Lessons Learned from the Fire Test of Westinghouse's New Type AF Package, the Traveller: (Nothing like the Real Thing)

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Abstract

Satisfying the thermal test requirements is a significant part of licensing a Type AF package. Regulations allow the thermal test requirements to be satisfied by several means including thermal analysis, thermal test inside a furnace, pool fire test, test using a scale model of the package, test using a segment or portion of a package, or test using a full-scale package. It was decided that a pool fire test using a full-scale package was the only way to adequately test the many features of the Traveller.

Items crucial to criticality safety are more subject to damage during the thermal test. The Traveller design includes a substantial amount of neutron moderating material built into the packaging. This is so that criticality safety would not be dependent on moderation by HAC immersion. A full-scale fire test proved to be the only method to verify that the moderator survives.

The Traveller also features a unique impact limiter system inside the packaging that is designed to lessen the impact of the contents in an end drop. It was determined that the full-scale fire test would be the only way to verify that the limiters would not ignite and burn inside the package.

Actual pool fire temperatures are more severe than the 800ºC minimum required in the regulations. Also it is impossible to model distortions and stresses caused by an actual fire, and these have a significant impact on any thermal analysis.

This paper describes the many exploratory and scoping tests that preceded the final fire test. The lessons learned, though perhaps not new to those regularly employed in the fire testing profession, proved to be valuable to the licensee in completing the Traveller design.

Introduction

A new Westinghouse Fresh Fuel Shipping Package, the Traveller, was designed to replace the existing Westinghouse MCC and the Model 927 shipping containers by 2005 internationally and 2007 within the United States. The Traveller is to transport a single fuel assembly in a rigid package that complies with TS-R-1 and 10CFR71 regulatory requirements.

The Traveller design utilizes two primary components: an aluminum clamshell that tightly packages the fuel assembly and prevents serious deformation and lattice expansion in the event of an accident, and an outerpack that surrounds the clamshell and absorbs the impact energy from hypothetical accidents. The outerpack consists of a stainless steel / urethane foam sandwich that also insulates the clamshell and the fuel assembly from the heat of an external fire. The outerpack also minimizes the internal temperature rise preventing the fuel assembly from over-pressurizing and rupturing the clad and from preventing loss of the polyethylene moderator from combustion. Ultra-high molecular weight (UHMW) polyethylene blocks are mounted on the inside surface of the Outerpack to increase the effectiveness of borated plates within the clamshell. The polyethylene is the lowest temperature component in the package, flammable above temperatures of 350ºC. The regulatory fire tests were performed to demonstrate that package would survive a petroleum fire after damage from a series of drops.

Thermal Analysis or Test

Regulations allow package compliance to be demonstrated by thermal analysis. Although it had been decided to demonstrate compliance by full scale testing, a thermal analysis was performed. The thermal model of the Traveller package was created in accordance with 10CFR 71.73 and TSR-1 Section 728. The analysis evaluated 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 package was also analyzed assuming an average fire temperature of 1000°C, which was the anticipated temperature during an actual test. The analytical burn model did not include potential damage to the outerpack because minimum damage was anticipated after drop test, anticipated minor damage would not have a significant impact of global performance, and 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 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

As stated earlier, it was determined that compliance under hypothetical accident conditions would be demonstrated with an actual burn test of a full-scale package, carrying a simulated fuel assembly, that had been subjected to the 9-meter drop and 1.2-meter puncture tests. This sequence allows the package to be tested with actual damage from drop tests and eliminates concerns over modeling the complex gas flow patterns around and potentially through the package.

The U.S. regulations present the thermal test criteria as follows. (TSR-1 criteria are similar):

> *"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."*

These relatively simple requirements hide a multitude of difficulties. Most hydrocarbon fires burn hotter than 800 C and, if sufficient smoke is produced, have average emissivities of at least 0.9. Obtaining an even flame coverage is very difficult, especially for objects almost six meters long. Secondly, instrumentation that is needed to verify fire conditions often cannot survive the test conditions they are to monitor. Even worse, there is an instrumentation equivalent to the Heizenburg uncertainty principle: The presence of sensors will alter the environment that the sensors are attempting to m easure. This principle was demonstrated in the first prototype burn test.

