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3.0 THERMAL EVALUATION

The Traveller series packages are limited to use for transporting unirradiated, low enriched uranium, nuclear reactor core assemblies. There is no packaging design feature for heat removal because the contents does not contain heat generating radioactive material. The use of polyethylene as a moderator requires controlled heat-up during accident conditions, to prevent loss of hydrogen within the moderator.

3.1 DESCRIPTION OF THERMAL DESIGN

3.1.1 Design Features

The Traveller series packages, as described in section 2, utilize an aluminum Clamshell to contain a single unirradiated nuclear fuel assembly. The Clamshell is mounted within a cylindrical Outerpack fabricated from 304 stainless steel and flame retardant polyurethane foam. The stainless steel/foam sandwich provides thermal insulation during hypothetical fire conditions. Most of the heat capacity is within the Outerpack, provided by the polyethylene moderator, the aluminum Clamshell and the fuel assembly itself reducing the peak temperatures within the package.

The fuel rods, that contain the radioactive material, are designed to withstand temperatures of 1204°C (2200°F) without substantial damage. The primary temperature limitation is the polyethylene moderator located on the inside surface of the Outerpack. Polyethylene was selected because it retains its chemical composition and therefore its hydrogen content past melt temperature (between 120° and 137°C). Because of its very high viscosity, it will not flow significantly and will not change chemical composition unless significant amounts of high temperature oxygen are present (320-360°C).

The design and test strategy employed for the Traveller was to utilize design approaches that had previously passed the thermal test requirements. A review of previous designs and associated test results led to the selection of a stainless steel/polyurethane sandwich for the Outerpack. Based on this design approach, scoping tests and thermal analysis were performed to size the Outerpack structure. These analyses showed that sufficient polyurethane was incorporated to effectively insulate the interior of the Outerpack. As described in section 3.3.1 below, anticipated heat transfer due to conduction and radiation was so low that peak temperatures within the Outerpack would be below the melt temperature of the polyethylene and well below its ignition temperature. The primary concern was hot gas flow into the interior of the Outerpack. If both inner and outer skins of the Outerpack are ripped or if the seam between the Outerpack door and base are opened during the drop tests, hot gas from the fire could flow through the Outerpack significantly increasing its temperature. The Outerpack was made sufficiently robust that the defined drops did not create air infiltration paths within the Outerpack.

During the development process, three Traveller test articles were built. All were subjected to drop testing. Afterwards, these units were subjected to multiple burn tests. The information obtained during tests was incorporated into the final design of the Traveller Certification Test Unit (CTU). The CTU was subjected to drop testing as described above (Section 2.12.4). The CTU was then transported to Columbia, SC where it was burned in accordance with 10CFR71.73(c)(4) and TS-R-1, paragraph 728(a).

The package survived the test with maximum internal temperatures less than 180°C. The results of this test are described in section 3.5 and appendix 3.6.4.

3.1.2 Contents Decay Heat

Decay heat and radioactivity of the contents are not applicable for this package type.

3.1.3 Summary Tables of Temperatures

The maximum temperatures that affect structural integrity, containment, and criticality for both normal conditions of transport and hypothetical accident conditions are provided in Table 3-1. The table also includes the maximum measured temperature of the package components. All measured temperatures are within the limits specified. These results show that hypothetical accident thermal conditions will not materially affect the fuel assembly, the neutron poison plates, clamshell or the polyethylene moderator

During hypothetical accident conditions, the polyurethane insulation in the Outerpack protects the interior from excessive heat up. The Clamshell and its contents will not experience temperature increases significantly greater than 100°C. Therefore, room temperature material properties adequately describe the Clamshell and fuel assembly. The polyurethane foam will experience significant temperatures during the hypothetical accident. Because the lack of data at higher temperatures, the thermal analysis assumed foam properties above 340°C were equivalent to dry air. As shown by tests described in section 3.5 below, this approximation reasonably bounded actual properties.

Table 3-1 Summary Table of Temperatures for Traveller Materials

Material	Temperature Limit and Rational (C)	Measured Temperature in CTU Fire Test (C)(1)
Uranium oxide	2750 (melt) 1300 (compatibility with zirconium)	104
Zircalloy	1850 (melt)	104
Aluminum	660 (melt)	104
Stainless steel	1480-1530 (melt)	177(2)
UHMW Polyethylene	349 (boiling/ignition)	177(2)
Fiberglass seals (Thermojecket S)	1000°F (long term)	Temperature not measured/ Seals present after fire test
Silicone Rubber Gasket	500°F (long term)	Seals not present after fire test
Shock Mounts (fully cross-linked natural rubber)	greater than 300 (combustion)	177(2)
Refractory fiber felt insulation	2300°F (melt)	177(2)

Notes:
(1) Temperature measurements made by non-reversible temperature strips. Exact time of peak temperature can be inferred from analysis. See section 3.3-1.
(2) One location was unreadable on inside Outerpack shell. See section 3.6-4.

3.1.4 Summary Tables of Maximum Pressures

The Traveller Outerpack surrounds the Clamshell and fuel assembly. It has silicone rubber or fiberglass seals to prevent rain, dirt, dust and spray from entering the package. The seals are not continuous, however, to avoid producing an air-tight seal. The Traveller Clamshell is not air tight and cannot maintain a different pressure than the air surrounding it. The double wall Traveller Outerpack also incorporates acetate seal plugs that melt in the event of a fire allowing decomposition products from the polyurethane insulate to vent to the outside air. Therefore, the Traveller interior pressure will always maintain itself in approximate equilibrium with external air pressure.

3.2 MATERIALS PROPERTIES AND COMPONENT SPECIFICATIONS

3.2.1 Materials Properties

The Traveller package series is fabricated primarily from four materials: 304 stainless steel, 6005 aluminum, Ultra-High Molecular Weight (UHMW) polyethylene, and flame retardant polyurethane foam. The Outerpack is fabricated from stainless steel and the polyurethane foam. The interior Clamshell holding the fuel assembly is fabricated from aluminum. The polyethylene is used as a neutron moderator and is located on the inside walls of the Outerpack, between the Outerpack and Clamshell. The important room temperature material properties are provided in Table 3-2.

The melt temperature of the polyurethane foam is not provided because it is a thermoset material that decomposes before melting. The urethane foam selected for use will be a fire retardant foam that, when heated above 204.4°C, produces an intumenscent char that seals voids and continues to provide insulation. This process is endothermic and produces gasses that must be vented. Vent plugs are placed along the length of the package to provide this venting. All Outerpack components containing polyurethane foam will have at least one vent plug.

The fuel assembly significantly affects the response of the overall package during a hypothetical fire. Because the fuel assembly may account for as much as 40% of the total package weight, the thermal capacity of the fuel assembly has a significant effect interior temperature. Key materials for the 17x17 XL fuel assembly to be shipped in the Traveller XL package is shown in Table 3-3A. Key materials for the VVER fuel assembly to be shipped in the Traveller VVER package is shown in Table 3-3B.

Traveller VVER requires a thermal evaluation to ensure the package design and fissile contents are in a safe condition following normal and hypothetical accident conditions. Structural evaluations (Chapter 2) have demonstrated that the expected mechanical damage is bounded by the Traveller XL. Since Traveller VVER is a similar fresh fuel shipping package with respect to expected mechanical and thermal performance to a Traveller XL, the Traveller XL thermal methodology forms the basis for Traveller VVER evaluation. Section 3.3.1.1 provides the technical justification for use of Traveller XL thermal analysis.

Table 3-2 Room Temperature Properties of Key Traveller Materials				
Material	**Density**	**Melt Temp**	**Conductivity**	**Specific Heat**
304 Stainless Steel	8.3 g/cc .29 lb/in^3	1400-1455°C 2550-2650°F	14.2 W/m-K 8.2 BTU/hr-ft-F	0.5 J/g-°C 0.12 BTU/lb-°F
6005 Aluminum	2.8 g/cc .098 lb/in^3	582-652°C 1080-1210°F	167 W/m-K 96.1 BTU/hr-ft-F	0.88 J/g-°C 0.21 BTU/lb-°F
UHMW polyethylene	.932-.945 g/cc .0337 - .0341 lb/in^3	125-138°C 257-280°F	0.42 W/m-K .24 BTU/hr-ft-F	2.2 J/g-°C 0.526 BTU/lb-°F
Polyurethane Foam	0.166 g/cc .0058 lb/in^3	NA	0.041 W/m-K .023 BTU/hr-ft-F	1.15 J/g-°C 0.275 BTU/lb-°F
Fiberglass seals (Thermojecket S)	NA(2)	538°C(1) 1000°F	NA(2)	NA(2)
Silicone rubber gasket	NA(2)	-73 to 250°C(1) -100 to 500°F	NA(2)	NA(2)
Refractory fiber felt insulation	0.097 g/cc .0035 lb/in^3	1260°C 2300°F	.06 W/m-K .034 BTU/hr-ft-F	1.0 J/g-°C 0.239 BTU/lb-°F

Notes:
(1) Temperature range that the gasket material and adhesive will withstand.
(2) Packaging weather gasket is to keep dust, dirt and spray from getting inside the Outerpack.

Table 3-3A Room Temperature Properties of Key Fuel Assembly Materials				
Material	**Mass in FA**	**Melt Temp**	**Conductivity**	**Specific Heat**
304 Stainless Steel	22 kg 49 lb	1400-1455°C 2550-2650°F	14.2 W/m-K 8.2 BTU/hr-ft-F	0.5 J/g-°C 0.12 BTU/lb-°F
Inconel	2.7 kg 6 lb	1354-1413°C 2470-2580°F	14.9 W/m-K 8.6 BTU/hr-ft-F	0.44 J/g-°C 0.106 BTU/lb-°F
Zircalloy 4	150 kg 330 lb	1850°C 3360°F	21.5 W/m-K 12.4 BTU/hr-ft-F	0.285 J/g-°C 0.0681 BTU/lb-°F
Uranium dioxide	608.3 kg 1341 lb	2750°C 4982°F	5.86 W/m-K 3.39 BTU/hr-ft-F	0.237 J/g-°C 0.0565 BTU/lb-°F

Table 3-3B Room Temperature Properties of Key VVER Fuel Assembly Materials				
Material	**Mass in FA**	**Melt Temp**	**Conductivity**	**Specific Heat**
304 Stainless Steel	47 kg 104 lb	1400-1455°C 2550-2650°F	14.2 W/m-K 8.2 BTU/hr-ft-F	0.5 J/g-°C 0.12 BTU/lb-°F
Inconel	5 kg 11 lb	1354-1413°C 2470-2580°F	14.9 W/m-K 8.6 BTU/hr-ft-F	0.44 J/g-°C 0.106 BTU/lb-°F
Zircalloy 4	152 kg 335 lb	1850°C 3360°F	21.5 W/m-K 12.4 BTU/hr-ft-F	0.285 J/g-°C 0.0681 BTU/lb-°F
Uranium dioxide	562 kg 1240 lb	2750°C 4982°F	5.86 W/m-K 3.39 BTU/hr-ft-F	0.237 J/g-°C 0.0565 BTU/lb-°F

3.2.2 Component Specifications

Stainless steel and aluminum materials are procured to ASTM A24 304 SS and ASTM B209/B221 respectively. Welding is performed in accordance with ASME Section IX and inspected per AWS D1.6. The polyurethane foam is poured in accordance with approved procedures and specifications.

3.3 GENERAL CONSIDERATIONS

Thermal evaluations of the Traveller were performed by analysis and actual test. The Traveller package utilizes a double wall, insulated, Outerpack to protect an interior box (Clamshell) containing a fuel assembly and blocks of polyethylene moderator. Because of the large length to diameter ratio (8.8), heat transport in most of the package is primarily radial. The thermal analysis performed examined this heat transport path. The seam burn tests, examined radial heat flow with prototypical gas infiltration through the Outerpack seams. The impact limiter burn tests, examined and measured the heat transport through the ends of the package. The final QTU burn test combined all of the possible heat transport mechanism and demonstrated the suitability of the design.

3.3.1 Evaluation by Analysis

The thermal model of the Traveller package was created to examine the response to the hypothetical fire accident conditions described in 10 CFR 71 and IAEA Regulations for the Safe Transport of Radioactive Material, Section VII-728. This analysis was performed to bound the anticipated response and was done by analyzing the response of the package at 800°C external conditions with a fire emissivity of 0.9 and a package emissivity of 0.8 as defined by 10CFR71.73. The analysis was also performed assuming an average fire temperature of 1000°C anticipated during an actual burn test. The analytical burn model did not include potential damage to the Outerpack because:

- Minimum damage was anticipated after drop test
- The anticipated minor damage would not have a significant impact of global performance
- The combined uncertainty of the package damage combined with uncertainty in modeling gas flow patterns around the package made a detailed thermal analysis undesirable.

The analysis results show that the outer skin of the package quickly rises to thermal equilibrium with the fire. The internal components heat up more slowly due to the insulation capability of the polyurethane foam between the inner and outer shell of the Outerpack. Fuel and Clamshell temperatures increase by approximately 50°C and are well within acceptable levels, see Figure 3-1 and Figure 3-2. This analysis is described in greater detail in appendix 3.6.1.

3.3.1.1 Traveller VVER

VVER fuel is comprised of the same materials of construction as Westinghouse type fuel design used in the thermal analysis. Table 3-3C provides a comparison of VVER fuel assembly thermal model input parameters compared to the 17X17 XL fuel design thermal model input parameters. The VVER fuel mass, clamshell length and heat sink mass are slightly less than the 17X17 XL corresponding parameters. Due to geometric differences in design, fuel assembly and clamshell masses per unit length are more than the 17x17 XL corresponding parameters. It is noted that the materials of construction are the same for the shipping packaging and fuel assemblies; thus those thermal properties are the same.

Table 3-3C VVER Fuel Assembly vs. 17X17 XL Fuel Assembly Thermal Analysis Parameters

Parameter	**VVER**	**17X17 XL**	**VVER Delta**	**Notes**
FA Mass	767 kg 1690 lb	783 kg 1726 lb	2.1% less	See Table 3-3A for 17X17 XL materials of construction
Clamshell (CS) Mass	163 kg 360 lb	163 kg 360 lb	None	See Table 3-3A for 17X17 XL materials of construction
Heat Sink Mass (FA + CS)	930 kg 2050 lb	946 kg 2086 lb	1.7% less	
CS length	4.7 m 185 in	5.1 m 202 in	8.9% less	
FA Mass/Unit Length	163 kg/m 9.1 lb/in	153 kg/m 8.6 lb/in	6.1% more	
CS Mass/Unit Length	35 kg/m 2.0 lb/in	32 kg/m 1.8 lb/in	8.6% more	

The thermal model was re-run using the fuel assembly and Clamshell parameters. There was no significant change in the Traveller VVER model's predicted maximum temperature of 108°C (versus 106°C for Traveller XL) for either the 800°C or 1000°C flame temperatures. Thus, Figures 3-1 and 3-2 also represent the predicted VVER maximum temperatures.

Traveller XL thermal analysis consisted of a smeared model based upon simplified geometry. The analysis illustrated the fundamental thermal mechanisms involved and provides a general expected package response assuming no significant hot gas infusion or significant geometry changes (from the drop tests). The thermal analysis was utilized to ensure that peak polyethylene moderator temperatures were below the material's melt temperature. Despite fundamental limitations (i.e. response assuming no hot gas infusion or significant geometry changes), the analysis model demonstrated close agreement to the actual seam burn fire tests (a continuous Outerpack hinge). The internal predicted temperature rise predicted by analysis was 50°C, which is in excellent agreement with the measured temperature rise of 60°C for the continuous hinge burn testing. The analysis predicted a maximum temperature of 106°C on the moderator cover, as compared to an average measured temperature (of the CTU) of 143°C.

The Traveller XL thermal analysis inputs to the smeared model represent the Traveller VVER. The remaining thermal sections; 3.3.2 and 3.3.3 provide Traveller XL evaluation by testing. Sections 3.4 through and including 3.6 provide the Traveller detailed thermal analysis and testing which demonstrated the Traveller XL's thermal design acceptability.

It is concluded that the Traveller VVER, by virtue of its fundamental design similarities to the Traveller XL, and results of the thermal analysis, offers an acceptable thermal design. Hereafter, Traveller thermal evaluations and testing represent the bounding Traveller XL thermal evaluations and testing applicable to Traveller VVER.

