# Early Thermal Testing of Type B Radioactive Material Packages in the US to Environments beyond the Regulatory Package Thermal Test Standards

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ABSTRACT

Three separate fire test programs exposing casks beyond the regulatory thermal test requirements were performed by Sandia National Laboratories during the late-1970s and mid-1980s. The results of these test programs can be used to assist in addressing the adequacy of the regulatory thermal test of fully-engulfing exposure at 800$^{o}$C for 30 minutes and how that test might relate to real accident thermal environments. The test programs were undertaken on obsolete and new casks on behalf of the U.S. Department of Energy, the U.S. Department of Transportation, and the Japanese Power Reactor and Nuclear Fuel Development Corporation (currently known as the Japan Atomic Energy Agency). Two of the tests involved exposure of casks in damaged transport vehicles to fully engulfing fires for 72 to 125 minutes, and the other test involved four exposures of a cask to torch environments for 30 minutes. Much of the original documentation regarding these tests and their results is no longer readily available. The documents relating to these tests have been surveyed; this paper presents summaries from this survey of the tests and their results. Specifically, for the pool fire exposures, the temperatures measured in the flames of both exceeded the flame temperature required by the Transport Regulations; yet an obsolete 67-tonne cask endured 90 minutes of exposure before evidence of failure was detected, and a new cask endured the 72 minute exposure while retaining its containment integrity For the exposure of a modified obsolete cask to four different torch environments, the integrity of the cask was retained and the relative temperature increases within the cask were well within acceptable limits and were well below the values that could be expected if the cask were exposed to the Regulatory thermal test. A review of these three thermal test programs, establishes that the two older cask designs and one new cask design have the ability to survive environments that were different from (the torch environments) or more severe than the environment specified by the existing thermal test requirement in the Transport Regulations. These results can be extrapolated to apply to modern casks that generally have more robust designs as well as better quality assurance applied during the manufacturing process.

## INTRODUCTION

When deliberations were undertaken with respect to specifying thermal test requirements in the international Transport Regulations for Type B and Fissile Material Packages, issues that were addressed included the extent of engulfment of the package in a thermal (i.e. a fire) environment, the source temperature of the thermal environment, and the duration of the thermal test [1]. As summarized in Ref. [1], these deliberations resulted in the current parameters specified in the thermal test requirements in the Transport Regulations. These requirements were first promulgated in the 1964 edition of the International Atomic Energy Agency Regulations for the Safe Transport of Radioactive Material [2]. They have essentially remained the same with minor textual variations in all editions of the Transport Regulations issued since that time. However, since their introduction, concerns have been and often continue to be voiced by the users of the regulations and by the public as to the adequacy of these thermal package test standards; specifically, whether the test standards provide an adequate level of safety.

Three separate fire test programs that went beyond the 30-minute, 800°C thermal test requirements of the international Transport Regulations were performed by Sandia National Laboratories during the late-1970's and mid-1980's. The results of these test programs can be used to address the concerns noted above. The three test programs that were performed in the late-1970s were undertaken on obsolete casks on behalf of the U.S. Department of Energy (DOE) and the U.S. Department of Transportation (DOT). The test program that was performed in the mid-1980s was undertaken on newly-designed test hardware on behalf of the Japanese Power Reactor and Nuclear Fuel Development Corporation (PNC).

Specifically, these three test programs were as follows:

(a) the exposure of an obsolete 67-tonne spent nuclear fuel (SNF) cask located in its 68-tonne transport railcar, the combination of which had been previously impacted at high speed [3] as part of the DOE's Full Scale Vehicle Test program to an open pool fire test for 125-minutes[4,5,6];

(b) the exposure of a 2-tonne mixed-oxide fresh fuel cask located its transport-trailer that had previously been tested with the motive-power tractor in a 90 km/h (56 mph) head-on impact as part of the DOE/PNC Joint Program on Transportation Technology to an open pool fire test for 72-minutes [7,8]; and

(c) multiple exposures of the 45-tonne obsolete Hallam Nuclear Power Facility (HNPF)[1] SNF cask, modified to resemble contemporary designs, as part of a DOT-sponsored test program to asses the effects of a hydrocarbon fuel torch fire, where the exposures occurred for a 30-minute duration [9 – 11].

