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COMPARISON OF UF_6 PACKAGES UNDER CERTIFICATION TEST AND ACCIDENT CONDITIONS

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ABSTRACT

Currently there are three packages approved by the NRC for U.S. domestic shipments of fissile quantities of UF_6: NCI-21PF-1, UX-30, and ESP30X. For approval by the NRC, packages must be subjected to a sequence of physical tests to simulate transportation accident conditions as described in 10 CFR Part 71. The primary objective of this project was to compare conditions experienced during these tests to conditions potentially encountered in actual accidents and to estimate the probabilities of such accidents.

Comparison of the effects of actual accident conditions to 10 CFR Part 71 tests was achieved by means of computer modeling of structural effects on the packages due to impacts with actual surfaces, and thermal effects resulting from tests and other fire scenarios. In addition, the likelihood of encountering bodies of water during transport over representative truck routes was assessed. Modeled effects and their associated probabilities, accident rates, and other characteristics gathered from representative routes were combined with existing event-tree data to derive generalized probabilities of encountering accident conditions comparable to or exceeding the 10 CFR Part 71 test conditions. This analysis suggests that the regulatory conditions are unlikely to be exceeded in real accidents.

INTRODUCTION

The Nuclear Regulatory Commission (NRC) approves new package designs for shipping fissile quantities of UF_6. Currently there are three packages approved by the NRC for domestic shipments of fissile quantities of UF_6: NCI-21PF-1; UX-30; and ESP30X. Packages approved by the NRC have been subjected to a sequence of physical tests to simulate transport accident conditions as described in 10 CFR Part 71 [1]. The physical tests consist of a 9-meter [30-foot] drop onto an unyielding surface, a 1-meter [40-inch] drop onto a puncture bar, a 30-minute fully engulfing fire, and water immersion. These designs must demonstrate that there has been no water infiltration into nor any loss of radioactive contents from the package following the tests described in 10 CFR Part 71. NRC approval of these UF_6 packages has been largely based on the packages' tested ability to withstand the hypothetical accident conditions of 10 CFR Part 71. The objective of the project described in this paper was to evaluate the performance of the three NRC-approved UF_6 packages and, in particular, relate the conditions experienced by these packages in the tests described in 10 CFR Part 71 to conditions potentially encountered in actual accidents.

METHODOLOGY

Event Trees

The event trees developed to support NUREG/CR-6672 [2], although developed to evaluate spent-fuel shipments, provided useful and up-to-date accident-related data for evaluation of UF_6 packages transported by overland modes (only truck transport was considered in the present study). Use of data from [2] was valid for UF_6 packages because accident frequencies are independent of the nature of the cargo. Furthermore, since water could potentially act as a moderator or generate toxic vapor (HF) if package contents were exposed to it, some event tree branches were modified to characterize the probability of water being present following an accident in which a package might be breached.

To this end, a Sandia-enhanced Geographic Information System was used to identify surface waters over which shipments might pass (bridges, overpasses) and beside which they might travel (e.g., lakes, streams within 30 meters of the route). Other potential means of water ingress following an accident of relatively high severity included: inappropriate actions by first responders and severe weather (rain) events. Both of these were accounted for in event-tree extensions using qualitative data on the frequency of inappropriate first-responder actions obtained from the Federal Emergency Management Agency (FEMA), and frequency of heavy rainfall data obtained from a multi-year NOAA database.

Route Characteristics

Six truck routes, selected by the U.S. NRC, were characterized using updated, standard tools similar to those employed in NUREG/CR-6672, e.g. route-lengths within regions of rural, suburban, and urban population densities, and population-density-dependent baseline accident rates, were compiled by use of the WebTRAGIS routing code [6], the GIS, and heavy-truck accident-rate compilations [7]. The routes considered were Paducah, KY to Portsmouth, OH; Portsmouth, OH to Portsmouth, VA; Portsmouth, OH to Wilmington, NC; Portsmouth, OH to Boston, MA; Portsmouth, OH, to Hanford, WA; and Portsmouth, OH to Seattle, WA [8].

Structural Analysis for UF_6 Packages

The NCI-21PF was chosen as a representative package for the structural analysis because the weight of this package is between the weights of the UX-30 and ESP-30X. Also, the construction of all three packages is similar, so use of this package could be expected to give results representative of all of the packages, especially in terms of kinetic energy and force generation. Finite element analyses of the 21PF were performed for impacts at various angles onto an unyielding target at 30 mph. The kinetic energy time histories from these analyses were used to develop force-displacement curves for the 21PF for each impact angle.

A method has been developed for using a force-displacement curve to relate 30-mph impacts onto an unyielding target to higher-speed impacts onto yielding targets. For each target type considered, a force-deflection relationship for the target was developed. For soil and concrete targets this was done in NUREG-CR/6672. For a relatively soft package, such as the 21PF, impacts with trucks and trains are also of concern. Therefore, force-deflection curves for these objects were developed from existing test data at SNL.

Thermal Analysis for UF_6 Packages

Even though the three UF_6 overpacks have the same overall dimensions (2.4m [96 in.] long, 1.1m [43.5 in.] diameter, 15cm [6 in.] thick wall), the UX-30 was selected for this thermal analysis because the thermal conductivity of the polyurethane foam used in the UX-30 is higher and the product of density with specific heat is lower than those of the phenolic foam used in the ESP-30X and the combination of phenolic foam and white oak used in the NCI-21PF-1. Therefore, the internal temperatures of the UX-30 when exposed to hot and transient external conditions will be higher than those for the ESP-30X and the NCI-21PF-1.

