposure time \(t_E\) versus temperature for ethylene propylene O-rings. This time is in excess of 1000 h for seal temperatures below \(T_{S,0} = 148^\circ C\), and it decreases as the temperature increases. The melt temperature for ethylene propylene is \(T_{S,M} = 328^\circ C\) (Ref. 15). At this temperature, the allowed exposure time is 0.25 h.

Figure 4 shows the seal temperature versus time for intact, NCR, and NIL casks in a regulatory fire (duration \(D = 0.5\) h). Results are presented for all four seal corners and all four side midpoints. A vertical dashed line shows the end of the fire at \(t = D = 0.5\) h. A horizontal line shows the temperature \(T_{S,0} = 148^\circ C\). The seal exhibits no significant degradation when its temperature is below this value. Another horizontal line shows the ethylene propylene melt temperature \(T_{S,M}\). Seal degradation is very rapid at that temperature.

For each package only one corner and one side temperature-versus-time curve is visible in Fig. 4. This is because the temperature of all four corners is nearly identical due to the symmetry of the finite element model and its boundary conditions. Likewise, the results for all four side midpoints are also nearly identical. The seal temperatures begin increasing a short time after the fire begins and continue to increase for a period after the fire is extinguished. Heat conducts to the seal from hotter exterior portions of the package for a period of time after the fire. For all three simulations, the corner locations reach higher temperatures than the sides.

For the intact, NCR, and NIL packages, the 0.5-h fire causes the seal corner to reach maximum temperatures of \(T_{S,Max} = 156, 254, \) and 355°C, respectively. The seal temperature reaches higher levels in packages with more of the impact limiter removed. For each package the seal spends some time above \(T_{S,0}\) and so experiences some degradation. The seal degradation time (the time the seal spends above \(T_{S,0}\)) in these respective packages is \(t_D = 5.4, 22.4, \) and 22.0 h. In the NIL package the seal temperature is above its melt temperature for \(\sim 1\) h. This causes it to lose containment integrity. However, it is not clear from these results if the 0.5-h fire causes the seal within the intact or NCR packages to lose containment integrity.

Figure 5a shows the maximum seal temperature \(T_{S,Max}\) versus fire duration for all three package versions.
Results from the refined finite element models are included for the intact and NIL packages. The differences between the nominal and refined grids are always small, which indicates that the results are essentially grid independent. Horizontal lines show the temperatures $T_{S,0}$, below which the seal does not exhibit degradation, and $T_{S,M}$, at which ethylene propylene melts.

One column in Table I presents the fire durations $D_{S,0}$ that cause the maximum seal temperature $T_{S,Max}$ in Fig. 4a to reach the initial seal degradation temperature $T_{S,0}$. Fire durations shorter than $D_{S,0}$ cause no seal degradation. Table I also includes the fire durations $D_{S,M}$ that cause the maximum seal temperature to reach the melt temperature $T_{S,M}$. These durations are expected to cause the seal to lose containment integrity. Durations between these two limits, $D_{S,0} < D < D_{S,M}$, cause some degradation. However, a more complete evaluation of the seal temperature-versus-time profiles must be performed to determine if they cause the seal to lose containment integrity.

V.A. Seal Degradation Model

In this section a method is developed to determine if the seal temperature-versus-time history causes the seal to lose its containment integrity. This uses the allowed exposure time versus temperature data $t_{E}(T)$ presented in the Parker O-Ring Handbook. The exposure time is the period that the seal material can experience the associated temperature before losing containment integrity. This information can be used directly if the seal experiences a constant temperature $T$ for time $t_{S}$. In that case the fractional seal degradation is $F_{D} = t_{S}/t_{E}(T)$. In this expression the allowed exposure time $t_{E}$ is determined for the temperature $T$. If this fraction is greater than or equal to unity, then the seal loses containment integrity.

Figure 4 shows that the seal temperature during and after a fire is not constant. For a time-varying seal temperature, the degradation rate must be determined and...
then integrated with respect to time to determine the cumulative or total degradation. In the current work, we assume the O-ring material degradation rate $R_D$ is a function of its temperature $T$ alone (and not a function of other factors such as the rate of change $dT/dt$, temperatures at earlier times, or seal age). This rate is equal to the inverse of the allowed exposure time from the Parker O-Ring Handbook, which is a function of $T$. In functional form, $R_D(T) = 1/t_E(T)$. Figure 6 shows the resulting seal degradation rate $R_D$ versus temperature $T$. It is zero for temperatures below $T_{S,0} = 148^\circ C$ and increases at higher temperatures.