<u>First Burn Test</u>

The first series of mechanical tests was conducted in early 2003 in Columbiana Ohio. Two TravellerXL prototypes were subjected to several drop and puncture tests that exceeded the regulatory requirements. One the these packages was modified to accommodate temperature instrumentation and shipped to the South Carolina Fire Academy in Columbia, SC, for the burn test. A total of 15 separate fire tests would eventually be performed. The South Carolina Fire Academy is a large state-operated facility that trains fire fighting groups from all over the southeastern United States in a variety of different conditions. The Fire Academy has a number of areas and "props" that it uses to facilitate training. One of their smaller water pools is equipped with a supply of kerosene base fuel and a water distribution system for cooling metal and concrete components. This pool was modified to accommodate the Traveller test by isolating one corner with steel plates and a separate fuel manifold to distribute fuel beneath the surface of the water within that area. A water-cooled stand was constructed and placed in the center of the pool subsection.

The Traveller package was instrumented with 20 thermocouples; 6 type J and 14 type K. Type K thermocouples were used to measure temperatures in the outerpack foam because of their higher operating temperatures. The type J thermocouples were used to measure temperatures inside the outerpack, including on the surface of the clamshell. The thermocouple cables ran through a water-cooled instrumentation tube out the end of the Traveller prototype to a data port extension that enabled the data to be read real-time and to be recorded by a lap top computer.

In addition to the thermocouples installed within the outerpack, THERMAX surface temperature indicating strips were applied to the upper surface of the clamshell and at selected places on the inside of the outerpack. These included type C strips (reading between 270 and 360 F) and type B strips (reading between 171 and 261 F)

The instrumented Traveller test article was set up on a water-cooled test stand for testing on February 28. During the morning, the thermocouple leads were connected to the data acquisition system and laptop computer located approximately 30 ft from the burn pool (Figure 1). The pool was filled with water and fuel flow was started at 12:38 PM. The fuel was ignited at one end at 12:39 and at the other end approximately 30 seconds later. The test was considered to have begun when the test article was completely engulfed in flames. (Figure 2). During most of the burn test, the fuel pumps were off and fuel was allowed to drain by gravity alone into the pool. However, pumps were started at least once to increase fuel flow. Approximately ten minutes into the burn, one of the steel plates on the outside of the pool fell into the pool. This reduced the fire confinement and knocked over the steel structure confining the fuel near the test article. This allowed the fire to spread, resulting in the need to restart the fuel pumps (Figure 3).

Figure 1 Test Article Before Burn Showing Insulation Wrapped Thermocouple Leads

Fuel flow was stopped by shutting the flow control valves 33 minutes after the test began. Within approximately 3 minutes, the fire inside the pool was almost completely out. Portions of the urethane foam within the outerpack continued to burn (Figure 4) for another 20 to 30 minutes.

External temperature measurements taken by optical pyrometer showed that the package continued to cool after the fire test was over. Several internal thermocouples indicated cooling also. Approximately one hour after the fire was out, a small flame was noticed between the top and bottom outerpack sections, immediately behind the second hinge on the right hand side. Plastic was observed to be melting and running out of the gap in that area. Shortly after this was observed, the flame expanded to extend between the second and third hinge section and smoke began to come out of the joint between the upper and lower outerpack over its entire length.

Figure 2 Traveller Burn Test

Thirty minutes after the small flame was detected, it was concluded that some material inside the Traveller was burning. The fire was put out in order to be able identify the source of this combustion, before all of the combustible material inside the package was consumed. Fire fighters extinguished the flame with CO_2 and within 15 minutes, smoke could be seen coming from the package interior. Data collection and storage continued for another 90 minutes. Then the operation was suspended and the package was left for the weekend.