Five different accident configurations were modeled in the thermal assessment of the UX-30 packaging.

1) **Fully engulfing**, 10 CFR Part 71 fire,
2) Package offset one meter [3.3 ft], **side** facing the fire at ground level,
3) Package offset five meters [16.4 ft], **side** facing the fire at ground level,
4) Package offset ten meters [32.8 ft], **side** facing the fire at ground level, and
5) Package offset one meter [3.3 ft], **end** facing the fire at ground level.

The normal conditions of transport were also modeled in order to compare and validate the model built for this study using the data presented in the Safety Analysis Report (SAR) of the UX-30. The simulation of the 10 CFR Part 71 fire environment provided the data necessary for the comparison of the results obtained from the simulations in which the package was offset from the fire. For the analyses of the package offset from the fire, the fire was modeled as a radiant surface with dimensions representing a fire cross-section.

In order to establish equivalence of each non-regulatory configuration with the regulatory fire, temperature history plots were generated that determined the time to reach a threshold temperature in the package. The threshold temperature was defined as the maximum temperature of the UF_6 contents at the end of the 30-minute fully engulfing regulatory fire simulation.

EVENT TREES

The event tree developed in NUREG/CR-6672 [2] for truck transport of spent fuel casks was used. As employed in that study and in the present study, the event tree describes the basic accident scenarios as they apply to spent fuel casks (and potentially to all Type B packages or equivalents). The probabilities associated with the end-points of the branches must be modified to take account of accident speeds, fire occurrence and, in the present study, exposure to water. These extensions are described more effectively by equations rather than addition of branches to the tree.

Each of the endpoints (except the "Fire only" branch) has an associated probability of occurrence of a fire with sufficient intensity to compromise package containment of the UF_6 directly, or to exacerbate releases resulting from mechanical forces. The probabilities of these events were defined using thresholds determined in the structural and thermal analyses, and probability distributions developed for NUREG/CR-6672. Mechanical damage thresholds were defined by accident speeds calculated to be equivalent to a 9-meter [30-ft] drop on an unyielding target.

Thermal thresholds were defined by the times required to reach a critical temperature in each of the cases. For each time, a probability was determined from the appropriate distribution function in NUREG/CR-6672.

For each accident scenario (event tree endpoint), a total probability of occurrence was defined by an equation of the form:

P = (event-tree probability)(threshold-speed prob.)(fire prob.)(fire-duration prob.).

As in NUREG/CR-6672, this general form was developed to take into account the fire probabilities relating to different types of collisions:

(fire prob.) = (optically-dense prob.)(flame-temp. prob.)(fire/scenario prob.)

= (0.2)(0.86) (fire/scenario prob.)

for accidents not involving trains and a flame temperature of ~800°C [1475°F].

= (1.0)(0.86) (fire/scenario prob.)

for train collisions with trucks and a flame temperature of ~800°C [1475°F].

(Note that the flame-temp. prob. value of 0.86 was interpolated from probabilities of 0.5 for ≥1000°C [[1832°F] and 1.0 for >650°C [1202°F] given in Section 7.4.4.3 of NUREG/CR-6672.)

Values of the probability that a fire will occur (fire/scenario prob.) under any of various accident scenarios (Table 7.6 of NUREG/CR-6672) are listed in Table 1. In NUREG/CR-6672, an average of the values in Table 1 was calculated using the accident scenario probabilities listed in the event tree; the resultant average probability that a fire occurs is 0.018. For the remaining terms in the equation, combinations of event-tree probabilities, speed probabilities for various surfaces, and fire durations for different fire locations were tabulated as shown in the results section. Certain additional concerns related to the unique character of UF_6 and its interaction with water required additional probabilities to be assessed as described below.

Table 1. Truck Accidents that Initiate Fires

	Fraction of Accident Type that Initiate Fires
Collision with	
Car	0.003
Truck	0.008
Other objects	0.013
Non-Collisions	
Ran off road	0.011
Overturns	0.012
Other	0.130

Probability of Water being Available after an Accident

Water could be available to interact with the UF_6 package following an accident because of actions of first responders, heavy rainfall, or the accident occurring near a body of water. Based on qualitative information from FEMA, the probability that water will be applied by first-responders was conservatively estimated to be 50% in the event of a fire (regardless of its size or duration). The comprehensive probability of rainwater entering the UF_6 container was calculated from cumulative data from all of the selected routes to be approximately $8x10^{-6}$. For each route, a total of the route length either crossing or lying within 30 meters [100ft] of water was calculated in a manner that significantly overestimates the presence of water (if there was water in the census block or within 30m [100ft] of the census block that the route passed through, it was assumed to be within 30 meters [100ft] of the route). For the six truck routes analyzed, the percentage of the routes that met these criteria ranged from 7 to 15%. The percentage presence of water was applied to all accidents that involved going off the roadway as the initiating event.