Figure 7a shows the seal corner (maximum) temperature versus time $t$ within the intact package for four different fire durations $D$ [in functional form, $T_{S,\text{Max}}(t; D)$]. For all four fire durations, Fig. 7b shows the resulting O-ring degradation rate versus time. It is determined from plugging the seal temperature results from Fig. 7a into the degradation rate model in Fig. 6, formally $R_D[T_{S,\text{Max}}(t; D)]$. This rate is zero when the seal temperature is below $T_{S,0} = 148^\circ C$ and positive at higher temperatures. Both the seal temperature and its degradation rate increase as the fire duration increases.

For each fire duration the total fractional O-ring degradation rate is the integral under the curves in Fig. 7b, as follows:

$$F_D(D) = \int_0^\infty R_D[T_{S,\text{Max}}(t; D)] \, dt.$$  \hspace{1cm} (3)

Figure 8 shows the cumulative degradation versus fire duration for the intact, NCR, and NIL packages. For each package the degradation increases with the fire duration. For a given fire duration, the cumulative degradation is larger in packages with more of the impact limiter removed. The fire duration of concern for the seal is the minimum duration that causes the fractional seal degradation to be $F_D = 1$. Table I shows the duration of concern for the seal based on fractional degradation $D_{S,\text{Fd}}$ for the intact, NCR, and NIL packages. For each package these values are within the range $D_{S,0} < D_{S,\text{Fd}} < D_{S,M}$.

The duration of concern for the intact package is 1.1 h, which is greater than the regulatory requirement of 0.5 h. However, this model predicts that the seal would not maintain containment integrity in a regulatory fire if the impact limiter compliant region is completely removed. The drop and puncture events precede the fire for 10 CFR 71 regulatory analysis. Since the package studied in this work relies on the compliant material to protect the seal, the level of impact limiter damage during these events must be determined. Fire response of the damaged package would then need to be simulated to determine if it complies with regulatory requirements. This is typically done in licensing analysis.

**VI. FUEL CLADDING PERFORMANCE**

Figure 9 shows the clad temperature versus time during and after a $D = 0.5$ h regulatory fire simulation at points A and B in Fig. 2. Results are shown for intact, NCR, and NIL packages. For each package these values are within the range $D_{S,0} < D_{S,\text{Fd}} < D_{S,M}$.
A vertical dashed line shows the time at which the simulated fire ends and the postfire conditions begin. The location of point A was described earlier. Point B represents the “outside” corners of the four fuel assemblies nearest the nonclosure end of the package.

The cladding temperatures at points A and B begin to rise after the fire ignites. They continue to rise after the fire is extinguished before peaking and then slowly decreasing. This behavior is similar to that exhibited by the seal. For the intact package, points A and B of the fuel are further inside the package surface than the seal. As a result, the delays before the temperatures at those locations begin to rise and begin to fall are longer than those for the seal.

The temperature versus time of point A, which is near the package midplane, is nearly the same for all three package versions. It is not affected by the impact limiter, which is at the package ends. The temperature of point B is more strongly affected by the impact limiter than that of point A because it is located near the limiter. Point A reaches the highest temperature of any fuel location for both the intact and NCR packages. When the impact limiter is completely removed (NIL package), point B attains the highest temperature of any location. For the $D = 0.5 \text{ h}$ fire, the maximum fuel temperature calculated for the intact and NCR package versions is $242^\circ \text{C}$. The maximum temperature for the NIL version is $340^\circ \text{C}$.

Figure 10 shows the maximum cladding temperature versus fire duration for the intact, NCR, and NIL packages. Horizontal lines show two temperatures of concern for the cladding. The lower is the long-term temperature limit for Zircaloy creep deformation, $T_{CD} = 570^\circ \text{C}$ (Ref. 16). Experiments show that two spent-fuel samples held at this temperature for 30 and 71 days did not exhibit any change. The higher temperature of concern is the cladding burst rupture temperature $T_{BR} = 750^\circ \text{C}$ (Ref. 3).

In Fig. 10, at $D = 0$ (no fire), the maximum cladding temperatures are the same as they are during normal transport (Fig. 3). As the fire duration increases, the maximum clad temperatures increase, and the values for each package separate from each other. For the intact package, the maximum temperature remains at the midplane between the two package ends for all fire duration investigated in this work. However, as the duration increases, it moves farther away from the package centerline. For the NCR package, the maximum temperature is located at point A for short-duration fires but moves toward and finally reaches point B for longer fires. For the NIL package the hottest location is at point B for all fire durations studied in this work.