Over the years, the results of these thermal test programs have been individually documented in various forms, including summaries at international meetings and in some documents that have received only limited distribution. However, the results the three disparate programs have never been assembled in a fashion that could be used to assist in effectively demonstrating whether the existing thermal test requirements in the Transport Regulations are, or are not, adequate. The purpose of this paper is to assemble a brief summary of the thermal test programs, using the results therefrom to assist in assessing the adequacy of the regulatory package thermal test

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[1] The HNPF was located in the Nebraska, USA. It was closed in 1966.

standards; and to precede this with a brief summary of the background of deliberations that led to the establishment of the current thermal test requirements in the Transport Regulations.

## THERMAL TEST REGULATORY BACKGROUND

Extensive discussions occurred during the early 1960's, relative to the establishment of the current test requirements. Following these deliberations, it was noted [1] that the experts felt it necessary to consider all factors in establishing the thermal test condition, not just the maximum average attainable temperature in "perfect" fire situation. They considered the ramifications of accounting for multiple, "real life" parameters, including inter alia radiant, conductive and convective heat inputs and exposure scenarios, which require specification of:

- an effective source (i.e. flame) temperature and effective flame thickness where, for pool fuel fires, this requires consideration of such parameters as:
    - fuel type,
    - size of package,
    - mass of package,
    - size of pool (too small, the flame is not luminous, too large and the flame suffers from oxygen starvation),
    - location of package above the pool,
    - intervening structure, and
    - wind effects;
- emissivity coefficient of the heat source (i.e. the flame and its luminosity);
- absorption coefficient of the package surface;
- duration of exposure;
- support of the package at specified height; and
- whether the package should be cooled following termination of heat source exposure.

It was further noted [1] that these deliberations resulted in inclusion of the statement in the Regulations that "any thermal test shall be considered as satisfactory provided that…." where the parameters for satisfying the test were then specified in terms of:

- source temperature (800 $^{o}$C),
- duration of test (30-minutes),
- source emissivity (0.9),
- package surface absorptivity (0.8),
- flame thickness – not less than 0.7-m (2-ft) and not more than 3-m (10-ft),
- the flame must surround the package during the entire test, and
- no intervention after exposure to the thermal source until the inner components of the package began to cool.

In addition, concerns arose that the Transport Regulations addressed a fully engulfing environment, whereas in some accidents, localized hot fire sources were possible. Specifically, during the late 1970s the Federal Railroad Administration (FRA) of the U.S. DOT was collecting data on rail accidents involving "torch fires". The source of these fires were torches emanating from a damaged railroad tank car carrying hydrocarbon fuel, where the torches could impinge upon other freight located close to the tank car in a railroad accident.

CASK THERMAL TESTS

## Cask Designs Tested

Each of the casks and, as appropriate, the associated transport hardware tested in the fire exposures are briefly described here.

*Railcar/Cask Design used in Pool Fire Testing*

The obsolete 67-tonne SNF cask, which was designed in the late 1950s and was fabricated in 1962, was of steel/lead construction. It was a stainless steel, double-walled, lead-shielded cylindrical vessel 3.96 m in length and 1.5 m in diameter. The lead was contained in a the cylinder between the two stainless steel shells, where the combination of stainless steel and lead provided gamma-shielding of the radiation emanating from the SNF. This early-designed cask utilized an auxiliary water cooling system of stainless steel channels welded to the outside of the inner shell of the cask body. The cooling system was provided, not for safety purposes, but for facilitating rapid handling of the cask and its contents after shipment. Also, copper fins were welded to the inside of the outer shell to facilitate heat transfer from the lead to the outer shell.

The cask, which is shown photographically prior to the fire test in Figure 1, had previously been impacted in its transport railcar into a massive barrier at 131 km/h (81 mph) [3]. As can be seen from Figure 1, the cask sustained only “cosmetic” damage as a result of this dynamic structural test; there was only minor bending of the external heat transfer fins.