STRUCTURAL ANALYSIS - EQUIVALENT IMPACT VELOCITIES

The packages used to transport UF_6 have been demonstrated to survive (no loss of containment) an impact at 13.4 m/s [30 mph] onto an essentially unyielding target (hypothetical accident conditions of 10 CFR Part 71 [1]). In conducting risk assessments, real accidents must be evaluated. Real accidents occur with impacts onto objects that are not unyielding with the consequence that the target absorbs a portion of the impact energy. This fact makes higher speed impacts onto these real targets no more severe than the hypothetical accident impact on an unyielding surface. To determine the velocity for impact onto a real target that has the same severity as the regulatory impact on an unyielding target, the amount of energy absorbed by the target must be determined [9, 10].

Finite Element Analyses

To compare the response of a typical UF_6 package to an impact onto a yielding target with the regulatory impact onto an unyielding target, the contact force between the package and unyielding target had to be quantified. To do this, finite element analyses of impacts of the NCI-21PF onto an unyielding target, using the Sandia National Laboratories-written explicit dynamic finite element code PRONTO-3D [11], were employed. These analyses included impacts at angles of 0° (end impact), 13.5° (CG-over-corner impact), and 75° (slap-down impact). Figure 1 shows the finite element mesh used for the analyses. Included in the model are the outer shell of the 21PF, the foam and wood impact absorbing material, the inner shell of the 21PF, the 30B cylinder, and its UF_6 contents. The finite element analysis outputs the total kinetic energy of the package at 100 time steps throughout the simulation time. If it is assumed that all of this kinetic energy is associated with motion in the direction of the impact, then the average velocity of the package at each time can be determined ($KE = \frac{1}{2} mv^2$). The contact force between the package and the unyielding target was calculated by numerically differentiating the velocity to get acceleration and multiplying this by the package mass to get force. A finite element analysis was not performed for impact in the side-on orientation. To approximate a result for this case, the slap-down analysis was used. In the slap-down orientation, only one end of the cask is exerting force at any given time; therefore, it was assumed that the contact force for a side-on impact, where both ends of the cask are exerting force simultaneously, would be twice that for the slap-down case. The displacement of the center-of-gravity (CG) was determined by numerically integrating the velocity. The results of these two operations are plotted together as a force vs. deflection curve for the package in the end-on, CG-over corner, and side-on orientations. Figure 2 shows these three curves. The maximum contact

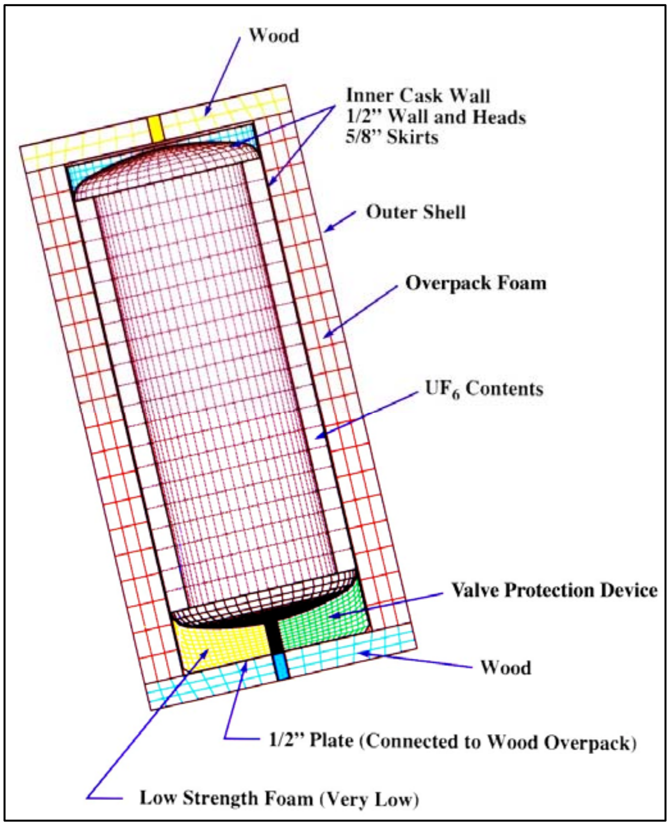

Figure 1. Finite Element Mesh for the NCI-21PF

force for the end-on orientation is 11.6 kN [2,600,000 pounds]. The maximum contact force for the corner and side-on orientations is 6.7 kN [1,500,000 pounds].