The fire continued to smolder over the weekend. The package was opened Monday morning and the fire was finally extinguished. Subsequent examination showed that the moderator blocks and rubber shock mounts at the top end of the package had burned away. However, the fire did not consume material at the bottom end of the outerpack, and nor was it hot enough to damage the fuel assembly.

This first fire test was a very important learning tool. It clearly demonstrated that a long term fire causes significant distortions in metal. The simple support metal plates isolating the active area of the pool distorted to the point that three of the plates fell into the water. All of the remaining plates buckled. It was determined that the weir structure needed to be water-cooled.

Figure 3 Fire Spread to Rest of Pool

The distorting effects of the fire was seen on the Traveller package as well. Uneven heating from the fire, combined with internal pressure from the burning polyurethane, caused the Traveller outer skin to distort, which caused the top and bottom sections of the outerpack to separate. The outerpack sections had remained closed in the drop tests. The separation between the top and bottom sections provided a path for oxygen into the package. The instrumentation tube also allowed oxygen to enter.

Some of the internal thermocouples were inserted into the polyurethane foam cavity by drilling holes through the inner wall of the Traveller Outerpack. It appears that pressure from the burning polyurethane forced hot gases through at least one of these holes into the package. This ignited the moderator blocks, which burned slowly over the weekend.

Finally, the fire test demonstrated the effects of wind on a burn test. Physical constraints in the Fire Academy's pool limited the size of the fire test area to a little more than the 1-meter minimum on either side of the package.

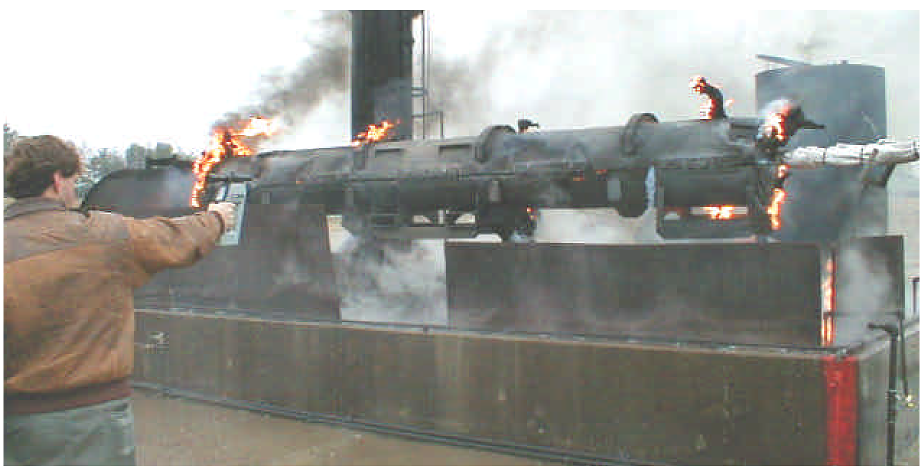

Figure 4 Traveller Prototype After Fire is Extinguished

The small test area showed that very low speed winds were sufficient to blow the flames away from the package, exposing it for extended periods of time.

Designing the Right Test Pool

Several months were spent designing and testing burn pool structures that would provide for a steady and even engulfing burn, prevent fuel from escaping, and minimize wind effects. One design was a solid metal wall extending approximately 2-meters above the surface of the pool. This wall incorporated inlet air openings immediately above the pool and was insulated in the fire side by 1.27-cm layer of refractory wool insulation (Figure 5). The back of the steel wall was cooled by radiation/convection. Figure 6 shows this burn wall during testing. The primary problem with the wall was that the interior became significantly hotter than a normal pool fire. Hot gas in the vicinity of the package could not radiate to anything except the flames above it and the hot insulation surface around it. The wall also suffered from heat distortion during testing

Figure 5 Insulated Interior of Burn Wall

Above the weir and the concrete pool walls the insulated metal walls were extended outward at 45 degrees to serve as a diffuser to increase the apparent pool size. Finally, the wall rose vertically above the diffuser to extend total height to the top of the package to minimize wind effects. This structure was modified slightly as additional tests were performed, changing the size of air inlet holes, total structure height, and water cooling arrangements. The final configuration is shown in Figure 7.