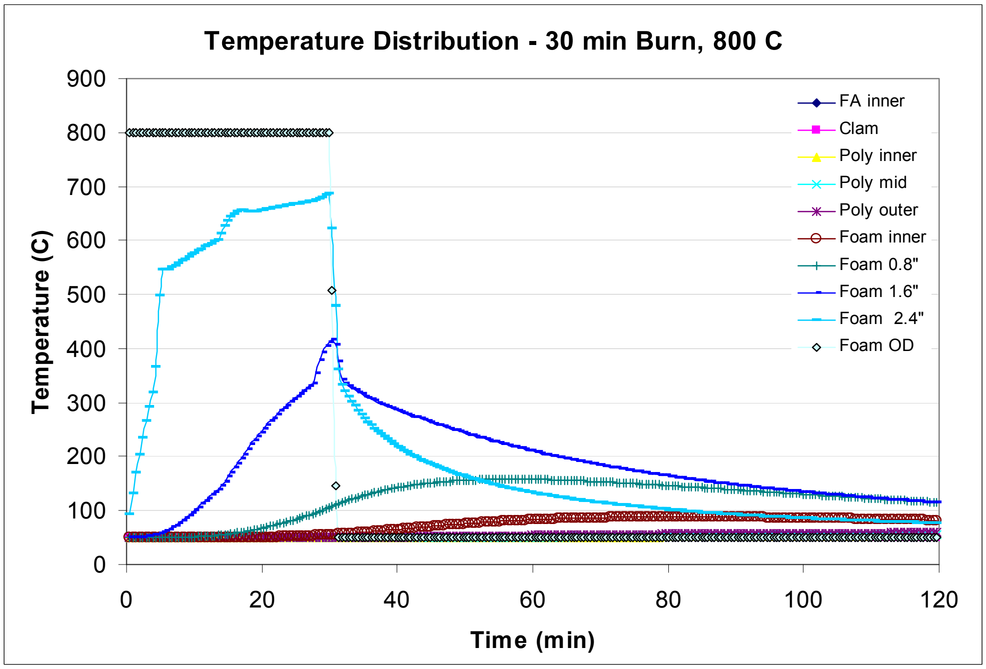

Figure 3-1 Calculated Radial Temperature Distribution for 30 Minute Fire (800°C)

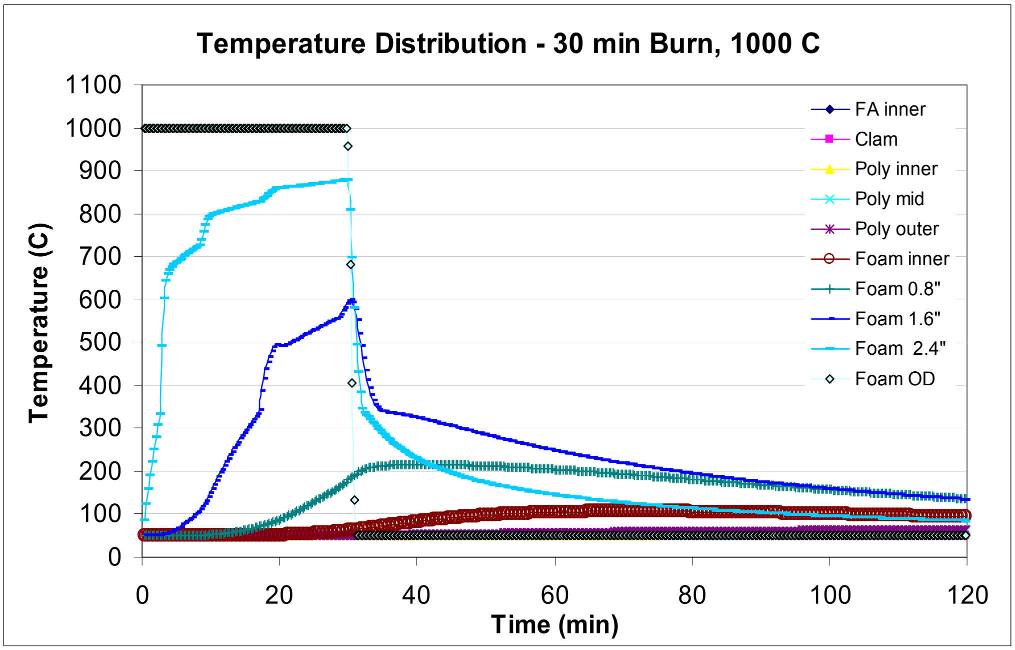

Figure 3-2 Calculated Radial Temperature Distribution for 30 Minute Fire (1000°C)

3.3.2 Evaluation by Test

Traveller performance under hypothetical accident conditions specified in 10CFR71.73 (c) and IAEA Regulations for the Safe Transport of Radioactive Material, Section VII-728 was initially calculated using the SCALE 4.4 thermal analysis code. The performance was subsequently demonstrated in a series of partial burn tests exposing selective portions of a full-scale package to pool fire conditions exceeding the hypothetical accident conditions. Finally, a full scale package was subjected to a full scale, fully engulfing, pool fire exceeding hypothetical accident conditions.

Two separate partial burn tests were performed to verify the final Traveller design. The first was the seam burn test. This test was designed to simulate the flow of hot gas through the Outerpack seams at the hinged joint between the Outerpack base and the Outerpack door and to measure the resulting heat transfer. The second, was the impact limiter burn test. This test subjected the end of a Traveller package to pool fire conditions to measure heat transfer at the package ends. These partial burn tests were then followed by a burn test of the qualification test article. This test, which followed the regulatory drop tests, completely immersed the full scale test unit in a pool fire for more than 30 minutes in flames significantly hotter than 800°C.

3.3.2.1 Seam Burn Test

The seam burn tests were designed to measure performance of different design approaches of protecting polyethylene moderator from excessive heat during the hypothetical fire conditions. Previous burn tests had revealed a tendency for package structures to deform in pool fires potentially allowing hot gasses to enter the package. The tests, performed in a previously burned package with large gaps left between the upper and lower Outerpack to allow hot gases to enter the package. One section, used as a control, had no protection for interior structures. The second section covered the Outerpack seam with stainless steel hinges to model a design with essentially continuous hinges. The third section used 26 gage stainless steel to cover the moderator blocks. The steel cover sheet was stitch welded in place, leaving gaps for combustion air to enter. The test approach is described in appendix 3.6.2

The first burn was of the control section. During the 30 minute burn, internal temperatures rose within the test section throughout the test due to the gap deliberately left in the seam between Outerpack base and lid Peak internal temperatures over 500°C were observed, Figure 3-3.

The second test burn was of the section protected with essentially continuous hinge material. This section had a similar gap between the Outerpack base and lid, but gas flow through the package was minimized by the hinge sections. This burn lasted for 35 minutes with internal temperatures rising to 75°C (from an initial temperature of 35°C). After the burn was completed, interior temperatures continued to rise, peaking after 30 minutes at approximately 100°C.

The third test section was burned for 35 minutes as well. The internal temperatures measured show temperatures rose at a much higher rate than in the second test. This was expected because of the large gapes in the Outerpack seam (varying between 0.5 and 1.5 inches at the bottom seam). One thermocouple showed temperature at the bottom moderator blocks rose above 350°C within 25 minutes after the start of the burn.

After the pool fire was extinguished, some smoke was observed at the top Outerpack seam. This corresponded with a high temperature measurement on the moderator surface. Later examination showed that a small section of moderator burned for a limited period of time.

The seam burn tests showed that, where the Outerpack seam was covered by a hinge, that hot gas ingestion was virtually eliminated. Peak internal temperatures were approximately 100°C. With gaps in the Outerpack seams, peak internal temperatures exceeded the 350°C, the ignition temperature of polyethylene. Covering the moderator with stainless reduced the heat up rate, even with larger seam gaps, but moderator combustion took place near gaps in the stainless steel cover sheet. The tests showed that the best approach to prevent moderator combustion is to incorporate continuous hinge sections to prevent hot gas ingestion. The tests also showed that, to prevent combustion of moderator, assuming higher temperatures are experienced within the package, the stainless steel cover must be welded closed to prevent significant amounts of oxygen from reaching the polyethylene.

Figure 3-3 Seam Burn Test

3.3.2.2 Impact Limiter Burn Test

The seam burn tests described above examined the performance of the center portion of the package. The impact limiter burn test examined the thermal performance of the bottom end of the Traveller package. Both burns engulfed the bottom impact limiter and approximately 1.2 meters (four feet) of the package beyond the bottom impact limiter. Thermocouples were mounted at 16 locations inside and outside the package. The

test unit was mounted over the small weir built for the seam burn tests and burned for 40 minutes, Figure 3-4. Because the ambient temperature dropped below freezing during the night, initial temperatures inside the package started the test at approximately 0°C. Temperatures within the impact limiter pillow climbed to between 70 and 95°C depending on location during and after the burn test. Temperatures within the Outerpack interior cavity varied from 50 to 320°C. The only temperature measurements above 200°C were at locations near the outside skin of the Outerpack and well away from the moderator or impact limiter pillow.

The relatively high temperature observed at the Outerpack top seam led to questions of heat transfer. Was hot gas entering past the lip on the Outerpack door, or was the temperatures the result of heat conduction through the metal of the impact limiter bulkhead? The impact limiter burn test was therefore repeated but with Kaowool insulation stuffed into the Outerpack upper seam to prevent hot gasses from entering the package from that location. A 30 minute burn was performed in the late afternoon, so the initial temperatures inside the package were higher than the previous day. Temperatures within the Outerpack interior cavity varied from 80 to 340°C with the high temperatures being the closest to the Outerpack outer skin. Temperatures within the impact limiter pillow climbed to between 70 and 95°C depending on location during and after the burn test. The Outerpack top seam temperature rose to the same levels with insulation stuffed into the seam, demonstrating that the primary heat transport mechanism in this region is conduction. The slightly faster heat up rate can be attributed to several factors including the fact that the polyurethane insulating foam in the Outerpack had already been burned in earlier tests. These tests are described in greater detail in appendix 3.6.3 below.

Figure 3-4 December 15, Impact Limiter Burn Test

3.3.3 Margins of Safety

The Traveller protects its contents with a polyurethane insulated, double walled, stainless steel Outerpack. This Outerpack provides sufficient insulation to prevent significant heat conduction and maintain low interior temperatures during a hypothetical fire accident. The Outerpack also incorporates design features that prevent convective heat transfer. The tests described in 3.3.2 above, identified features (continuous hinge lengths and a large lip over the bottom seam) that prevent hot gases from entering the Outerpack seams. The results of these tests, as described in sections 3.5.2 and appendices 3.6.3 and 3.6.4 show that internal temperatures remain low when the Outerpack seams are adequately protected. These features were incorporated into the CTU test article and the production design. When the CTU was tested, significant margins of safety were observed as illustrated by Table 3-1 above. The most temperature sensitive component, the polyethylene moderator blocks, have an additional level of protection. The blocks are sealed by stainless steel cover sheets and are insulated at the ends. In the event that local conditions exceed the combustion temperature of the polyethylene, the moderator is protected by an insulating air gap (and refractory fiber felt insulation at the ends). Additionally, the moderator is isolated from oxygen preventing significant combustion.

3.4 THERMAL EVALUATION UNDER NORMAL CONDITIONS OF TRANSPORT+

The package will only be used to ship non-irradiated nuclear fuel. The contents contains no heat generating radioactive material. Therefore, the surface temperature of the package will not rise above ambient temperatures. As such, there is no need to evaluate by analysis or perform tests to demonstrate the maximum package surface temperature. All materials used within the Traveller package retain their desired properties over the entire range of possible ambient temperatures. The package is not hermetically sealed allowing interior pressure to adjust with changes in elevation and allowing expansion/contraction of internal air during temperature changes.

3.5 THERMAL EVALUATION UNDER HYPOTHETICAL ACCIDENT CONDITIONS

The primary verification of the Traveller's performance in a hypothetical accident was demonstrated in the burn test of a full-scale package loaded with a simulated fuel assembly. This unit was identified as the certification test unit (CTU). According to 10 CFR71.73 "Thermal. Exposure of the specimen fully engulfed, except for a simple support system, in a hydrocarbon fuel/air fire of sufficient extent, and in sufficiently quiescent ambient conditions, to provide an average emissivity coefficient of at least 0.9, with an average flame temperature of at least 800ºC (1475ºF) for a period of 30 minutes, or any other thermal test that provides the equivalent total heat input to the package and which provides a time averaged environmental temperature of 800ºC. The fuel source must extend horizontally at least 1 m (40 in), but may not extend more than 3 m (10 ft), beyond any external surface of the specimen, and the specimen must be positioned 1 m (40 in) above the surface of the fuel source. For purposes of calculation, the surface absorptivity coefficient must be either that value which the package may be expected to possess if exposed to the fire specified or 0.8, whichever is greater; and the convective coefficient must be that value which may be demonstrated to exist if the package were exposed to the fire specified. Artificial cooling may not be applied after cessation of external heat input, and any combustion of materials of construction, must be allowed to proceed until it terminates naturally." (The IAEA Regulations for the Safe Transport of Radioactive Material, Section VII-728 have similar specifications.)

A Traveller XL package was fabricated by Columbiana High Tech to serve as the certification test article. This unit was subjected to a regulatory drop test performed February 5, 2004 in Columbiana, Ohio. This package was transported to the South Carolina Fire Academy in Columbia, South Carolina on February 6. The package was installed in the burn pool and subjected to a 32 minute burn test on February 10, 2004. Although the Outerpack had suffered minor damage that allowed some urethane decomposition products to escape into the package interior, the fuel assembly, Clamshell, and polyethylene moderator were essentially undamaged.

The testing was conducted on a calm day. To further minimize the impact of winds, the burn pool was surrounded with an insulated steel diffuser that extended to the top of the package and expanded the effective fire area. The maximum distance between the package and the diffuser was less than the 3 meters maximum proscribed distance, Figures 3-5 and 3-6.

Twenty-two, inconel sheathed type-K thermocouples were used to measure flame temperature immediately around the Traveller and the Outerpack outer skin as shown in Figure 3-7. Before and during the pool fire, temperature measurements were made at 16 locations using type K thermocouples located. During the test temperatures were measured at six locations on the package skin, at twelve locations inside the pool fire, at four locations using directional flame thermometers (DFTs) facing away from the package, and from outside the fire using two optical thermometers.

Figure 3-5 Pool Fire Test Facility

Figure 3-6 Traveller CTU During Pool Fire Test

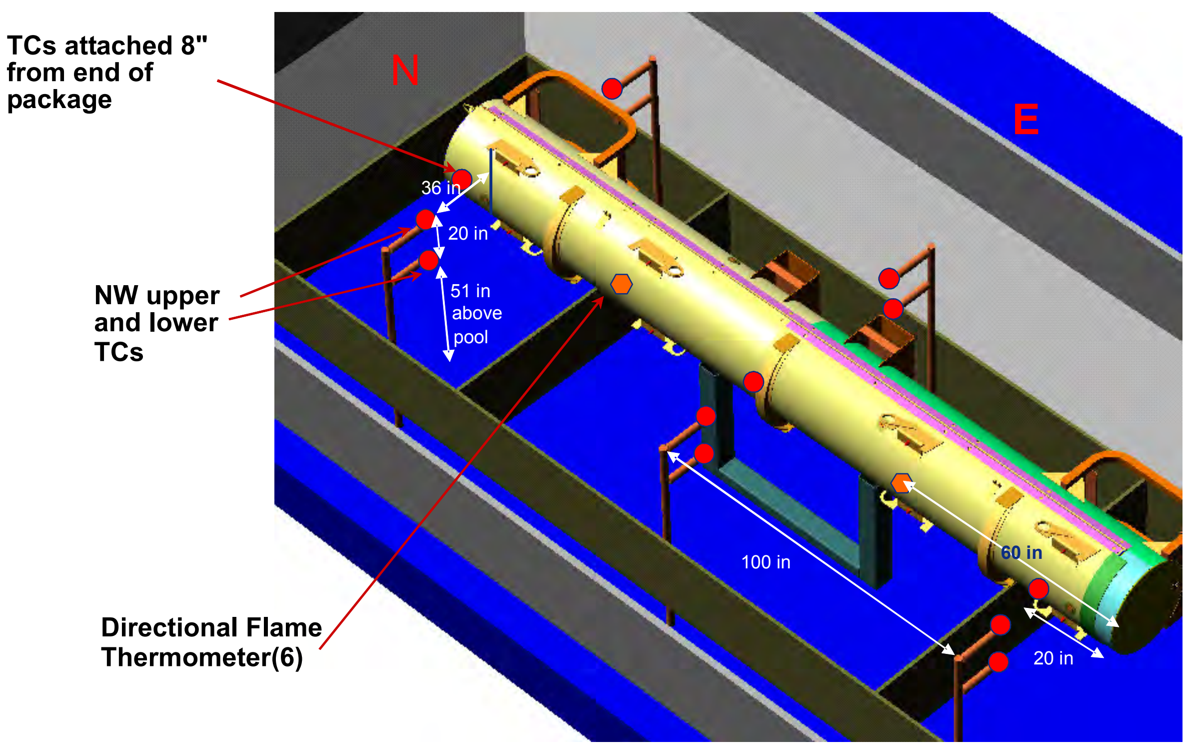

Figure 3-7 Thermocouple Locations Measuring Fire Temperature During CTU Burn Test

3.5.1 Initial Conditions

The package was covered with a canvas tent approximately 16 hours before the burn test. Two 44 kWth (150,000 BTU/hr) kerosene heaters were used, alternately, to maintain air temperature within the tent to above 37°C. The heaters were secured and the tent removed approximately 75 minutes before the beginning of the fire test. Air temperature around the package at this time averaged at 50°C (122°F). The air temperature and outside surface temperature dropped to approximately 5°C (41°F). Additional information can be found in appendix 3.6-4.

3.5.2 Fire Test Conditions

The CTU burn test was performed on a cool, calm, lightly overcast morning. The test article was located on a stand in a water pool. Fuel was pumped into manifolds under the surface of the pool to provide an even distribution of fuel for the pool fire. Approximately one minute after the fuel on the surface of the pool was ignited, the test article was completely engulfed. The fuel system continued to pump fuel into the fire until 32 minutes after the pool was lit. The pool fire was extinguished approximately one minute later. Fire temperatures were measured using four directional flame thermometers (DFTs) and 12 thermocouples suspended in the fire 0.9 m (3 feet) from the surface of the package. The 30 minute average temperatures measured by the DFTs were 833°C (1531°F). The 39 minute average temperature measured by the thermocouples suspended in the fire was 859°C (1578°F). Two, hand-held, optical thermometers that measured flame temperature from outside the pool supplemented these measurements. The average readings made with these thermometers was 958°C (1757°F).