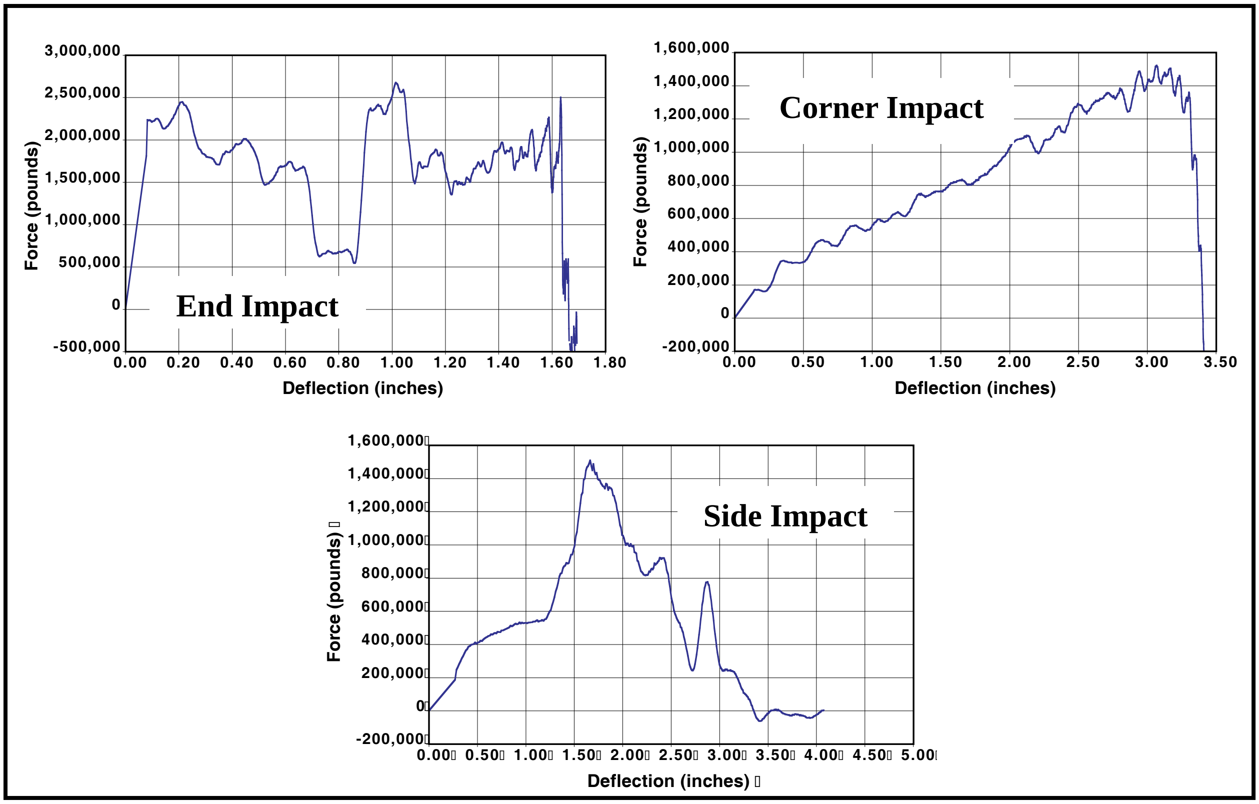

Figure 2. Force-Deflection Curves for the NCI-21PF Impacting an Unyielding Target

<u>Impacts on Yielding Targets</u>

In order for an impact on a yielding target to produce as much damage to the cask as the impact on the unyielding target, the contact force between the package and the yielding target has to be as large as the peak contact force between the package and the unyielding target. For the contact force to be of this magnitude, the target must be strong enough to exert this magnitude of force. Impacts with low mass, non-fixed objects, such as automobiles, sign posts, telephone poles, etc. cannot produce a force this large; consequently, none of these impacts is as severe as the regulatory impact, no matter how large the impact velocity. Impacts with objects of large mass, such as trucks and trains, and with fixed surfaces or objects (soil, asphalt, concrete, rock) have the potential to be as severe as the regulatory impact if the impact velocity is sufficiently large.

The general method used to compare impacts with yielding targets to the regulatory impact onto an unyielding target is to calculate the amount of energy absorbed by the target, add this energy to the initial kinetic energy of the package, and compute an equivalent velocity for the package that gives this sum as its kinetic energy. A basic assumption of this method is that the damage to the package as a result of an impact onto a yielding target is in the same mode as the damage due to impact onto the unyielding target. This is generally the case for relatively flat targets or targets for which the impact interface between the package and the target remains essentially planar. Table 2 contains the velocities for various impacts onto yielding targets that are equivalent to the regulatory impact onto an unyielding target.

Table 2. Equivalent Velocities for Impacts onto Yielding Targets

Impact Surface (Target)		End		Corner		Side	
		m/s	mph	m/s	mph	m/s	mph
Soil Type	Hard	58	130	35	78	29	65
	Stiff	93	208	55	122	42	94
	Medium	142	318	80	179	60	135
	Soft	207	462	117	262	88	197
Concrete Slab Thickness	6 inches	21	46	16	36	15	34
	9 inches	17	39	15	33	14	32
	12 inches	16	35	14	32	14	31
	18 inches	15	33	14	31	14	31
Rock Type	Hard	13	30	13	30	13	30
	Soft	42	94	27	61	24	53

THERMAL ANALYSIS

Three UF_6 packages were examined for this study. These were the UX-30 [4], ESP-30X [5], and NCI-21PF-1 [3]. From these, the UX-30 was selected as the reference package to build the finite element model (FEA). The overall dimensions of the FEA model that was built for this study are shown in Figure 3. The MSC PATRAN/Thermal [12] computer code was used to generate the model and run the thermal calculations. This model was then used for the simulation of all the cases that were described in the Methodology section by applying the appropriate boundary conditions.

The 30B cylinder was assumed to be concentric with the UX-30 overpack. The uniform 1 cm [0.375-in.] air gap shown in Figure 3 allows radiation exchange between the inner wall of the UX-30 overpack and the outer wall of the 30B cylinder. A view factor of one was assumed as well as emissivity values of 0.5 and 0.8 for the stainless steel inner wall of the UX-30 and the outer wall of the 30B cylinder, respectively. This radiation exchange was included in all the thermal simulations. The material properties used in this model were the same as those presented in the SAR for the UX-30 overpack, including the emissivity values mentioned above. The UF_6 was not assumed to generate any significant decay heat. As shown in Figure 3, the 30B cylinder was assumed to be completely full of UF_6 and its ends are as far from the overpack inner wall as the sides. In other words, the valve region and the bottom region where the cylinder would sit if it were positioned vertically were not included in the model (i.e., the UF_6 is modeled as closer than the actual distance from the overpack inner wall). Therefore, the temperature results for the UF_6 near the ends of the overpack are expected to be conservative values.