Fire Suppression

It was learned that even a slight wind will blow a thin fuel layer around enough so that the fire is not all-engulfing. Therefore it was necessary to have a thicker layer of fuel in the pool to ensure an engulfing fire. The additional fuel resulted in the fire continuing to burn for as long as 10 minutes after the test ended, unnecessarily exposing the package to fire. Therefore a fire suppressant system was installed to introduce foam at the surface of the pool and not come in contact with the package. This system was tested and found to extinguish the fire with 2 minutes.

Internal Instrumentation

The several prototype tests also highlighted the problems associated with instrumenting a burn test. Mounting thermocouples inside the package and routing the thermocouple wires through a water-cooled tube changed the way the package behaved in the fire. It was therefore decided that for the official burn test, thermocouples

Fuel Distribution

These tests also demonstrated the importance of proper fuel distribution under the pool. An even fire requires that a thin layer of fuel cover the entire surface of the pool. If the fuel manifold below the water surface does not distribute fuel evenly, a higher fuel flow rate is needed to keep the test article fully engulfed, resulting in a higher flames and longer burn time after the fuel flow has stopped.

Based on this experience, the fire test structures were redesigned. A new fuel manifold was installed with two independent fuel lines entering at opposite ends of the pool. Each line had a shutoff valve and a fuel flow meter.

Wall Design

The weir structure was modified to use a water-cooled square tube to minimize heat distortion.

Figure 6 Test Fire Within Wall Structure

would be used only on the outside of the test article to monitor outer surface temperature and flame temperature. There would be no thermocouples inside the package. Inconel- sheathed thermocouples were mounted on and around the Traveller package with the leads and connectors located in a pipe below the pool water level. Peak internal temperatures were measured using non-reversible temperatures strips that were covered with high temperature tape to prevent polyurethane deposition for obscuring the readings.

Figure 7 Final Burn Pool Configuration

Partial-Package Burn Tests

Detailed internal temperature readings were taken in several partial-package burn tests using already burned prototypes. These tests were performed to evaluate different methods of protecting the low temperature components inside the Traveller. Two series of partial-package burn tests were performed. One test subjected a short mid-length of the package to a 30+ minute fire. A second series of tests exposed the end of the package to a 30+ minute fire. These are seen in Figure 9.

Because of the large length-to-diameter ratio of the Traveller and the lower internal conductivity of the outerpack materials, internal response to a partial burn is very similar to the response to a burn engulfing the entire package. Inconel clad instrumentation leads were run out of the burn area where they entered water-cooled tubing to provide additional protection. These tests showed that the internal temperatures were very close to those predicted by finite element analysis, if the seams remained closed.

These tests were also performed at the South Carolina Fire Academy using a small weir especially fabricated for these tests. The tests were performed in a smaller pool using fuel distribution techniques similar to the large regulatory burn tests.

Figure 8 Partial Package Burn Tests

Regulatory Burn Test

The regulatory burn test was conducted February 10, 2004. A Traveller XL package that had been subjected to the required mechanical tests was installed in the burn pool, instrumented, and subjected to a 32 minute burn test. the test pool incorporated all the design improvements described above. Figure 9 shows a sketch of the pool.