3.5.3 Maximum Temperatures and Pressures

Temperatures were measured on the CTU Outerpack outer skin using six type K thermocouples, attached by screws. These thermocouples were located as shown in Figure 3-7 above. The 30 minute average temperature measured by these thermocouples was 904°C (1659°F). Temperatures inside the CTU Outerpack were measured using 13 sets of non-reversible temperature strips. One set on the inner stainless steel skin covering the Outerpack lid moderator was unreadable. All of the remaining temperature strips on the Outerpack lid recorded temperatures of 177°C (351°F) or below. Temperatures on the inside surface of the top and bottom impact limiters were 116 (241°F) and 149°C (300°F) respectively. Temperatures inside the Clamshell were below 104°C (219°F). An example of the temperature strip sets attached to the Outerpack lid moderator cover sheets is shown in Figure 3-8.

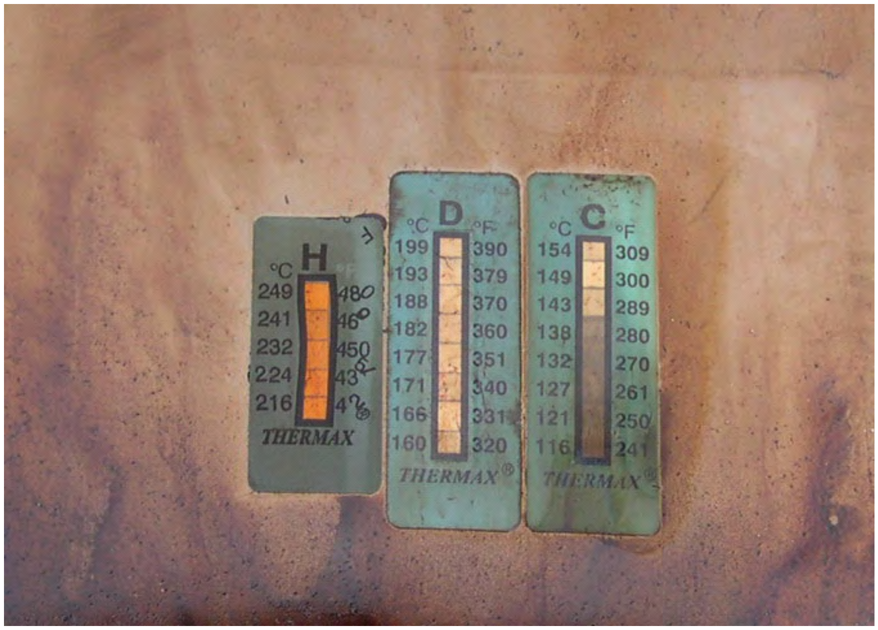

Figure 3-8 Temperature Strip Condition After CTU Burn Test

Although the thermal testing was done with the fiberglass seal, the detailed evaluation of the package after test revealed that the Outerpack hinge was the effective heat shield [1]. The temperature of the moderator blocks during this testing never reached even 100ºC, well below the ignition temperature of the polyethylene moderator blocks or melting temperature of the aluminum clamshell material. The braided fiberglass gasket material alone was not an effective heat shield and did not provide any significant barrier to limiting the heat-up of the interior of the package during the thermal testing. The fiberglass seal was retained to provide packaging weather gasket to keep dust, dirt and spray from getting inside the Outerpack. The seal material may be either braided fiberglass or soft conformable silicone rubber as shown in Figure 3-8A.

The Traveller package design is non-pressurized and cannot retain internal pressure. Weather gasketing seals are discontinuous to prevent internal pressurization during the hypothetical fire and during normal variations in temperature and atmospheric pressure. The polyurethane foam space between the inner and outer shells of the Outerpack is protected from pressurization through the use of vent plugs. Every internal foam compartment within the Outerpack is protected by at least one acetate vent plug that will melt in the event of a fire and allow the internal spaces to vent. As a result, no significant increase in pressure was observed during the testing, nor is anticipated in any hypothetical accident condition.

The Traveller design surrounds the fuel assembly and polyethylene moderator with an insulated outer package. As a result, the outer surface of the package quickly reaches equilibrium with the fire while the interior remains cool. This is indicated by analysis and by the burn tests described above. The peak temperature measured on the Clamshell and the moderator covers were consistent between the seam burn test, the impact limiter burn test and the CTU burn test. All temperatures remained below 177°C and most locations remained below 100°C. No significant thermal damage was observed in the fuel assembly,

Clamshell or moderator blocks after the fire test. Moderator blocks were weighed before and after the fire test. No measurable reduction in mass was found.

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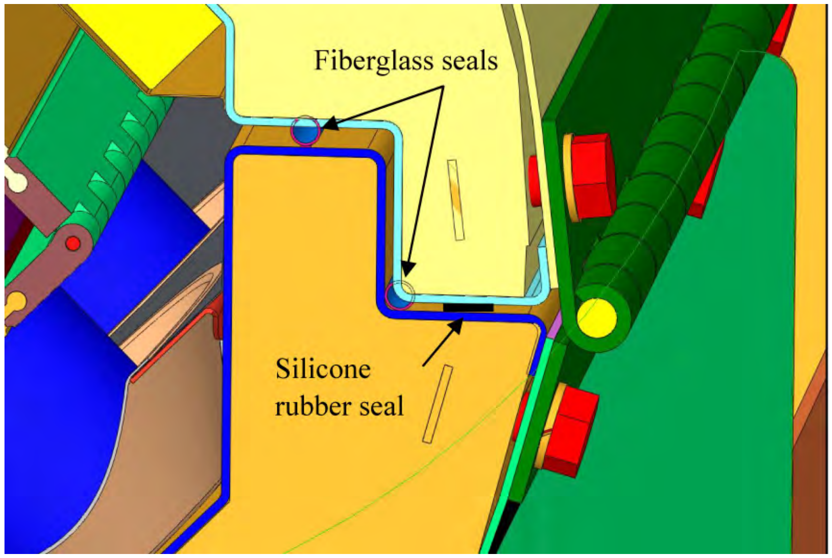

Figure 3-8A Outerpack Flange Joint Showing Location of Packaging Weather Seal Gasket Options (1) Fiberglass Seal or (2) Silicone Rubber Seal

3.5.4 Accident Conditions for Fissile Material Packages for Air Transport

Application will be made for air transport at a later date.

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3.6 APPENDICES

The following appendices are included to provide amplifying information on material contained elsewhere in section 3.

- 3.6.1: References
- 3.6.2: Traveller Thermal Analysis
- 3.6.3: Traveller Seam Burn Tests
- 3.6.4: Traveller Impact Limiter Burn Tests
- 3.6.5: Traveller Certification Test Unit (CTU) Burn Test

3.6.1 References

1. CN-NFPE-09-86, (7/14/2009), "Justification for Removal of Traveller Heat Seal," Westinghouse Proprietary Class 2.

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3.6.2 Traveller Thermal Analysis

A simplified computer model was developed using the HEATING7.2 code distributed by Oak Ridge National Laboratory as a part of SCALE 4.4. The model was built in cylindrical coordinates using the simplified geometry shown in Figure 3-9. This simplification was possible because:

- Primary temperature variations occur in the Outerpack foam that is cylindrical on the outside
- Simplifying interior foam surface by making it cylindrical is conservative
- The large length to diameter ratio (8.9:1) minimize end effects
- The ends have twice the thickness of polyurethane foam as the sides further reducing end effects

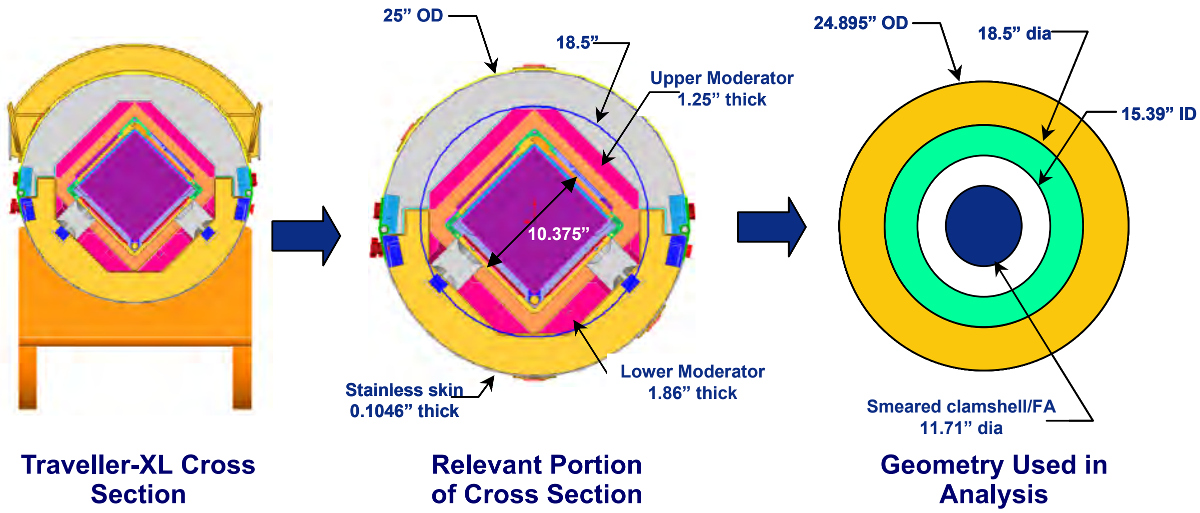

Figure 3-9 Approach Used to Generate Analytical Model Geometry

Three material regions were used in the analysis: Polyurethane foam with an average density of 10 lb/ft^3, Polyethylene, and a smeared mixture representing the mid-section of the Clamshell and fuel assembly.

The Clamshell and fuel assembly region was modeled as a heat sink representing a 17x17 XL fuel assembly within the 9.50 inch (24.13 cm) inside dimension aluminum Clamshell. Because the end effects were to be ignored in this model, the fuel assembly nozzles and the Clamshell end plates were not included in this calculation. This resulted in the following material ratios:

- Aluminum Clamshell – 359.7 lb (163.2 kg) with a specific heat of 0.23 BTU/lb-°F (0.96 J/g-°C),

- Uranium Dioxide – 1341 lb (608.3 kg) with a specific heat of 0.0565 BTU/lb-°F (0.237 J/g-°C)

- Zircalloy 4 – 330 lb (149.7 kg) with a specific heat of 0.0681 BTU/lb-°F (0.285 J/g-°C)

The Traveller XL Clamshell is 202.0 inches (513.1 cm) long. The heat sink region weighs 2031 lb (921.1 kg), has an average specific heat of 0.891 BTU/lb-°F (0.373 J/g-°C) and a smeared density of 0.0934 lb/in^3 (2.58 gm/cc).

A volumetric average conductivity was generated for the Clamshell and fuel assembly region by calculating a volume smeared conductivity by using the ratio of conductivity to volume for each material.

- Aluminum Clamshell – 3560 in^3 (58,300 cc) with a conductivity of 104 BTU/hr-ft-F (182 W/m-K)
- Uranium Dioxide – 3380 in^3 (54,500 cc) with a conductivity of 3.39 BTU/hr-ft-F (5.86 W/m-K)
- Zircalloy 4 – 1400 in^3 (23,000 cc) with a conductivity of 12.4 BTU/hr-ft-(21.5 W/m-K)

Total volume used in the Clamshell/fuel assembly region is 21,700 in^3 (356,000 cc). This results in a smeared conductivity of 18.3 BTU/hr-ft-F (32.1 W/m-K). This approximation is valid only because the heat input rate is very low allowing the region to be almost isothermal, even with low conductivities.

The Traveller XL Outerpack contains approximately 426 lb (193 kg) of UHMW polyethylene with specific heat of 0.526 BTU/lb-°F (2.2 J/g-°C) and a conductivity of 24 BTU/hr-ft-°F (0.42 W/m-°C). The total length of the moderator within the Outerpack is approximately 206 inches (523 cm). For the geometry defined for the model, this results in a smeared polyethylene density of 0.0249 lb/in^3 (0.689 g/cc) which is 74% of predicted minimum density. The polyethylene acts as a heat sink and an insulation of primary heat sink.

The polyurethane foam room-temperature properties are given in Table 3-4. The properties change significantly, however, as the foam temperature increases resulting in pyrolization which occurs between 600 and 650°F (316 and 343°C). After charring, the material has the general appearance of very low density carbon foam. For the analytical model, the room temperature specific heat and conductivity were used up to 600F. Above 650°F, the temperature dependent conductivity of air was used instead. Between 600 and 650°F, foam specific heat is assumed to drop to zero.

Table 3-4 Temperature Dependent Thermal Conductivity Used to Model Polyurethane Foam

Temperature (F)	Conductivity (BTU/hr-ft-F)	Conductivity (W/m-K)
100	.0230	.0398
600	.0230	.0398
650	.0249	.0431
700	.0268	.0464
800	.0286	.0495
1000	.0319	.0552
1500	.0400	.0692
2000	.0502	0.0869

The surface emissivity of the foam was set at 0.8. The first analysis performed modeled a 30 minute fire with flame temperature of 800°C. This analysis, Figure 3-1, showed significant temperature variation through the thickness of the polyurethane foam. Peak temperatures on the inside surface of the foam reached 100°C approximately 80 minutes after the beginning of the fire (50 minutes after the fire was put out).

Because the planned fire test facility burns at a higher temperature, the same analysis was performed assuming a 1000°C fire temperature. As shown in Figure 3-3, peak temperature within the polyethylene (at the interface between the polyurethane foam and the polyethylene) was calculated to reach 106°C. This is below the 125 – 138°C melt temperature of the polyethylene and well below the temperature that the melted polyethylene viscosity is low enough to flow easily.

The thermal analysis performed demonstrated several important features/characteristics of the design. Because of the urethane foam insulating the Outerpack, exterior skin temperatures quickly rise to near equilibrium with the fire outside the package. The clamshell and fuel assembly temperature, rise very slowly due to the insulation and the specific heat of the aluminum clamshell, polyethylene moderator, and the fuel assembly. The primary mechanisms that can result in significantly higher internal temperatures is hot gas infiltration during the fire and internal combustion during and after the fire test. We do not believe that these mechanisms can be accurately predicted by analysis. As a result, the Traveller team chose to demonstrate the package using pool fire tests, culminating with a full-scale fire test.

The seam burn tests with continuous hinge sections demonstrated approximately 60°C temperature rise during and after the test which was in close agreement with the 50°C temperature rise predicted by the analysis. The CTU burn test demonstrated internal temperatures between 116° and 177°C. This is 112° to 173°C higher than the air temperature that morning. These values are only 66° to 127°C higher than the equilibrium package temperatures maintained by heaters before the fire. As noted above, the external skin temperature at the middle of the package was significantly higher at the middle. Secondly, the amount of hot gas entering the package at different locations along the length clearly affects the local internal temperatures. Greater quantities of hot gas probably entered that package at that location.

Because of the fundamental limitations of the analysis (e.g., inability to predict precise geometry changes during the fire) the analysis model was never refined and exact agreement was never anticipated with test results. The analysis does illustrate the fundamental mechanisms involved and the general characteristics of the package response, assuming no significant gas infiltration or geometry changes.

3.6.3 Traveller Seam Burn Tests

This test examined two methods of protecting the polyethylene to prevent combustion and/or significant melting. One was the use of continuous hinges to seal the gap at the seam and the second was to cover the moderator with stainless steel sheet to prevent combustion. A third test section was also created to act as the test control. This section did not have any additional protection for the moderator.

The test was performed as series of three burns, heating the reference or control section, the section with additional hinge to model a package with continuous hinges, and the section with stainless covering over the moderator respectively. The first burn lasted 30 minutes. The two subsequent burns lasting for 35 minutes. A small pool fire (approximately 30 x 80 inches) was be created under the region of the package to be tested, Figure 3-10. Each region was approximately 57 cm (22.4 inches) across separated from the adjacent test region by 61 cm (24 inches) of refractory fiber felt insulation. This insulation was stuffed between the Clamshell and the moderator to prevent air flow from the section being tested to other test regions within the prototype package. The test regions were selected based having intact moderator left from previous tests. The test section with stainless steel cover over the moderator was selected based on the minimum distortion of the inner Outerpack shell and moderator blocks. The outside of the package was insulated on the bottom and sides using at least 2.5 cm (one inch) of refractory fiber felt insulation. This insulation will extend at least 1.2 m (48 inches) from each end of the test region, Figure 3-11.

Six thermocouples were attached in each test section. Two were screwed to the moderator bottom edge nearest the seam, one was screwed to the moderator/Outerpack where the two moderator blocks meet, one was screwed to the moderator block near the top seam, one was screwed to the Clamshell J-clip, and one was run through the bottom seam to hang approximately four inches below the package in the flames. Thermocouple connections and Teflon coated wires were routed out of the package at each end.