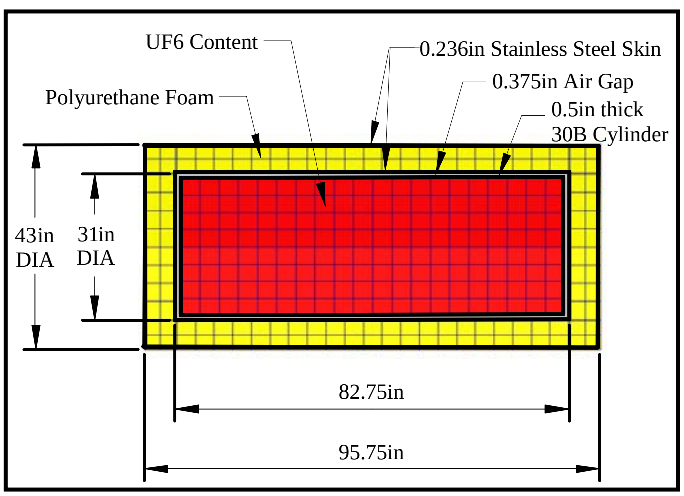

Figure 3. Overall Dimensions of the UX-30 Package FEA Model

Normal Transport Conditions

An analysis of the normal conditions of transport was performed to calculate the initial conditions for all fire accident simulations. The results from this simulation were compared to those presented in the Safety Analysis Report (SAR) to validate the computer model. A comparison of the analysis results to those reported in the SAR is presented in Table 3.

Table 3. Comparison of the Steady-State Solutions

Location	Temperature (°C [°F])	
	UX-30 SAR	Current Analysis
Top outer surface of the UX-30	62.9 [145.3]	63.2 [145.7]
Top inner surface of the UX-30	52.1 [125.7]	54.2 [129.6]
Top of 30B cylinder	51.1 [124.0]	52.3 [126.1]
Closure interface at the outer surface	51.9 [125.4]	51.7 [125.0]
Closure interface at the inner surface	49.8 [121.7]	51.3 [124.3]
UF_6	51.1 [124.0]	51.2 [124.1]

Regulatory Fire Accident Conditions

In order to determine how long it takes for fire environments other than the regulatory environment described in 10 CFR Part 71 [1] to present a similar threat to the undamaged UF_6 package, the regulatory accident conditions had to be modeled. At the end of the fire simulation, the entire outer surface of the package was 799°C [1470°F]. The temperature histories of three points in the UF_6 are presented in Figure 4. Note that the peak temperature of the UF_6 occurred after heating by the 30-minute regulatory fire had ceased. As shown in this figure, the temperature of the corner node heated the fastest due to the fact that heat is entering the corner from the side and the end simultaneously. On the other hand, only the temperatures of the end and the side will be considered in this study since they are a better representation of the bulk temperature of the UF_6 at the boundaries. The maximum temperature of the UF_6 at the side and the end in this simulation was used as thresholds to determine equivalent conditions in the following analyses.

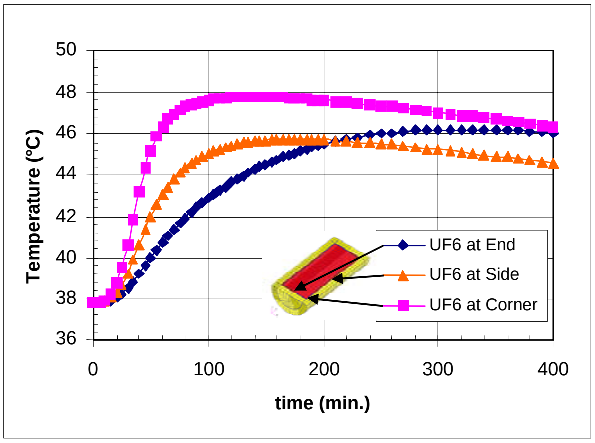

Figure 4. Temperature History of Three Outer Boundary Points of the UF_6

UF_6 Package Away from a Fire

Four simulations, in the configurations described in the Methodology section were performed with a fire represented by an 8m (base) x 17m (height) with a 4m top trapezoidal surface. A top view of the package and fire positions is illustrated in Figure 5. The boundary conditions used for the offset fire simulations are presented in Table 4. The offset fires were assumed to continue until the temperature threshold was reached.

The diameter of the assumed fire extends to the maximum recommended pool fire diameter according to 10 CFR Part 71 relative to the length of the package. That is, three meters from the outer surface of the package to the edge of the pool. In reality, an oval or rectangular pool would be necessary in order not to exceed this limit when measured from the side of the package, but for the purpose of this study, the pool was assumed to be circular, allowing the boundary of the fire to extend 0.66 m [2.2 ft] further beyond the cask diameter. This will introduce some conservatism, relative to the slightly smaller fire diameter, in the calculation of the package response when one of its ends was directly exposed to the fire. The height of the fire was assumed to be two pool diameters, which is typical of open pool fires.