Fire durations that do not bring the cladding temperature to or above $T_{CD}$ do not cause it to deform by creep. The two fuel cladding samples examined by Johnson and Gilbert\textsuperscript{16} are not expected to lose cladding integrity under
that condition. Fire durations that cause the cladding to reach or exceed $T_{BR}$ cause the cladding to burst and lose containment integrity.

The fire durations that cause the cladding to reach the long-term creep deformation temperature and burst rupture temperatures, $T_{CD}$ and $T_{BR}$, are denoted $D_{C,CD}$ and $D_{C,BR}$, respectively. They are the durations at which the maximum cladding temperature curves in Fig. 10 cross the horizontal lines for these temperatures. Table I summarizes $D_{C,BR}$ and $D_{C,CD}$ for all three packages.

Fires whose duration equals the burst rupture duration $D_{C,BR}$ cause the cladding temperature to exceed the initial creep deformation temperature for a period of time. We define the creep deformation time $\Delta t_{CD}$ as the amount of time the cladding exceeds the creep deformation temperature. Table I shows that for $D = D_{C,BR}$ the creep rupture time is between 3.6 and 10.3 h for the three package versions studied in this work. Creep deformation that occurs before the cladding reaches its burst rupture temperature decreases the fuel rod internal pressure and its cladding thickness. Depending on the relative magnitudes of these factors, this may cause the cladding to lose containment integrity in fires whose duration is shorter or longer than $D_{C,BR}$. The true fire duration of concern for cladding is the minimum that causes the cladding to lose containment integrity. While the true duration of concern is greater than $D_{C,CR}$, since we do not have the information on the cladding degradation rate versus temperature, we cannot determine its value more precisely than this.

The data in Table I show that the duration of concern for the seal $D_{x,FD}$ is shorter than the minimum estimate for the cladding $D_{C,CR}$. The seal would lose containment integrity in shorter-duration fires than the minimum duration that causes the cladding to lose containment. However, since the package system involves multiple containment barriers, loss of a single barrier does not necessarily constitute a loss of containment.

**VII. SUMMARY AND CONCLUSIONS**

The response of a truck package designed to transport four PWR fuel assemblies to a simplified radiation fire model is simulated for a range of fire durations using three-dimensional finite element analysis. A model is developed to determine the cumulative seal degradation from its temperature-versus-time history. This model is used to determine the minimum fire duration that causes the seal to lose containment integrity. The fire durations that cause the cladding to reach its long-term creep deformation and burst rupture temperatures are determined and found to be longer than the duration that causes the seal to lose containment integrity. The duration of concern that causes the cladding to lose containment integrity is between these two values. It cannot be determined more precisely until more is known about its degradation rate versus temperature.

These simulations are repeated for package models without the compliant regions of the impact limiters and for a package with the impact limiter completely removed. These simulations quantify the level of thermal protection the impact limiters provide to the seals and cladding during simulated fires.

**NOMENCLATURE**

- $D$ = fire duration
- $D_{C,BR}$ = minimum fire duration that causes clad to reach its burst rupture temperature
- $D_{C,CD}$ = minimum fire duration that causes clad to reach its initial creep deformation temperature
- $D_{S,FD}$ = duration of concern based on seal fractional degradation
- $D_{S,M}$ = minimum fire duration that causes seal to reach its melt temperature $T_{S,M}$
- $D_{S,0}$ = minimum fire duration that causes seal to reach its initial degradation temperature $T_{S,0}$
- $F_D$ = fractional seal degradation
- $R_D$ = seal degradation rate
- $T_{BR}$ = fuel cladding for burst rupture temperature
- $T_{CD}$ = initial fuel cladding creep deformation temperature
- $T_E$ = environment temperature
- $T_{F,Max}$ = maximum cladding temperature
- $T_{Fire}$ = fire temperature
- $T_{S,0}$ = initial seal degradation temperature
- $T_{S,M}$ = seal melt temperature
- $T_{S,Max}$ = maximum seal temperature
- $t_D$ = seal degradation time
- $t_E$ = seal exposure time
- $t_S$ = time seal is exposed to a constant temperature
- $\Delta t_{CD}$ = time cladding temperature exceeds initial creep deformation temperature

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