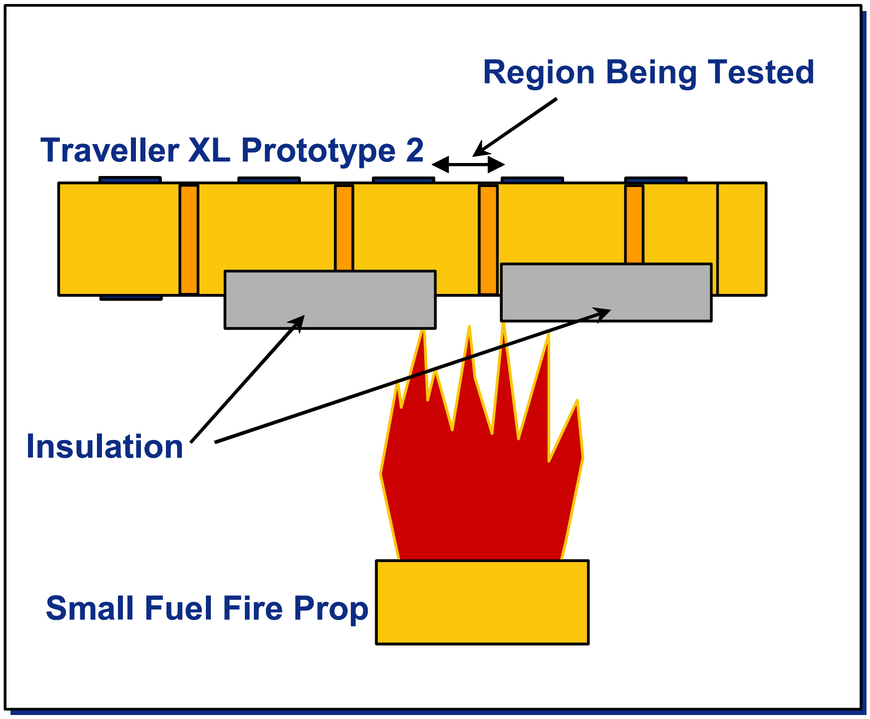

Figure 3-10 Seam Burn Test Orientation

Figure 3-11 Package Exterior Wrapped with Ceramic Fiber Insulation

3.6.3.1 Test Results

The first test burn was on the unprotected, control section of the package on October 3. Due to strong winds, flames did not stay on the test section. As a result, temperatures remained low and ultimately the thermocouple wires were burnt before the test was completed. Afterward, the weir was modified to extend the height up to the bottom of the package to confine the flames to the test region.

The burn of the control section was then repeated on October 6. The new weir confined the fire to the test section and temperatures rose within the test section throughout the test, Figure 3-12. After the pool fire was extinguished, burning polyurethane was observed along the top seam of the package and at the bottom seam of the test section. This was extinguished after approximately 10 minutes and the package was opened. Significant moderator was lost.

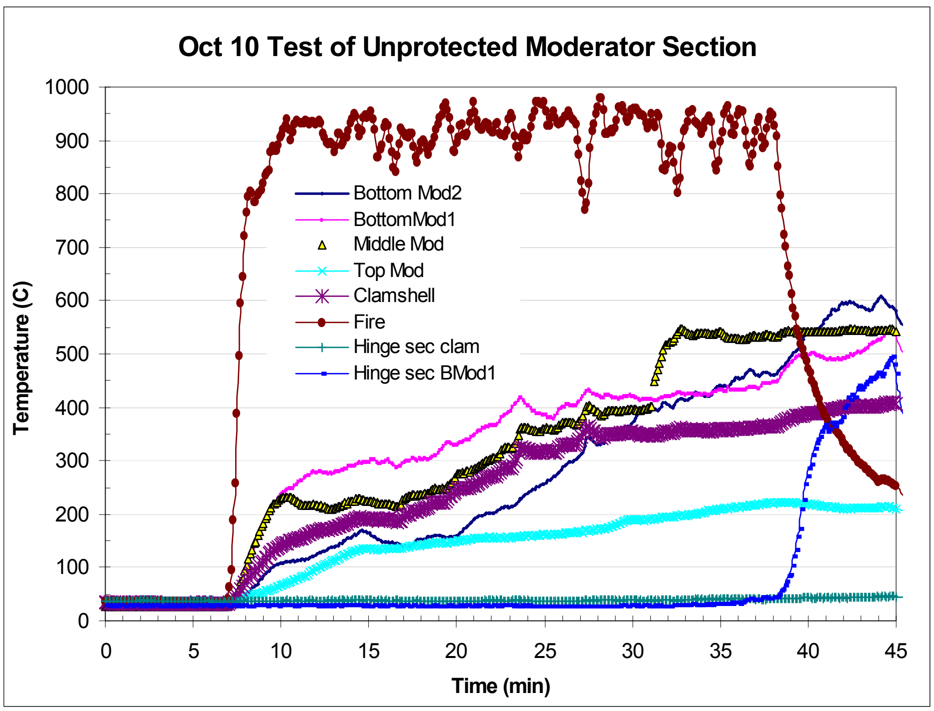

Figure 3-12 Measured Temperatures During Second Burn of the Control Section

The package was then closed, reinsulated, and the section modeling continuous hinges tested. This burn lasted for 35 minutes instead of the 30 minutes in the previous test. Thermocouple data, Figure 3-13, was incomplete because two of the channels (the external fire temperature and the middle moderator thermocouples) were bad. The latter produced very noisy data indicating that a connector was bad and the former did not change values throughout the test. Subsequent inspection revealed that the thermocouple itself was broken at the Outerpack seam. The data that was gathered from the internal thermocouples in the hinge test section and in the adjacent control section showed little change in internal temperatures. Temperatures rose very slowly during the burn test, with internal temperatures reaching a peak of 75°C at

the end of the test. After this data was collected and saved, additional temperature data was collected during the next 30 minutes after the burn, Figure 3-14. Temperatures slowly increased to approximately 100°C. This is consistent with thermal analysis that shows that heat transfer by conduction through the Outerpack polyurethane foam will continue to add heat to the interior for over an hour after the beginning of the burn, see section 3.1.

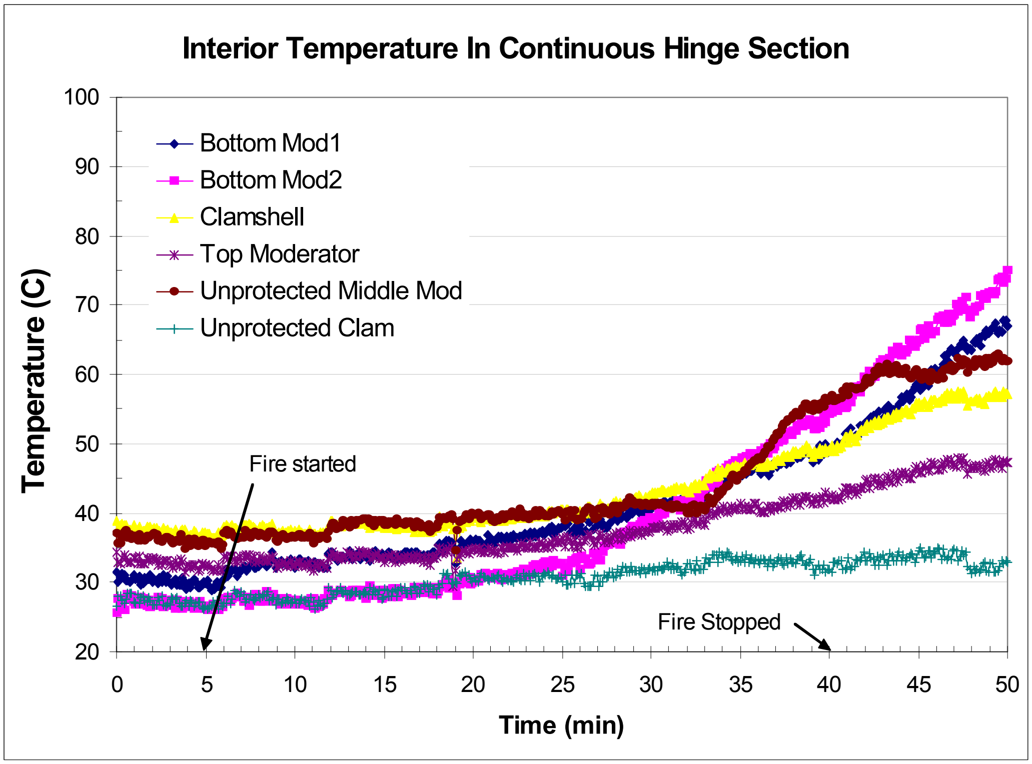

Figure 3-13 Interior Temperature Measurements During Test of Continuous Hinge Section

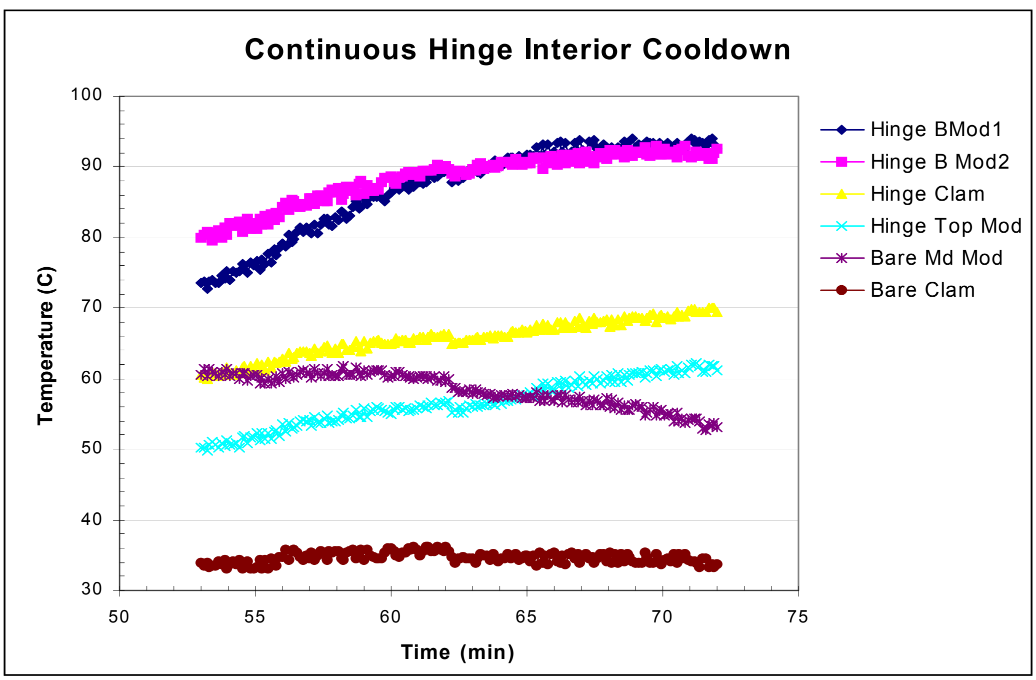

Figure 3-14 Interior Temperature Measures After Test of Continuous Hinge Section

The package was then moved on the test stand and positioned with the third test section, the covered moderator, over the burn weir. This section was burned for 35 minutes as well. The internal temperatures measured, Figure 3-15, show temperatures rose at a much higher rate than in the second test. This was expected because of the large gapes in the Outerpack seam (varying between 0.5 and 1.5 inches at the bottom seam), Figure 3-16. One thermocouple showed temperature at the bottom moderator blocks rose to above 350°C within 25 minutes after the start of the burn. After the pool fire was extinguished, some smoke was observed at the top Outerpack seam. This corresponded with an eventual rise in moderator temperature at one location after the external fire had been extinguished. After approximately 15 minutes, the package was cooled by water spray and removed from the burn pool. When opened, there was not initial sign of damage. After the stainless steel covering the moderator was removed, however, it was confirmed that small amounts of the moderator had burned.

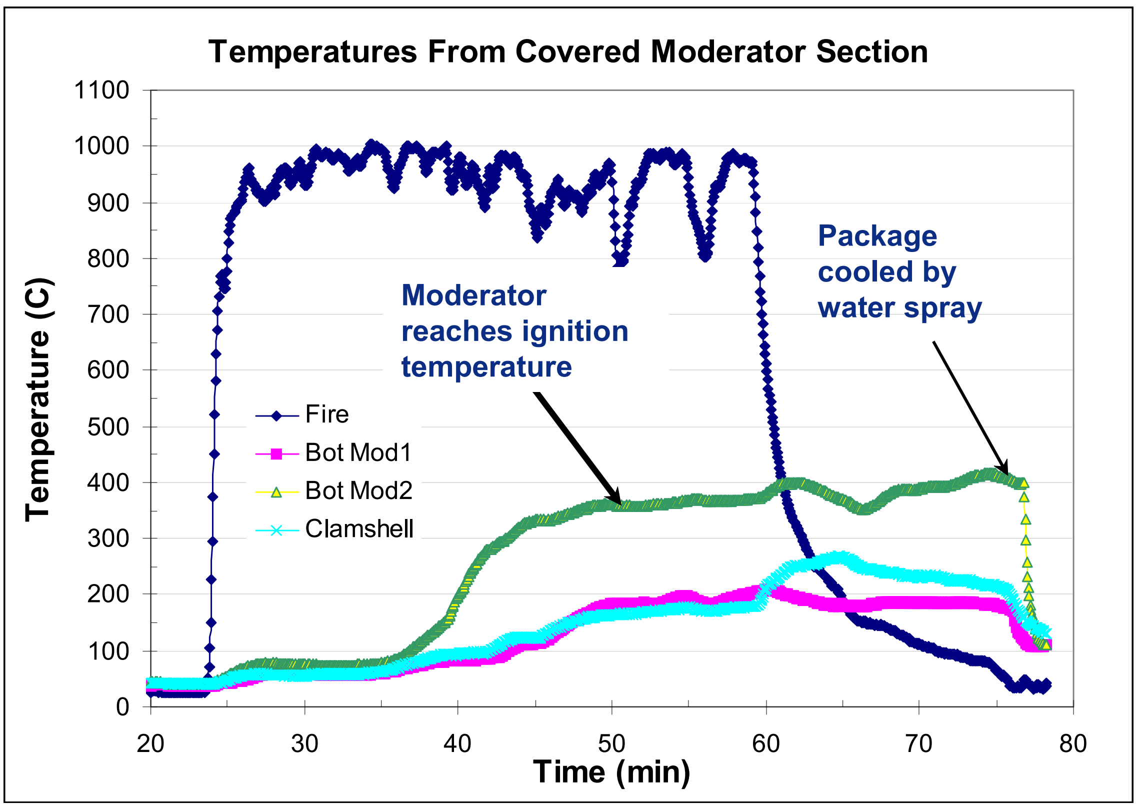

Figure 3-15 Interior Temperature Measurements During Test of Covered Moderator Section

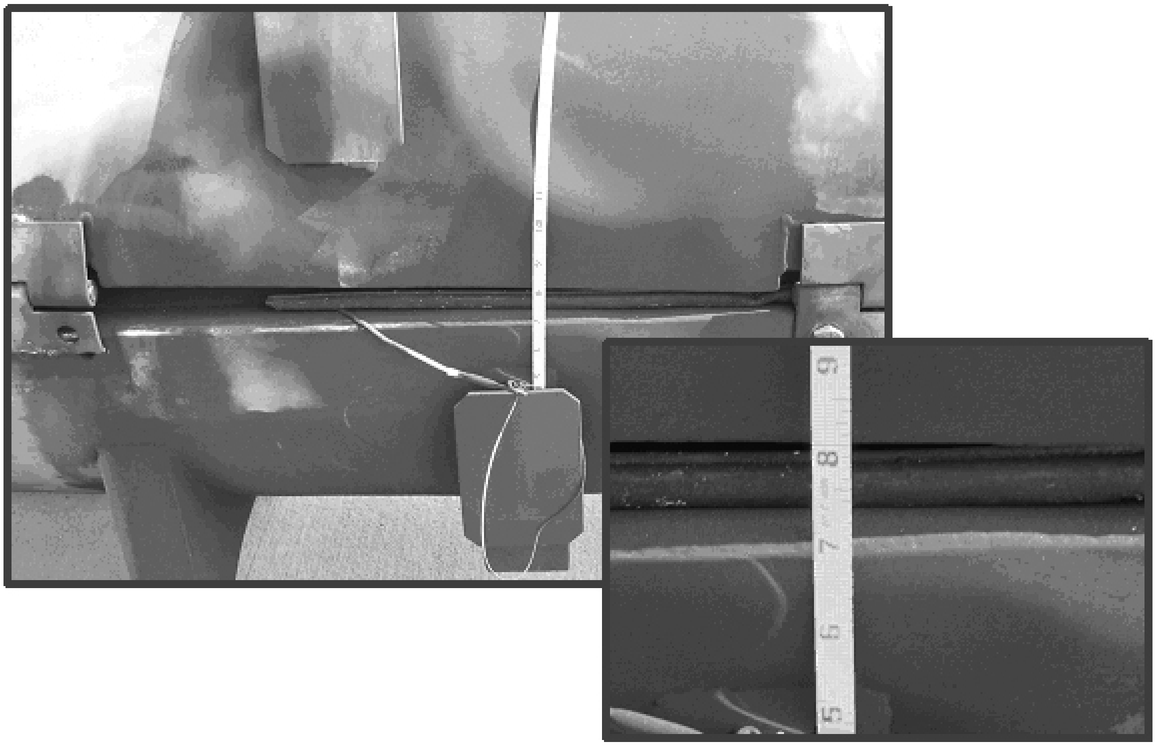

Figure 3-16 Gaps in Outerpack Bottom Seam at Covered Moderator Test Section

3.6.3.2 Conclusions

Tests showed that, where the Outerpack seam was covered by a hinge, that hot gas ingestion was virtually eliminated. Peak internal temperatures were approximately 100°C. With gaps in the Outerpack seams, peak internal temperatures exceeded the 350°C ignition temperature of polyethylene. Covering the moderator with stainless did appear to reduce heatup rate, even with larger seam gaps, but moderator combustion took place anyway. The tests showed that the best approach to prevent moderator combustion is to incorporate continuous hinge sections to prevent hot gas ingestion during the burn test.