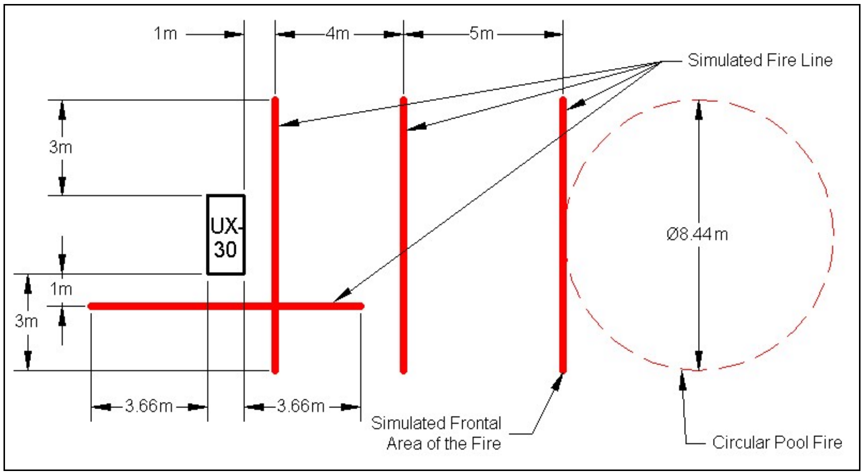

Figure 5. Top View of the Four Scenarios Modeled

Table 4. Boundary Conditions Used for Offset Fires

<table>
<tr><th>Boundary Condition</th><th>Application Region</th><th>Value</th></tr>
<tr><td>Fire temperature</td><td>External node</td><td>800°C</td></tr>
<tr><td>Environment temperature</td><td>External node</td><td>38°C</td></tr>
<tr><td rowspan="3">Radiation exchange between the cask and the fire</td><td>Outer surface of UX-30</td><td>Surface emissivity of 0.5</td></tr>
<tr><td>Fire surface</td><td>Surface emissivity of 0.9</td></tr>
<tr><td>View factor</td><td>Position dependent
(calculated by P/Thermal)</td></tr>
<tr><td rowspan="3">Radiation from the cask to the environment (only used for 5 and 10 m away fires)</td><td rowspan="2">Outer surface of UX-30</td><td>Surface emissivity of 0.5</td></tr>
<tr><td>Environment emissivity of 1</td></tr>
<tr><td>View factor</td><td>1</td></tr>
<tr><td rowspan="2">Insolation (Solar irradiation)</td><td>Curved surface
$0 \le \theta \le 180°$</td><td>Heat transfer coef. of
193.9 W/m^2</td></tr>
<tr><td>Vertical flat surfaces</td><td>Heat transfer coef. of
96.95 W/m^2</td></tr>
<tr><td>Natural convection</td><td>All external surfaces of UX-30</td><td>Heat transfer coef. of
3.64 W/m^2-K</td></tr>
</table>

The temperature contours on the surface of the package after 30 minutes of exposure to the prescribed fires are presented in Figure 6.