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 9. 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

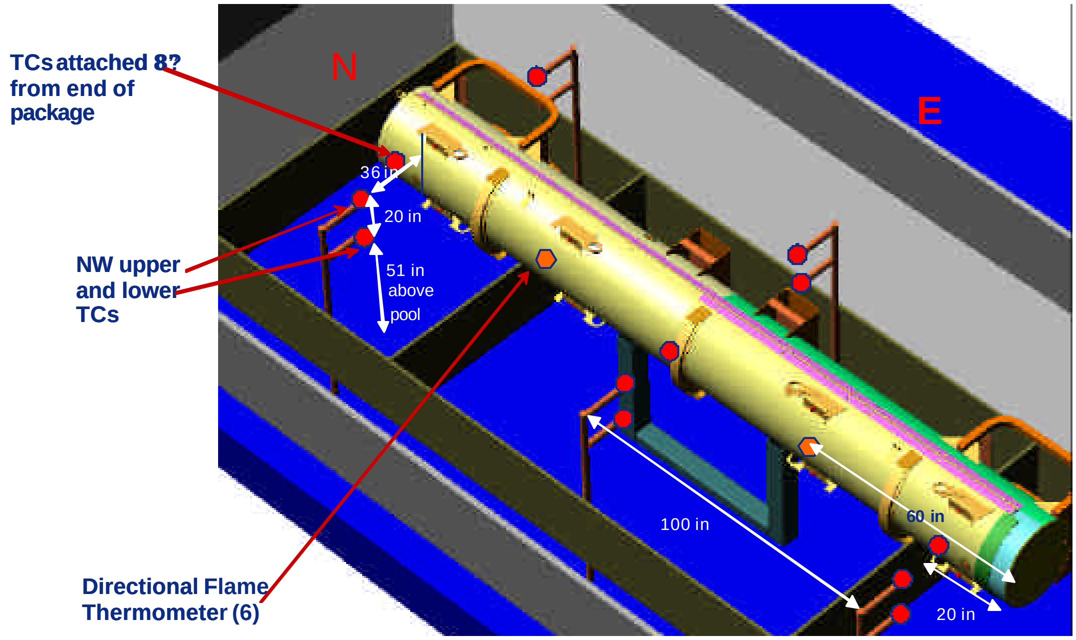

Figure 9 Sketch of Test Pool Showing Thermocouple Locations

directional flame thermometers (DFTs) facing away from the package, and from outside the fire using two optical thermometers.

Figure 10 Thermocouples Connected to Outerpack

The package was covered with a canvas tent approximately 16 hours before the burn test. Two kerosene heaters were used 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).

The burn test was performed on a cool, calm, lightly overcast morning. The test article was located on the stand in the 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 was ignited, the test article was completely engulfed. The fuel system continued to pump fuel into the fire until 32 minutes after the fire was started. 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 30 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).

Figure 11 Temperature Strips Inside the Package

Temperatures were measured on the outer surface of the outerpack using six type K thermocouples, attached by screws. These thermocouples were located as shown in Figure 10 above. The 30 minute average temperature measured by these thermocouples was 904°C (1659°F). Temperatures inside the outerpack were measured using 13 sets of non-reversible temperature strips, shown in Figure 11. These temperature strips were mounted on the stainless steel covering the moderator blocks, the inside faces of the end-impact limiters, and the inside doors of the clamshell. One set on the stainless steel skin covering the moderator blocks 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).

Although the outerpack had suffered minor damage from the mechanical tests that allowed some urethane decomposition products to escape into the package interior, the fuel assembly, clamshell, and polyethylene moderator blocks survived the fire essentially undamaged.

Conclusions

Westinghouse performed 15 separate fire tests over a 12 month period. Five were conducted solely for the purpose of testing facilities and burn test equipment. The tests demonstrated the importance of having proper fuel distribution in the pool to ensure an engulfing fire, a fire suppression system to protect the test article from unnecessary fire beyond the test, a proper wall to minimize wind effects and promote proper burn, and instrumentation that provides necessary temperature data on both the fire and the test article, but that does not adversely impact test results. These tests further showed that long-term exposure to fires of this magnitude distorts metal significantly beyond what was expected, affecting seals and potentially allowing flame and hot gases to enter the package.

The Traveller package ultimately survived the fire testing by incorporating reinforcement at the seams of the outerpack and multiple boundaries to prevent minimize metal distortion and prevent significant amounts of flame and hot gases from entering the package.