3.6.4 Traveller Impact Limiter Burn Tests

A Traveller package was subjected to two burn tests after being tested in a full series of regulatory drops. This test series focused on the heat transfer characteristics of the bottom end of the package. This end is referred to as the bottom impact limiter. The top and bottom impact limiters are divided into two regions with high (20 lb/ft^3) density foam in the outer regions and low density foam (6 lb/ft^3) pillows inside. The foam pillow is separately encased in stainless steel with a 0.64 cm (0.25 inch) impact plate to minimize the chance of exposing the foam. Each pillow also has a 0.64 cm (0.25 inch) thick plate out the outer end as a heat sink to reduce peak temperatures in a fire. The foam pillow is also separated from the inside end of the outer impact limiter foam with approximately 0.32 cm (0.125 inches) of refractory fiber felt insulation.

During both tests, the package was instrumented with 16, inconel sheathed, type K thermocouples (Omega part numbers XCIB-K-4-2-10 and XCIB-K-2-3-10). Seven thermocouples were mounted on or around the impact limiter pillow, one midway through the outer impact limiter foam, and one on the outer impact limiter skin, Figure 3-17. The remaining seven thermocouples were mounted inside the Outerpack. The location of the thermocouples is shown in Figure 3-18.

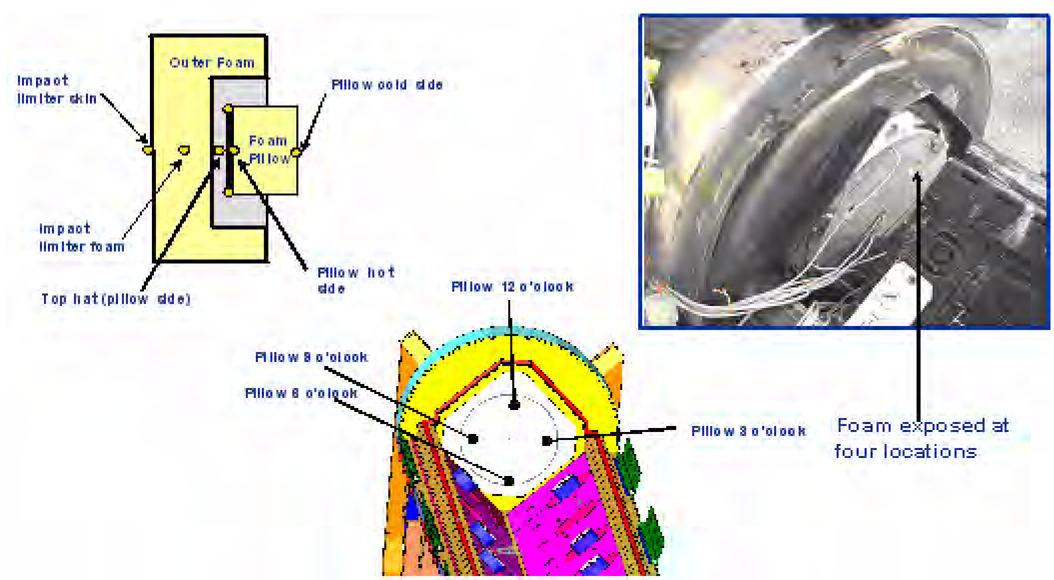

Figure 3-17 Thermocouple Locations in Impact Limiter

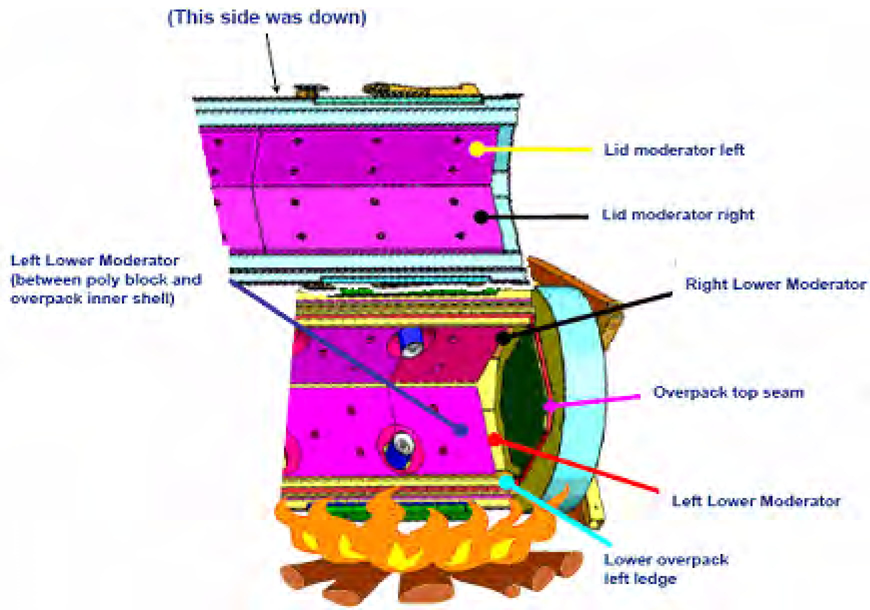

Figure 3-18 Thermocouple Locations in Outerpack Interior

The thermocouples were connected to thermocouple wire extensions using standard Type K plugs connecting the thermocouples to 20 gage type K extension wire. The 16 thermocouple cables were connected to two data acquisition systems. One system used an Omega OM-CP-OCTTEMP 8-channel data logger. This unit was set in operation before the test using a laptop computer and stored data from each channel at a rate of 12 samples per minute. After the test was completed, the data was download to the same laptop computer. The second system used an 8-channel Omega INET-100 external A/D box connected to an INET-230 PC-Card controller with a INET 311-2 power supply. This recorded data directly into the laptop computer allowing these channels to be monitored during the test.

Additional data was taken on external temperatures using two OMEGA OS523 handheld optical thermometers during the December 15 test. These units were used to measure flame temperatures and outside package skin temperature after the pool fire was extinguished.

A previously drop tested unit was modified to incorporate these changes in the bottom impact limiter and was subjected to two burns, one on December 15, and the second on December 16. Both burns engulfed the bottom impact limiter and approximately 3 feet of the package above the bottom impact limiter. Thermocouples were mounted at 16 locations inside and outside the package. Data from eight of the thermocouples were recorded by a laptop PC based Instrunet system that allowed data to be monitored in real time. The other eight channels were recorded using a battery powered Omega data logger.

3.6.4.1 First Impact Limiter Burn (December 15)

The test unit was mounted over the small weir built for the seam burn tests and burned for 40 minutes, Figure 3-19. Because the ambient temperature dropped below freezing during the night, initial temperatures inside the package started the test at approximately 0°C. Temperatures within the impact limiter pillow climbed to between 70 and 95°C depending on location during and after the burn test, Figure 3-20. Temperatures within the Outerpack interior cavity varied from 50 to 320°C, Figure 3-21.

Figure 3-19 December 15, Impact Limiter Burn Test

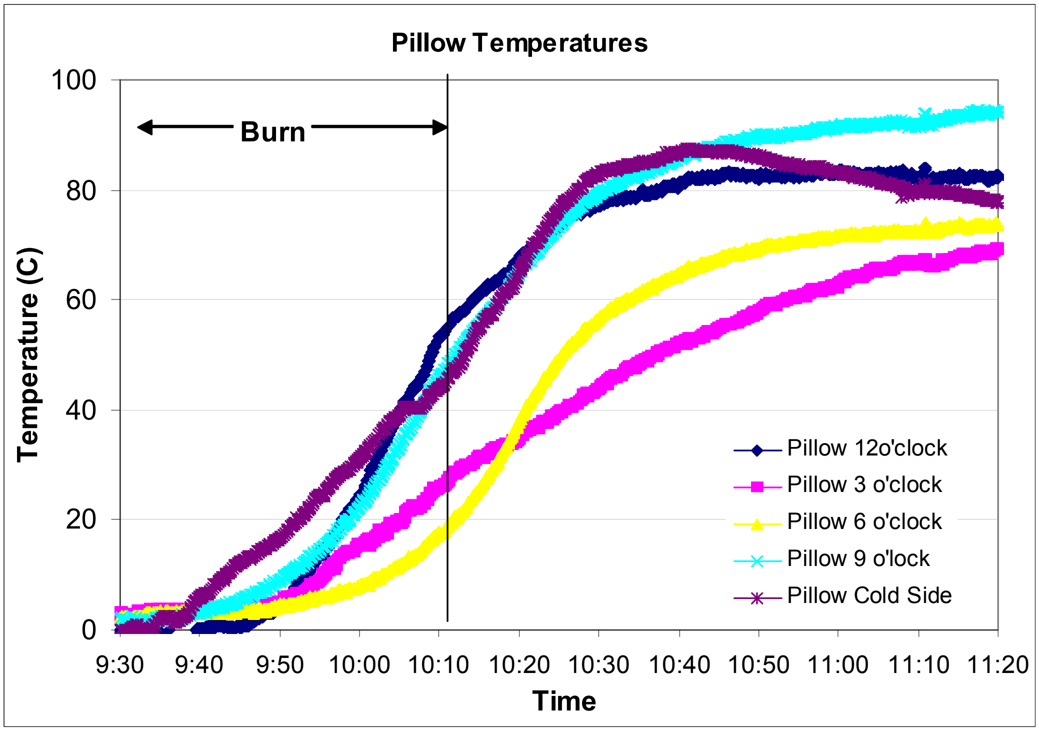

Figure 3-20 Impact Limiter Pillow Temperatures

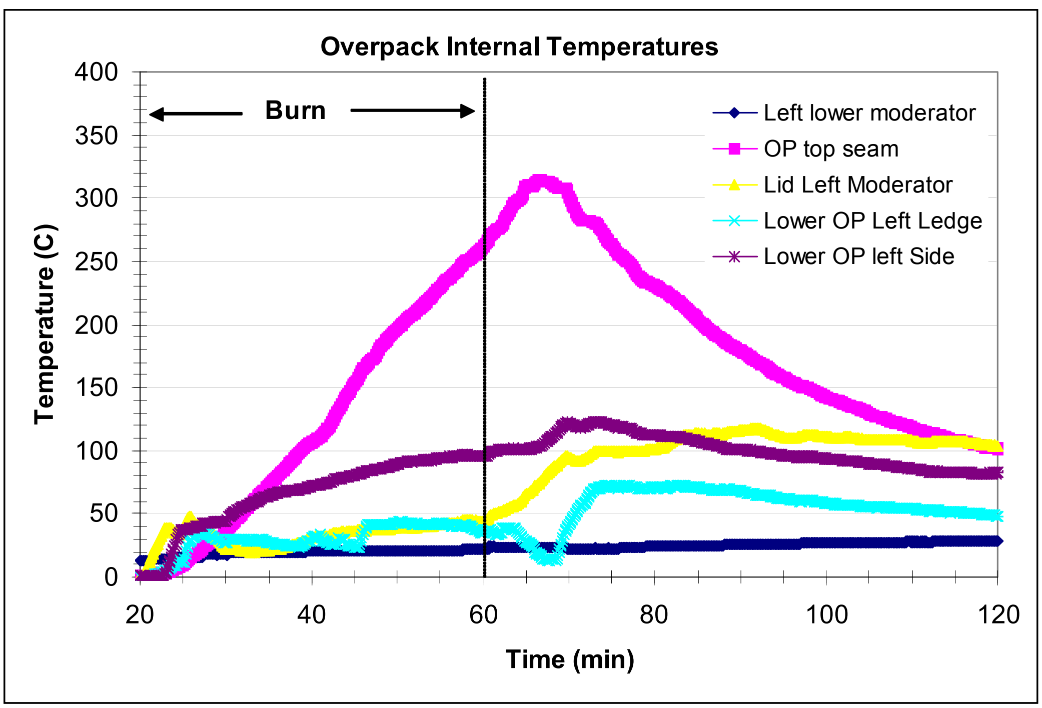

Figure 3-21 Internal Outerpack Skin Temperatures (December 15 Burn)

During this test, external temperatures were measured with two optical thermometers. Readings were taken every five minutes, Figure 3-22. After the test was completed, the Outerpack was opened. Other than a thin layer of soot lining the inside surfaces, there was no noticeable change in the Outerpack or Clamshell, Figure 3-23.

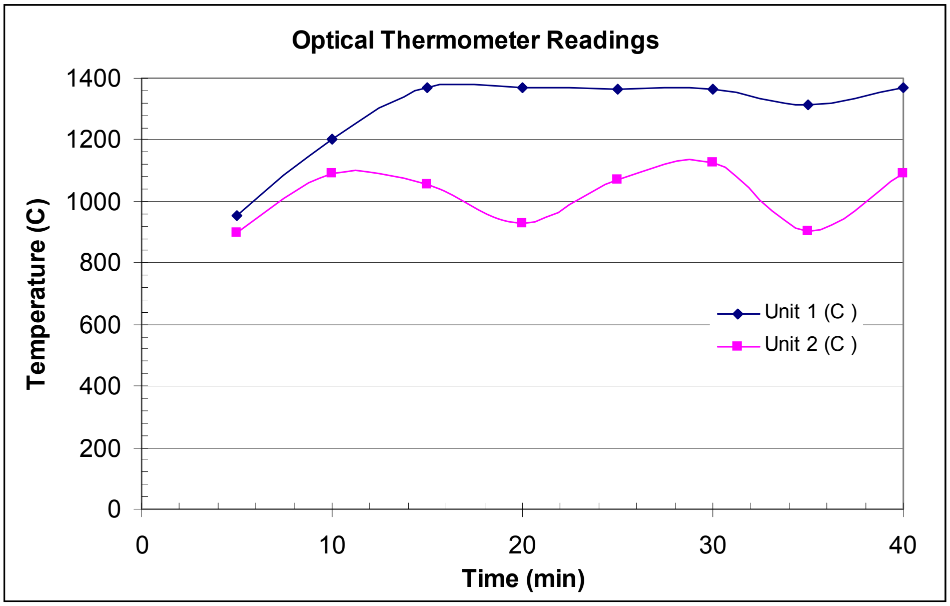

Figure 3-22 Flame Temperatures Measured by Optical Pyrometers

Figure 3-23 Outerpack Internals after December 15 Burn Test

3.6.4.2 Second Impact Limiter Burn (December 16)

The relatively high temperature observed at the Outerpack top seam led to questions of heat transfer. Was hot gas entering past the lip on the Outerpack door, or was the temperatures the result of heat conduction through the metal of the impact limiter bulkhead. The impact limiter burn test was therefore repeated but with Kaowool insulation stuffed into the Outerpack upper seam to prevent hot gasses from entering the package from that location, Figure 3-24. This burn lasted for 30 minutes, Figure 3-25. This test was performed in the late afternoon, so the initial temperatures inside the package were higher than the previous day. Temperatures within the Outerpack interior cavity varied from 80 to 340°C, Figure 3-26. Temperatures within the impact limiter pillow climbed to between 70 and 95°C depending on location during and after the burn test, Figure 3-27. The Outerpack top seam temperature rose to the same levels with insulation stuffed into the seam, demonstrating that the primary heat transport mechanism in this region is conduction.