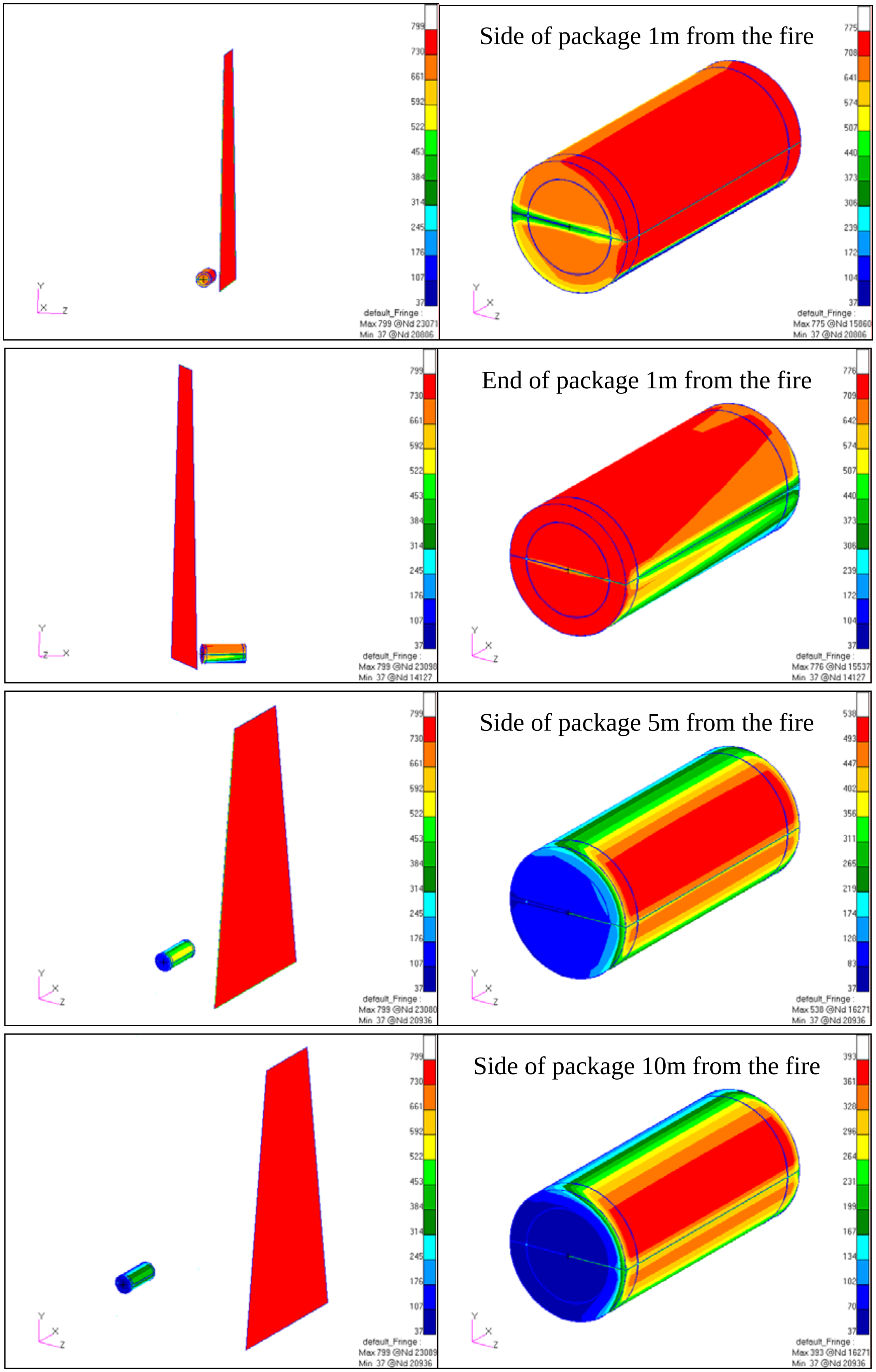

Figure 6. Temperature distributions for offset fires at 30 min. Temperature in °C [°F=9/5C+32]. The temperature legends are different scales.

Results Summary

The temperature history records of all the transient simulations are compared to the temperature reached in the 30 min. regulatory fire (45.73 °C and 46.21 °C) in Figure 7.

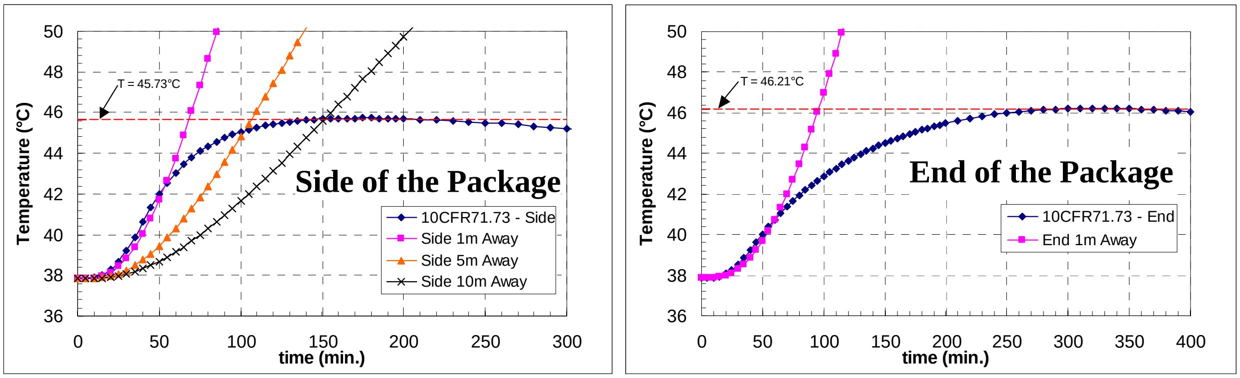

Figure 7. Comparison of Time-to-Threshold of UF_6 Temperature.

Note that the maximum temperature observed from the 10 CFR Part 71 simulation was 45.73°C for the UF_6 on the side and 46.21°C for the UF_6 at the end of the package. These temperatures were the threshold temperatures used to determine the time at which the other scenarios pose a similar threat to the UF_6. Table 5 lists the times (as defined by the finite time-steps of the simulation) at which these temperatures (or closest calculated values) were reached for each of the transient simulations. It is important to understand that these simulations were performed under the assumption that the overpack was undamaged. Also, in the non-regulatory cases, the fire was assumed to burn continuously. In reality, these non-regulatory fires could burn for shorter times and still reach the temperature thresholds defined by the regulatory simulation. Shorter fire burn-times would, in turn, yield higher probabilities of occurrence.

Table 5. Threshold Temperatures and Times

Simulation	Temp. (°C [°F])	Time (min.)
10 CFR 71 - Side	45.73 [114.3]	175
Side 1m [3.3ft] Away	46.06 [114.9]	69
Side 5m [16.4ft] Away	46.10 [115.0]	107
Side 10m [32.8ft] Away	45.98 [114.8]	152
10 CFR 71 - End	46.21 [115.2]	310
End 1m [3.3ft] Away	46.97 [116.5]	96

PROBABILITIES

For each event tree end-point, the fractional occurrence was multiplied by a fraction representing the probability of the corresponding accident speed, as defined by speed probability distributions in NUREG/CR-6672 [2] and threshold values displayed in Table 6. Fire duration probabilities determined from probability distributions in NUREG/CR-6672 and threshold values are listed in Table 7. The probability distributions from NUREG/CR-6672 are tabulated in that document as cumulative probabilities, i.e. probability (P_c) of a threshold or smaller value being reached. In Tables 6 and 7, the complement of that value ($1 – P_c$), i.e., the probability that the threshold value will be exceeded, is used; this yields a conservative estimate of the probability that the regulatory conditions are exceeded. Total probabilities of exceeding regulatory thresholds for specific accident types and fire scenarios of interest are computed by multiplication of a conditional probability from Table 6, the distance weighted average accident rate [8], the route length [8], the probability that a fire occurs (0.018), and the probability of a specific fire scenario from Table 7.

The combinations of probabilities in Table 6 and fire-scenario probabilities in Table 7 can be modified further by the probabilities for special circumstances leading to immersion of the package in water or intrusion of water into the inner cylinder, as discussed in the "Event Tree" section of this paper. The probability of water being applied to a fire by first-responders was estimated to be 50%. The probability that water could enter the cylinder as a result of heavy rainfall, 8E-6, can apply to the scenarios in Table 6 because the speed probabilities include values greater than the thresholds, leading to a small probability of damage to the fill-valve for each scenario except fire-only. Finally, for each of the hypothetical routes, the corresponding fraction of the route bordering or over water may be applied to the total probabilities in Table 6 for "Off road" scenarios to estimate (very conservatively) the probability of immersion of the package in water. All of the probabilities in these three categories of exposure to water indicate a further reduction, below the small likelihood of accidents exceeding the regulatory conditions, for the probability of any special consequences relating to such exposures to water. The following example illustrates this procedure:

> *For the suburban portion of the route from Portsmouth, OH, to Wilmington, NC, the probability of an accident in which the shipment runs off the road and over an embankment, to impact hard soil at a speed equivalent to the regulatory limit is:* $Prob_{Accident}$*=(409km)(3E-7acc./km)(1.3E-5)=1.6E-9*
>
> *If the package careens into a nearby body of water, the probability of an immersion accident is:* $Prob_{Immersion}$*=1.6E-9(0.07)=1.1E-10*
>
> *If, instead, there is a fire (1 meter from the package side, lasting for the equivalent of a regulatory fire) after the impact on hard soil:* $Prob_{Fire}$*=1.6E-9(0.018)(0.0002)=5.8E-15*

Table 6. Accident Scenarios with Probabilities of Exceeding Regulatory Speed Equivalents

Event Tree Scenario	Scenario Probability	Speed Probability	Total Probability
Collisions, Non-fixed Objects			
Truck, bus	0.13320	0.018	**0.0024**
Train	0.00770	1.0E-5	**7.7E-8**
Collisions, On-road Fixed Objects			
Bridge Rail., Railb. or Roadb.	0.00399	0.58	**2.3E-3**
Bridge Rail., Clay or Silt	0.00008	1.1E-6	**8.8E-11**
Bridge Rail., Hard S. or Soft R.	4.0E-6	0.018	**7.2E-8**
Bridge Rail., Hard Rock	3.0E-6	0.72	**2.2E-6**
Large Column	0.00006	0.0051	**3.1E-7**
Abutment	0.00001	0.17	**1.7E-6**
Non-collisions, Off-road			
Slope, Clay or Silt	0.02297	1.1E-6	**2.5E-8**
Slope, Hard S. or Soft R.	0.00126	0.0097	**1.2E-5**
Slope, Hard Rock	0.00101	0.26	**2.6E-4**
Embankment, Clay or Silt	0.01314	1.1E-6	**1.4E-8**
Embankment, Hard S. or Soft R.	0.00072	0.018	**1.3E-5**
Embankment, Hard Rock	0.00058	0.72	**4.2E-4**
Non-collisions, Other			
Fire Only	0.00970	1.0	**9.7E-3**

Table 7. Probabilities of Fire Exceeding the Regulatory Temperature Equivalents (Average Fire Occurrence = 0.018)

Fire Scenario	Time to Temp. (minutes)	Non-Collision Accidents	Off-Road Accidents & Fixed-Object Collisions	Truck Collisions	Train Accidents
Side Exposure 1 meter Away	69	0.00004	0.0002	0.15	0.10
Side Exposure 5 meters Away	107	0.0	0.0	0.12	0.068
Side Exposure 10 meters Away	152	0.0	0.0	0.090	0.045
End Exposure 1 meter Away	96	0.0	0.0	0.13	0.076

If, in addition, first-responders fight the fire with water, the probability of this accident consequence is:

$Prob_{Water} = 5.8E\text{-}15(0.5) = 2.9E\text{-}15$

Note that all of these probabilities are per shipment.

CONCLUSIONS

Examination of the results in Tables 6 and 7 indicate that the probabilities of exceeding regulatory conditions in accidents of the various types defined by the truck accident event tree in NUREG/CR-6672, and by structural and thermal analyses of possible conditions resulting from such accidents, reveals a limited number of circumstances under which regulatory conditions may be exceeded. Furthermore, their probabilities are small, i.e. the likelihood of UF_6 being dispersed by impact or fire is small while the probability that accidents will lead to conditions within the regulatory limits is substantial. Similarly, applying the probabilities of further consequences resulting from exposure to water by fire-fighting, heavy rain or off-road excursion into a body of water leads to even lower probabilities, by factors ranging from 0.5 to $8x10^{-6}$.

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