Figure 3-24 Kaowool Layers on Outerpack Bottom Impact Limiter

Figure 3-25 December 16 Impact Limiter Burn

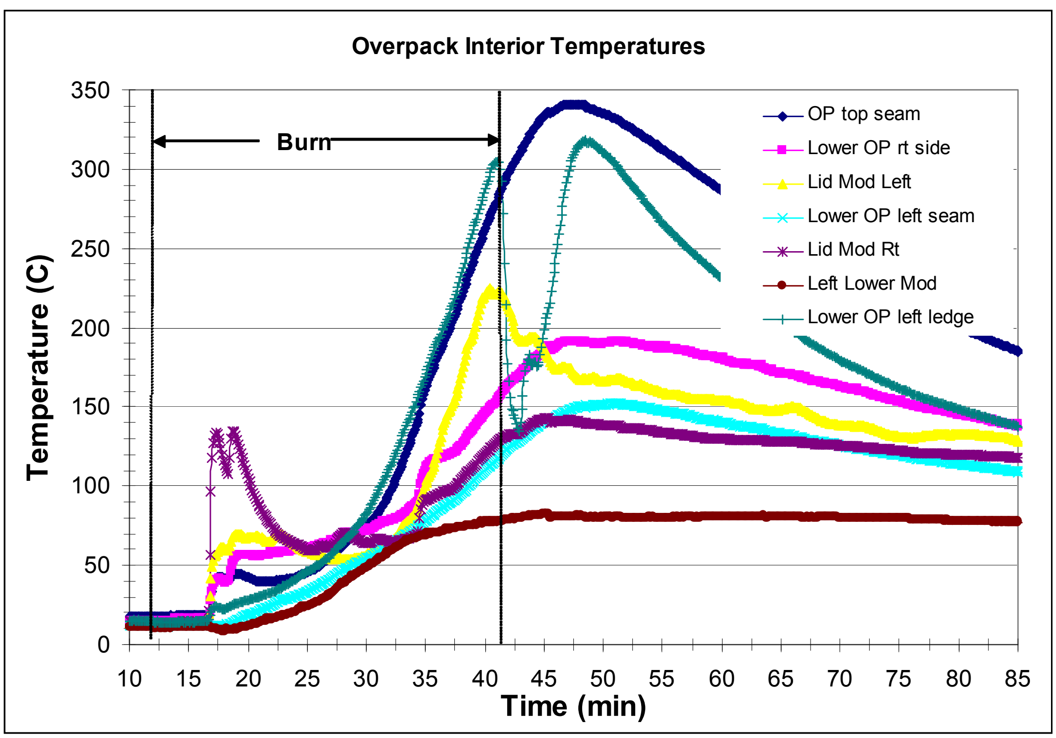

Figure 3-26 Internal Outerpack Skin Temperatures (December 16 Burn)

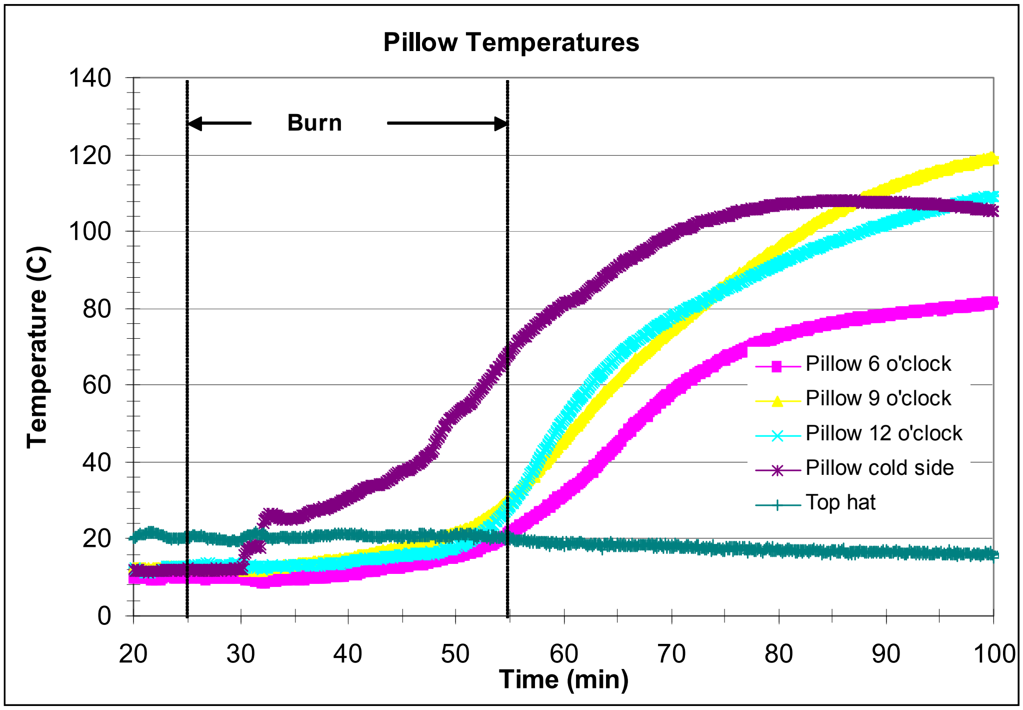

Figure 3-27 Impact Limiter Pillow Temperatures (December 16 Burn)

3.6.4.3 Test Conclusions

The purpose of the December 16 test was to repeat the previous day's test ensuring that hot gases did not flow around the Outerpack lid bottom lip. The heat up rate of the Outerpack top seam was slightly higher during the second burn than the first. Three factors may explain the higher temperatures during the second test.

- Foam in the impact limiter was charred during the first test resulting in higher heat transfer during the second test.
- The kaowool used to fill the bottom seam prevented the lid from closing as tightly as in the first test. This may have allow small amounts of combustion gas from the pool to enter the package
- During the first 5-6 minutes of the burn, fuel was sprayed directly on the outer skin of the package.

The test demonstrated that the revised impact limiter design will not overheat during a regulatory burn test. Even if the initial temperature is raised by 50°C, final temperature of the impact limiter pillow is anticipate to be less than 150°C. The test also demonstrated that very little gas is entering the Outerpack through the side or top seams. The interior skin is heating up however, due to conduction through metal parts of the Outerpack and through the polyurethane foam. The impact limiter tests results are conservative because the

foam in the cylindrical section of the package was not replaced and, therefore, did not provide the insulation that a unburnt package would have.

3.6.5 Traveller Certification Test Unit Burn Test

A Traveller XL package was fabricated by Columbiana High Tech to serve as the certification test article. This unit was subjected to a regulatory drop test performed February 5, 2004 in Columbiana, Ohio. This package was transported to the South Carolina Fire Academy in Columbia, South Carolina on February 6. The package was installed in the burn pool and burned February 10, 2004, Figure 3-28. Although the Outerpack had suffered minor damage that allowed some urethane decomposition products to escape into the package interior, the fuel assembly, Clamshell, and polyethylene moderator were essentially undamaged. (Please see section 2.12.4.2.3 in the Safety Analysis Report (pp 3-183 through 3-192) for description of the CTU drop tests and the resulting damage.)

The test was performed with the following objectives:

- Test Traveller package in manner that meets or exceeds regulatory requirements of TS-R-1 and 10CFR71.
- Demonstrate that the fuel assembly survives intact, without potential release of radioactivity.
- Demonstrate that the polyethylene moderator survives essentially intact retaining at least 90% of the hydrogen within the polyethylene.
- Demonstrate that the fuel assembly survives without cladding rupture caused by excessive temperatures inside the Clamshell

Figure 3-27A shows the orientation of the Certification Test Unit (CTU) for the thermal test. The bottom of the package was positioned approximately 1 meter from the top of the fire pool surface. The distance of the outer facility walls beyond the edge of the package were 67" at the ends and 71.5" at the sides.

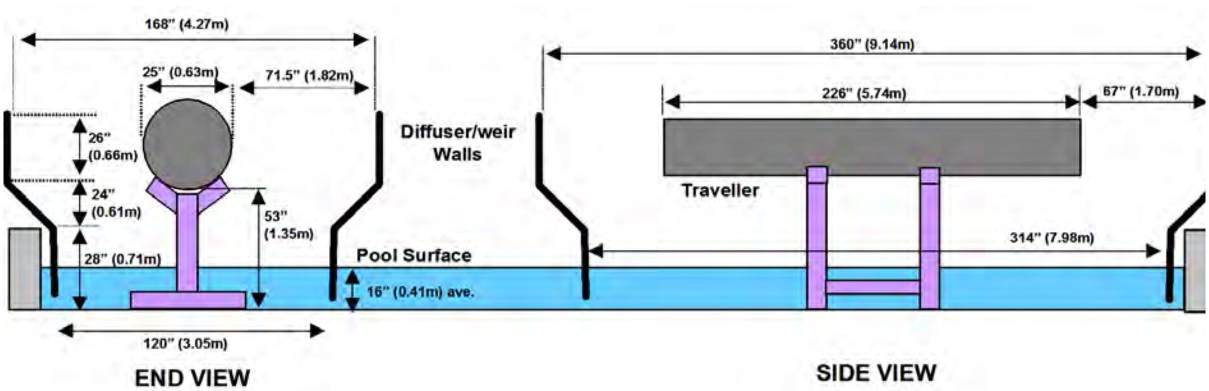

Figure 3-27A Orientation of CTU for Thermal Test

During this test, the package was engulfed for approximately 32 minutes. Prior to the burn test, the package was heated overnight to ensure that the interior of the package remained above 38°C (100°F). During the test temperatures were measured at six locations on the package skin, at twelve locations inside the pool fire, at four locations using directional flame thermometers (DFTs) facing away from the package, and from outside the fire using two optical thermometers, Figure 3-29. The 30 minute average temperatures were 904°C (1659°F) on the package skin, 859°C (1578°F) within the flame, 833°C (1531°F) as measured by the DFTs, and 958°C (1757°F) as measured by the optical thermometers.

The fire test facility was originally designed to terminate the fire test by shutting off fuel flow and allowing the fuel at the surface of the pool to burn off. Testing revealed that, in some circumstances, excess fuel could buildup on the pool surface causing the fire to continue burning for five minutes or longer. As a result, a simple fire suppression system was added to the facility. A water hose was connected to a nearby fire hydrant, Figure 3-27B. This hose utilized a suction line to siphon standard fire suppressant foam into the line, Figure 3-27C. The hose discharged into a single pipe that fed into the pool a few inches above the water level. When activated, the system would inject foam horizontally onto the surface of the pool, well below the test article. When used in combination with the fuel shutoff valves, the pool fire was extinguished within 60 seconds. This system did not cool the test article when in use and the package was allowed to naturally extinguish itself after the test. This was demonstrated by the CTU burn test, where the polyurethane at the Outerpack vent ports continued to burn many minutes after the fire suppressant was used on the pool surface.

Figure 3-27B Fire Fighters Standing by Fire Suppression System

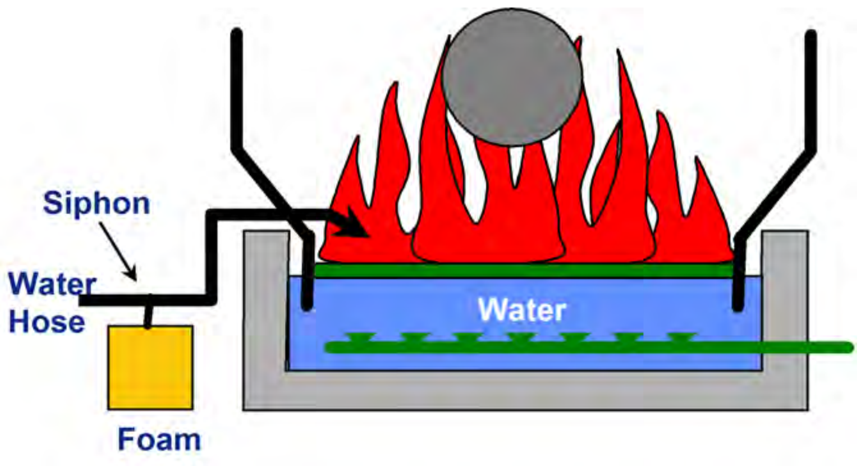

Figure 3-27C Approach to Suppress Pool Fire at End of Test

After the pool fire was extinguished, the package was removed from the pool and allowed to cool. Small amounts of smoke were observed to be coming from the package seams. The package was opened and the interior was examined. Significant amounts of polyurethane intumescence residue were observed along the Outerpack seam, Figure 3-30, and brown tar from the polyurethane was observed inside the package, Figure 3-31. Internal temperature strips recorded peak temperatures under 150°C throughout the package with one possible exception. Approximately 2 m (6 ft) from the bottom of the package, one set of temperature strips was unreadable due to heating and urethane deposits. An examination of the fuel assembly and the moderator blocks showed no significant heat damage.

Figure 3-28 Traveller CTU Burn Test

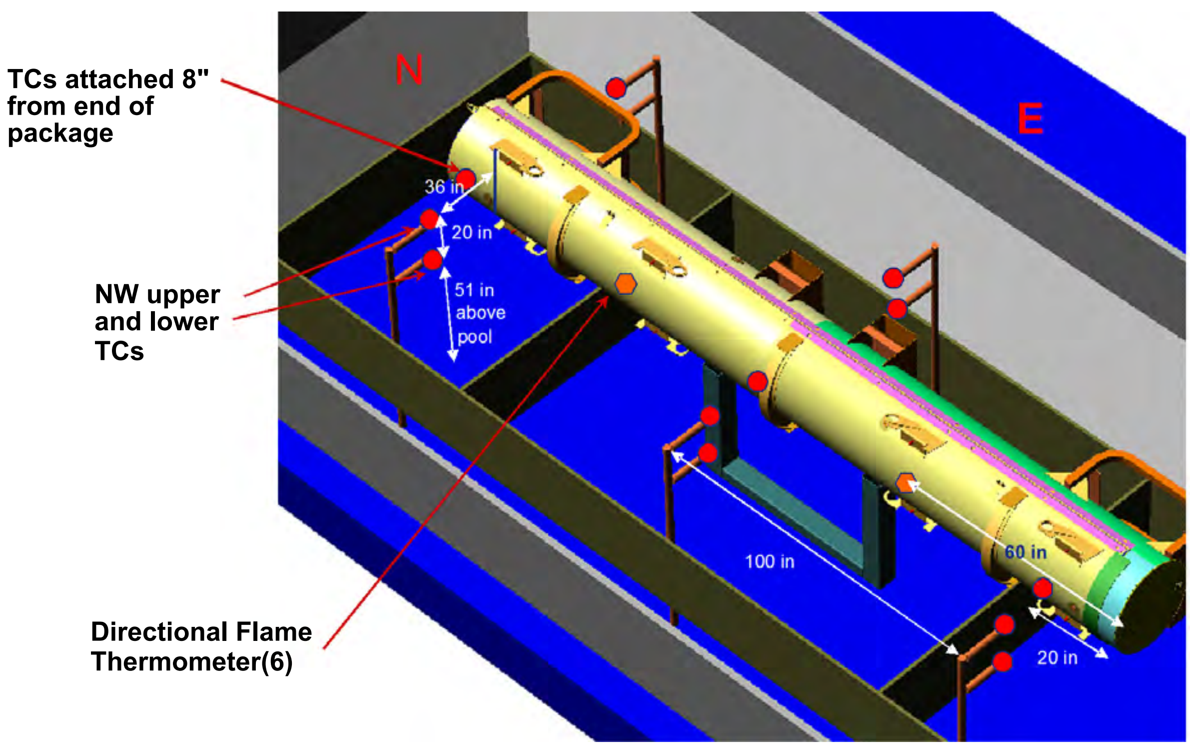

Figure 3-29 Thermocouple Locations on CTU Burn Test

Figure 3-30 Polyurethane Char in Outerpack Seam After Burn Test

Figure 3-31 Brown Polyurethane Residue Inside Outerpack After Burn Test

The following test equipment was used to conduct the burn test:

- Video cameras (4)
- Digital camera
- Omega type K thermocouples with Inconel overbraided 10' leads to measure skin temperature and flame temperature depending on location (XCIB-K-4-2-10 with screw attachment ends and XCIB-K-3-2-10 with air hoods)
- Omega OM-CP-OCTTEMP data loggers (2)
- Omega USB recorder Data Acquisition Modules with weather tight electronics box
- Laptop computer
- Hand held optical pyrometer with adjustable emissivity setting (s)
- Adhesive temperature measurement strips (TL-E-170, TL-E-250, TL-E-330)
- Edmund Scientific Propeller Wind Anometer

The package rested on a steel support structure placed in a burn pool, Figure 3-32. The burn pool was limited by a water cooled weir and the fuel was evenly distributed throughout the pool. The pool was also surrounded by a steel diffuser, Figure 3-33. The top of the diffuser was approximately 1.6 m (5.4 ft) above the top of the pool surface, the height of the top of the test article.

The primary sensors used in the tests were Omega XCIB-K-4-12 thermocouples connected via approximately 50 ft of 20 gage type K, Teflon coated, extension wire. The type K thermocouples have standard limit of 4°F (2.2°C) or 0.75% between 32° and 2282°F (0° and 1250°C). The 20 gage chromega/ alomega wire has a resistance of 0.586 ohms per double foot of length. Two types of data recorders were used. Two Omega OM-CP-OCTTEMP 8 channel data recorders were used for 14 channels of data. These recorders have a -270° to 1370°C temperature measurement range for Type K thermocouples and 0.5°C accuracy for type K thermocouples. The recorders were purchased new from Omega and were used within the time limit of their original factory calibration. Eight channels of data were recorded using a Instrunet, data acquisition system with an INET-100 external A/D box connected to a Toshiba Satellite notebook computer running Windows XP Professional using a INET-230 PC card controller. This system, with Type K thermocouples has an accuracy of ±0.6°C between -50° and 1360°C. The lowest average temperatures from the CTU burn test were the DFT readings which had an 834°C, 30 minute average temperature. Adding the worst case thermocouple and data recorder errors results in a 6.8°C average error. This is not sufficient to lower average temperature below 800°C.

Figure 3-32 Test Stand for Fire Test

Figure 3-33 Test Setup with Steel Diffuser Plates

3.6.5.1 Test Procedures and Results

The Certification Test Unit 1 (CTU) was burn tested on February 10, 2004. Because the overnight temperatures dropped to near freezing, the package was covered with a tarp, Figure 3-34 and heated by two 150,000 BTU/hr (44 kWt) kerosene heaters used alternatively. The heaters maintained the air temperature under the tent between 40 and 80°C (104 and 176°F) with readings at one location climbing to 115°C (239°F). The heater was turned off shortly after 7:15 AM and the tarp was removed between 7:20 and 8:00 AM. Temperatures around the package were measured and recorded on the two data loggers. This data is shown on, Figures 3-35 and 3-36. The ambient temperature shown is air temperature outside of the heated tent.

This test was performed between 8:32 and 9:06 AM Tuesday morning. Fuel was added to the pool starting at 8:26 AM and continued until 150 gal had been added. The pool was lit at 8:32 and full engulfment was achieved one minute later. After full engulfment was achieved, fuel flow was adjusted to between 61 and 83 l/min (16 and 22 gal/min) depending on the flame coverage within the pool. The fuel flow was secured at 9:04 and the fire suppression system was activated one minute later. The pool fire was extinguished within approximately one minute, although burning polyurethane from the package reignited residual fuel at one end of the pool shortly afterwards. This was extinguished using the fire suppression system.

Figure 3-34 Test Article Under Tent to Maintain Temperature Overnight

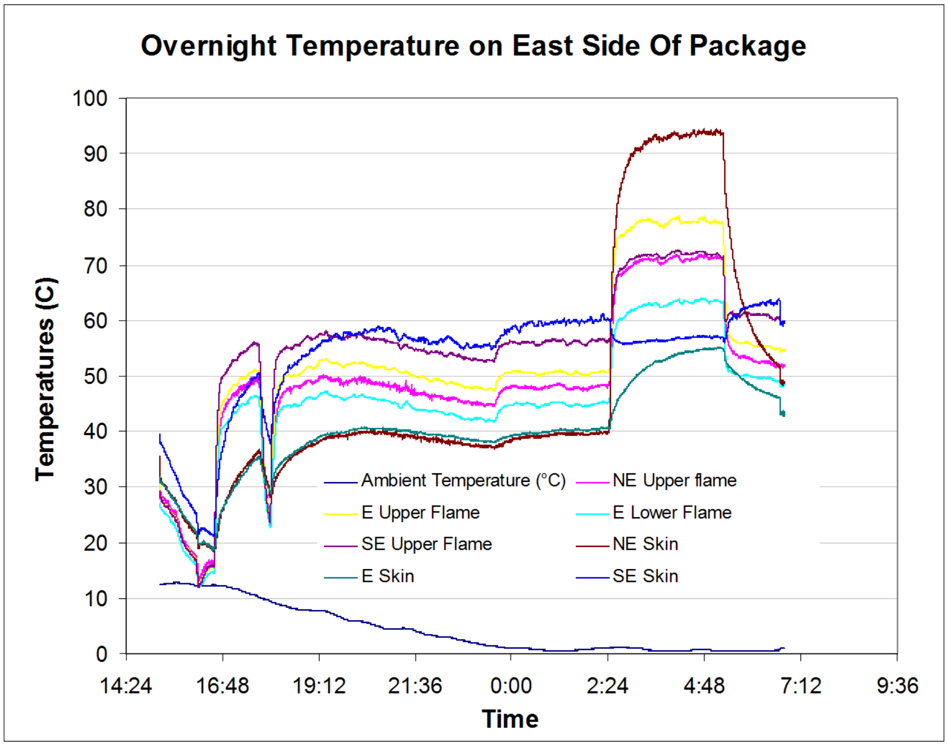

Figure 3-35 Overnight Temperatures on East Side of Test Article

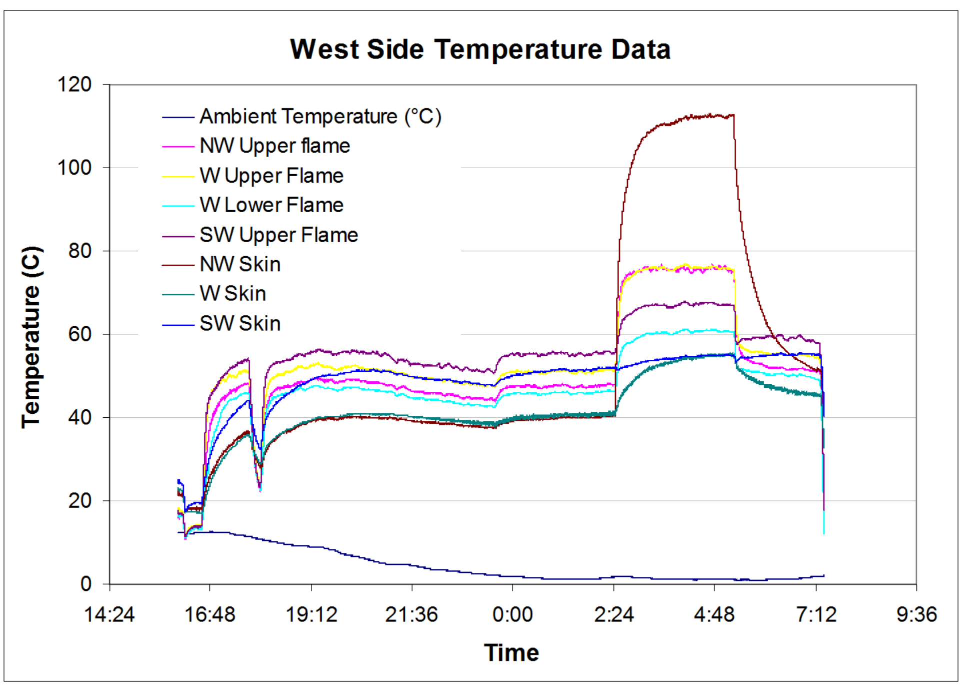

Figure 3-36 Overnight Temperatures on West Side of Test Article

During the fire test, data recorded by the instrument system was monitored in real time. This data included the following thermocouples:

- NE lower flame temperature (same height as center of test article)
- NE DFT
- SE DFT
- SE lower flame temperature
- NW lower flame temperature
- NW DFT
- SW DFT
- SW lower flame temperature

The data from the thermocouples within the fire is shown in, Figure 3-37. The data from the DFTs is shown in Figure 3-38.

Two data loggers were used to record a total of 14 channels of data. One data logger recorded temperatures on the east side of the CTU other, the west side of the CTU. Figures 3-39 and 3-40 show the skin temperature data collected on the east and west sides of the CTU. Figures 3-41 and 3-42 show data collected from the remaining thermocouples in the fire on the east and west sides respectively.

Twenty-two (22) thermocouples were used to measure external conditions on and around the Traveller package during the February 10, 2004 fire test. These sensors were located as shown in Figure 3-30 in the SAR. Due to the natural instability of open flames, combined with wind effects, these thermocouples were periodically uncovered. As shown in Figures 3-38 through 3-43, this resulted in large variations in measured temperature. These variations are largest at the corners of the pool fire where small disruptions in the flame would change air temperature at the thermocouple location. These disruptions were the smallest at the package skin because it was in the center of the pool fire.

Table 3-4A below, summarizes the thermocouple data for the test. Some of the thermocouples had average temperatures under 800°C but all experienced temperatures above 900°C during the test, demonstrating that the fire covered the complete pool area. Some of the minimum temperatures recorded are due to the time selected for the 30 minute average. A fire this size cannot start instantaneously, nor did it end instantaneously. As a result, the 30 minute period selected for averaging data includes data when some TC were beginning to heat up and when some were already cooling off after the fire. The data still shows that the average skin temperature, the average DFT temperature and the average temperature of TCs in the flame were all above 800°C for the 30 minute period selected.

Table 3-4A Summary of Recorded Temperatures During Burn Test			
TC Location	**30 Minute Ave (°C)**	**Max Temp (°C)**	**Min Temp (°C)**
NE Lower Flame	727	959	275
NE Upper Flame	925	1245	493
E Lower Flame	926	1155	489
E Upper Flame	904	1163	532
SE Lower Flame	714	962	291
SE Upper Flame	924	1245	484
NW Lower Flame	630	906	329
NW Upper Flame	748	1059	458
W Lower Flame	997	1162	640
W Upper Flame	1027	1173	661
SW Lower Flame	827	1032	230
SW Upper Flame	1000	1213	598
NE DFT	804	907	454
SE DFT	801	964	338
NW DFT	854	1016	541
SW DFT	876	1003	594
NE Skin	878	1058	610
E Skin	917	1073	699
SE Skin	903	1088	542
NW Skin	725	990	492
W Skin	974	1080	682
SW Skin	1028	1143	719

Because the thermocouples in the corners of the pool were not engulfed as long as the package itself, the 30 minute average temperature for the corners is lower than in the center of the pool. The total average for all of the thermocouples in the flame was 862°C versus 812°C for the corner thermocouples in the flame. The DFT average readings are also lower for similar reasons. The DFTs insulated the thermocouple and attached face plate from convective heat transfer. Radiative heat transfer was dominate by design. Because these devices faced away from the package, they recorded equilibrium temperature based on radiation from the fire and reradiation to cold surfaces outside the fire, without contribution from convection. The skin temperature is an equilibrium temperature that includes convective heat transfer from hot combustion gasses. As a result, its temperatures should be higher.

As described in the discussion of thermal analysis results (section 3.6.1) the long length to diameter ratio of the Traveller package minimizes the role of axial heat transfer inside the package. Non-uniform external temperatures produce non-uniform internal temperatures during fire tests. This fundamental mechanism allowed useful data to be obtained in the seam burn and impact limiter burn tests described in sections 3.6.2 and 3.6.3. This mechanism was demonstrated by the very low clamshell temperatures measured adjacent to the heated sections in those tests. During the CTU burn test, the average skin temperature at the North end, middle and South end of the package was 801°, 946°, and 915°C respectively. Peak interior temperatures recorded by the non-reversible temperatures strips were 116°C at the North end of the package, 177°C at the middle of the package, and 143°C at the South end of the package. At the center of the package, where the average exterior skin temperature was 946°C, the corresponding interior temperatures were acceptable for all materials in the package.

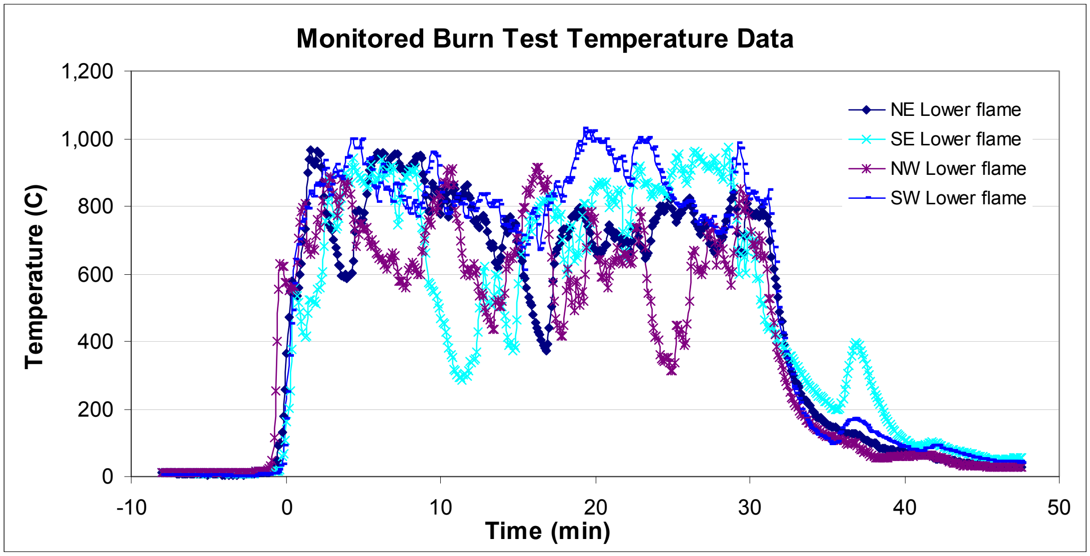

Figure 3-37 Fire Temperatures Measured at the Corners of the Pool

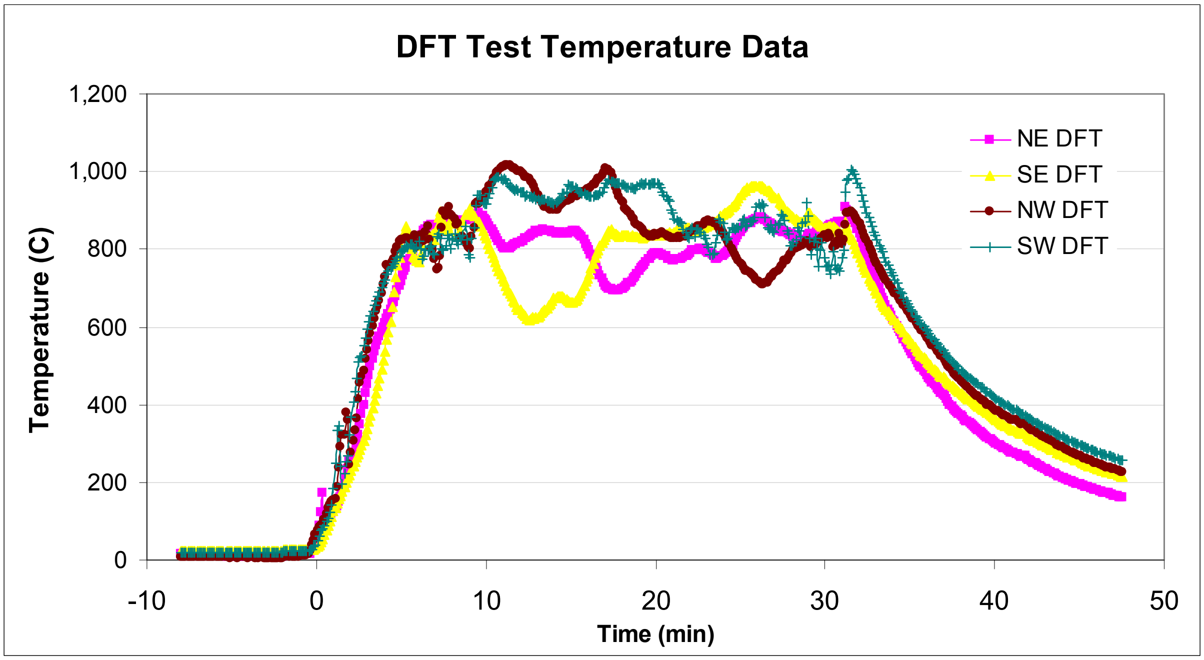

Figure 3-38 Data from Direction Flame Thermometers (DFTs)

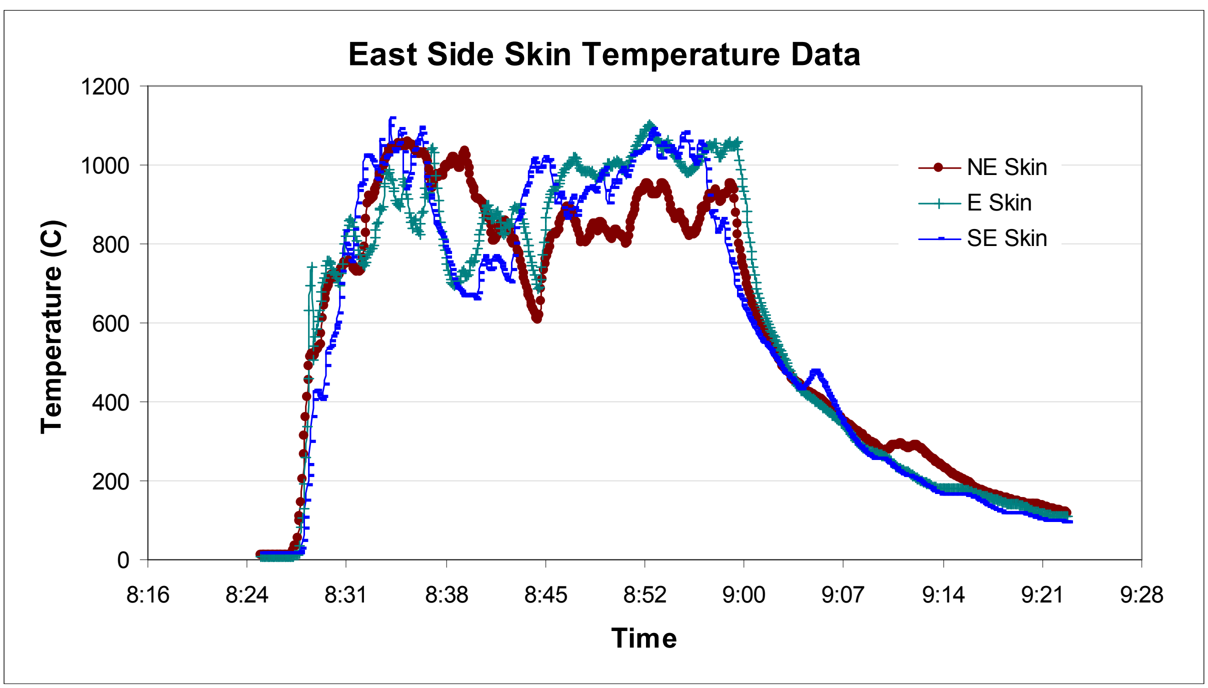

Figure 3-39 Skin Temperature Data from East Side of CTU

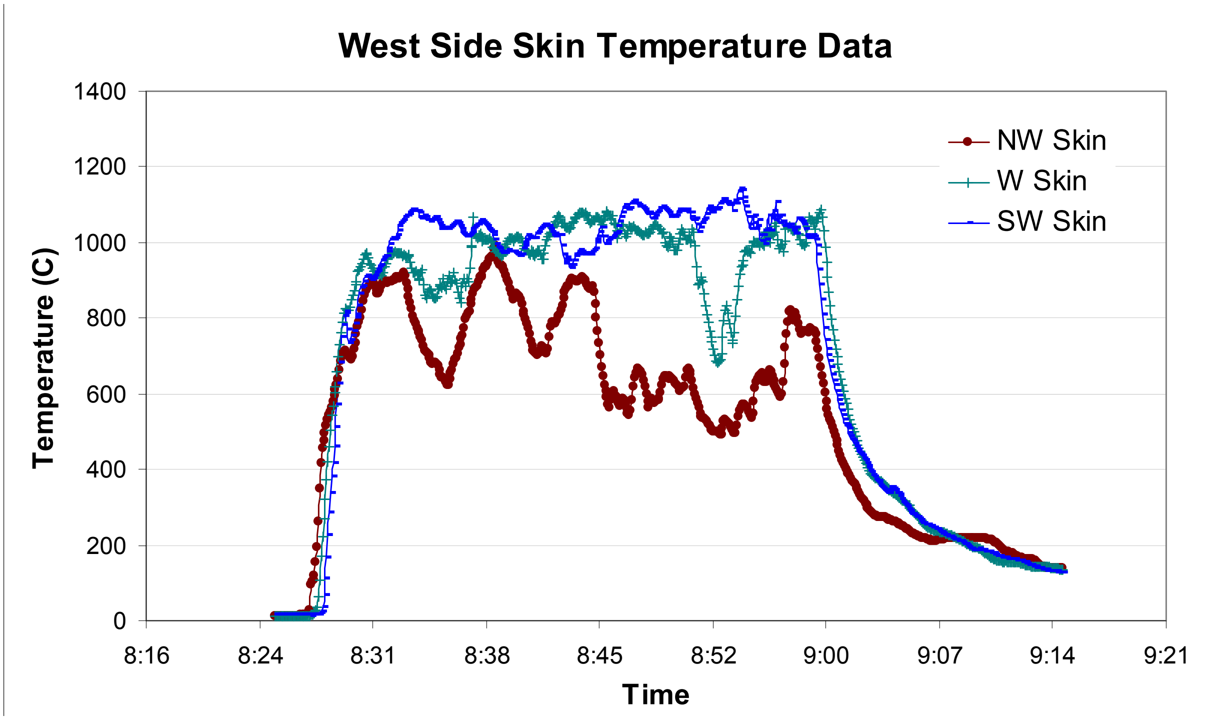

Figure 3-40 Skin Temperature Data from West Side of CTU

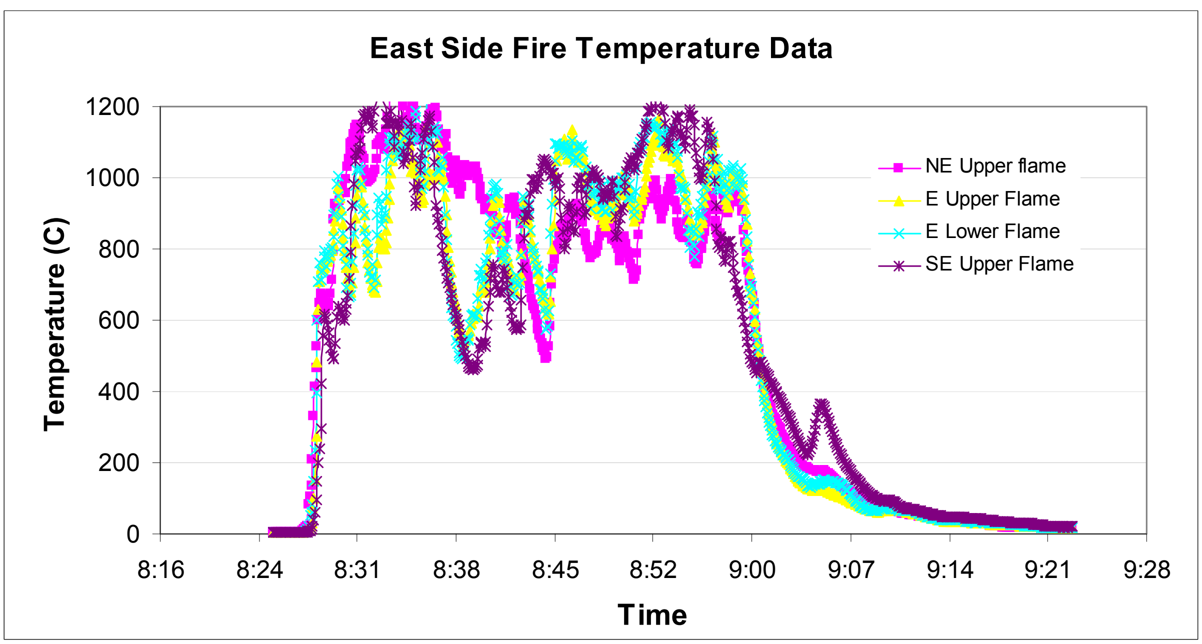

Figure 3-41 Fire Temperature Data from East Side of CTU

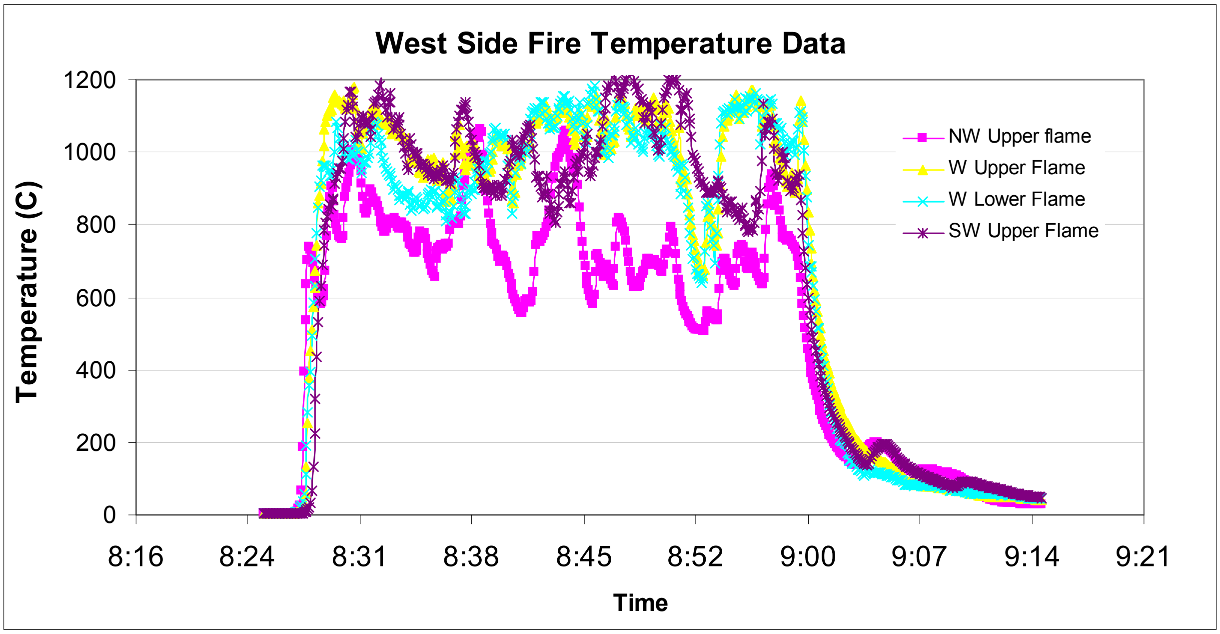

Figure 3-42 Fire Temperature Data from West Side of CTU

Temperature data was also collected using two portable, single wavelength optical thermometers. One was located on a raised platform on the west side of the package. The second was located on the east side of the package. Temperature data was recorded by hand. This data is shown in Tables 3-5 and 3-6.

Table 3-5 Optical Thermometer Data Sheet (West Side, Degrees C)

Time After Pool Fire Ignition	Temperature (North End)	Temperature (Middle)	Temperature (South End)
0 minutes	922	944	874
5 minutes	1047	973	1025
10 minutes	1002	1092	993
15 minutes	937	847	987
20 minutes	1177	982	942
25 minutes	1062	1073	1058
30 minutes	898	1162	968
35 minutes	525	460	484
40 minutes	318	362	294

Table 3-6 Optical Thermometer Data Sheet (East Side, Degrees C)

Time After Pool Fire Ignition	Temperature (North End)	Temperature (Middle)	Temperature (South End)
0 minutes	800	1000	936
5 minutes	978	1062	837
10 minutes	1037	948	932
15 minutes	842	996	835
20 minutes	590	1120	978
25 minutes	552	969	1048
30 minutes	1098	740	980
35 minutes	No Data	No Data	No Data
40 minutes	No Data	No Data	No Data

Wind speed measurements were made before, during and after the burn test. Average wind speed during the test was 0.9 miles per hour (0.4 m/s). Peak wind speed measured during the test was 2.2 miles per hour (1.0 m/s). The data was recorded by had at five minute intervals. This data is shown in Table 3-7.

An examination of the moderator blocks after the burn test revealed no significant damage. One small portion of moderator at the bottom end of the package showed signs of combustion, Figure 3-43. The very localized nature of the burn marks (on both the moderator and the refractory fiber felt insulation that covered the moderator) indicates that this was probably caused during the fabrication process. The stainless steel cover sheets are welded into place after the moderator blocks are bolted in and covered with insulation. It appears that the welding torch was applied to the moderator causing a small amount of damage. A brown spot was observed on the back side of one moderator block attached to the Outerpack lid. The polyethylene at this location appears to have been heated to melt temperature, Figure 3-44. A very small amount of flow occurred away from the hot spot. This melt spot was small, affecting only a few cubic centimeters of material. A visual examination of the shock mounts indicated that they were all intact.

Ultra-high molecular weight (UHMW) polyethylene was selected as the neutron moderator for the Traveller package because of its high hydrogen content, its ductility at very low temperatures and its high viscosity at temperatures well above its melt point due to the long molecular chains (MW=3,000,000 to 6,000,000). The relative solution viscosity as measured by ASTM D4020 must be greater than 1.4[1] and is typically found to be 2.3 to 3.5 dl/gm[2] (at 135°C). As a result, UHMW polyethylene does not liquefy above its melt temperature and molded UHMW polyethylene parts are typically made at relatively high temperatures (190°–200°C) and very high pressures (70-100 bar)[3]. Its excellent stability allows it to be used in some applications at temperatures as high as 450°C[4]. Experience in the Traveller test program has shown that the material will soften but not run, even when heated to near vaporization temperature (349°C). However, the Traveller design encapsulates the moderator with stainless steel. This is primarily done to prevent oxygen from reaching the moderator, should it reach vaporization temperature, but it does serve a secondary function of ensuring that the moderator does not significantly distort or flow at high temperatures.

The highest measured temperature inside the package was 171°C which is lower that the typical process temperature used to create the UHMW sheets installed in the Traveller. Unchanged appearance and more importantly, unchanged weight indicate that the plastic did not loose a significant amount of its hydrogen during the test.

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1. Stein, H.L., "Ultra High Molecular Weight Polyethylene (UHMWPE)," Engineered Materials Handbook, Vol. 2, Engineering Plastics, 1998.
2. This is a typical value observed in many manufacturers specifications: Crown Plastics (crownplastics.com/properties.htm).
3. Ticona Engineering Polymers information on compression molding, www.ticona.com/index/tech/processing/compression_molding/gur1.htm.
4. Stein, H.L., "Ultra High Molecular Weight Polyethylene (UHMWPE)," Engineered Materials Handbook, Vol. 2, Engineering Plastics, 1998

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Table 3-7 Wind Data Sheet

Time	Wind Speed (mph)	Wind Direction	Temperature F
8:05	1.7	E	42
8:10	2.0	NE	-
8:15	1.7	E	-
8:20	2.0	E	42
8:25	0.8	E	-
8:30	0.8	E	42
8:35	0.8	E	-
8:40	0.6	E	42
8:45	1.3	E	-
8:50	2.2	N	42
8:55	0	-	-
9:00	1.5	N	-
9:05	0	-	43
9:10	1.3	W	-
9:20	1.7	SW	43
9:30	1.3	SW	44

Wind data was taken every five minutes starting approximately 15 minutes before the burn until 30 minutes after the burn was completed.

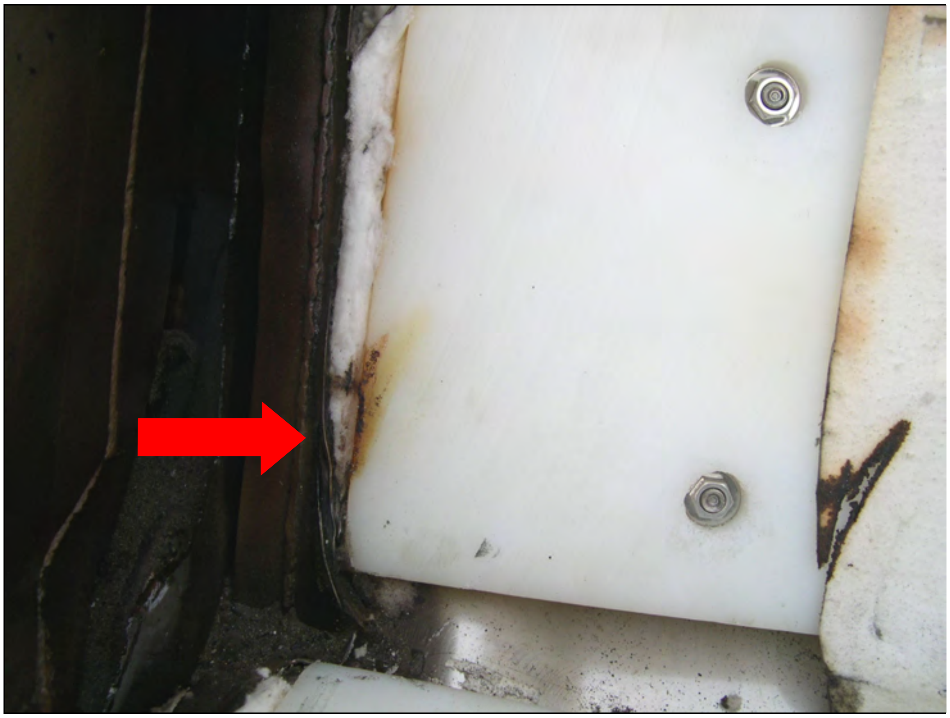

Figure 3-43 Location of Possible Combustion of Moderator

Figure 3-44 Localized Melt Spot in Lid Moderator Block

Twelve sets of non-reversible temperature strips were attached to the CTU. Two were placed on the inside faces of the impact limiters (one at each end), six were placed on the stainless steel covering the moderator in the Outerpack lid, and five were attached to the inside doors of the Clamshell. Except for one set that was unreadable after the test, the peak indicated temperature was 177°C. Locations of the temperature strip sets are shown in Figure 3-45. Readings on one of the Outerpack lid temperature strip sets is shown in Figure 3-46.

Earlier analysis and tests had shown that, if there was no substantial infiltration of hot gas into the package, interior temperatures would remain low during the fire test. This is shown in the results of both the seam burn tests and the impact limiter burn tests (sections 3.6.2 and 3.6.3). In these tests, interior temperatures rose between 50° and 110°C during and after the test. These values are conservative because the tests were performed on a previously burned package where the polyurethane had already turned to char. The primary design concern was hot gas infiltration during the CTU burn test. This would add substantially more heat and cause higher temperatures. This was observed in an earlier burn test (QTU-1). This package was oriented in the same fashion as the CTU, with one Outerpack seam facing the pool surface. Distortion of the Outerpack walls caused hot gasses to enter the package and flow around the clamshell. Because of the geometric arrangement of the Outerpack seam lip, this flow was directed preferentially over the top of the clamshell (as oriented when the package is resting on its feet). Polyurethane ignited at four locations in this region and burned. The moderator under the clamshell was undamaged. Based on this evidence, it seemed best to concentrate the temperature indicating strips on the moderator surface that was expected to be the hottest if significant hot gas infiltration occurred.

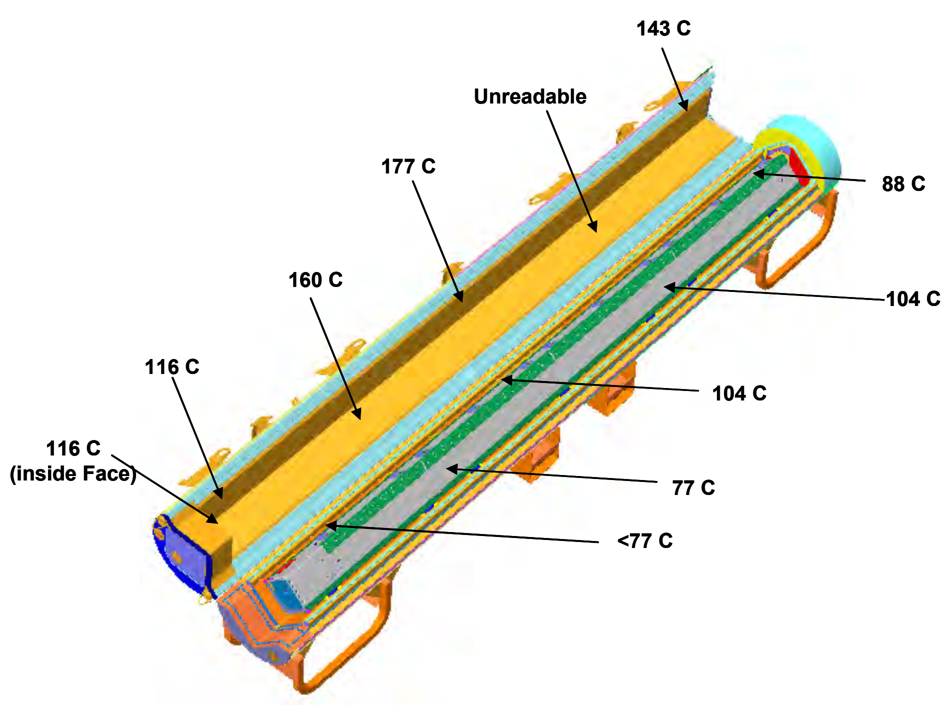

Figure 3-45 Location and Indicated Temperatures of Temperature Strip Sets

Figure 3-46 Temperature Strip Set After Fire Test