Fig. 1. Photograph of the obsolete 67-tonne cask prior to fire test.

*Truck/Cask Design used in Pool Fire Test*

A special nuclear material (SNM) package (i.e. a 2-tonne mixed-oxide breeder reactor fresh fuel cask) was designed by PNC during the early 1980s. The design of the transport system was intended to allow up to three of these packages to be transported in a tractor/trailer road vehicle domestically in Japan. The DOE/PNC Joint Program included a full-scale simulated accident test of a head-on collision of three of the casks in the tractor/trailer conveyance impacting a massive concrete barrier at a speed of 90 km/h (56 mph). This impact accident-simulation test was followed by testing one of the casks to the regulatory 9 m drop test of the cask onto an unyielding target, and then to the regulatory 1 m puncture test onto a probe mounted on the unyielding target. Finally the impacted cask/transport system, using the cask that had been tested three times along with the two casks that had only been involved in the simulated impact crash, was exposed to a fully-engulfing fuel fire for one hour. This paper only addresses the one-hour fire test of the cask/transport system.

The cask tested is shown photographically in Figure 2 and schematically in Figure 3.

Fig. 2. Photograph of the PNC SNM cask and a schematic of its design.

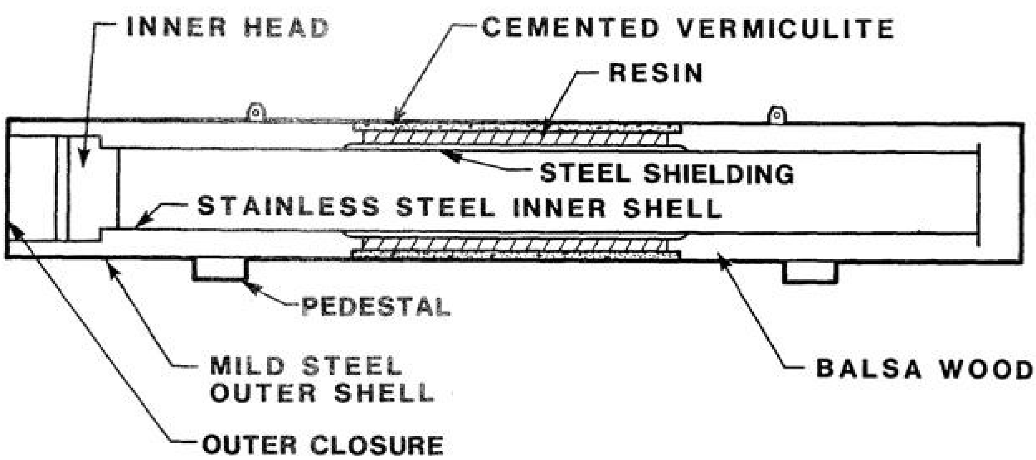


Fig. 3. Schematic of the PNC SNM cask design.

The cask sustained only minor structural damage during the series of mechanical tests that preceded the thermal test. The cask design consisted of thin concentric steel shells; the annular spaces were filled with balsa wood. Although the cask had sustained some deformation [up to approximately 5 cm (2 in) deep], the inner lid and seals were still intact. The cask was relocated into the tested trailer for the thermal test.

*Cask Design used in the Torch Tests*

The cask selected for the torch tests was a design that had been retired, which had been fabricated in 1967 for the transport of SNF from the Hallam Nuclear Power Facility (HNPF). This cask consisted of an inner cylindrical shell of stainless steel, an annulus of lead to provide gamma shielding, and an outer carbon steel cylindrical shell. With changes that had occurred in the design, testing and operational regulatory requirements for such casks, the HNPF cask could no longer be utilized; it was lacking adequate neutron shielding and adequate impact limiting capability. In order to test a cask system that more closely resembled contemporary casks, a neutron shield was added to the cylindrical outer shell of the cask and impact limiters were added to the ends of the cask. The resulting cask is shown schematically in Figure 4, which also illustrates the locations that the torch was applied during testing.

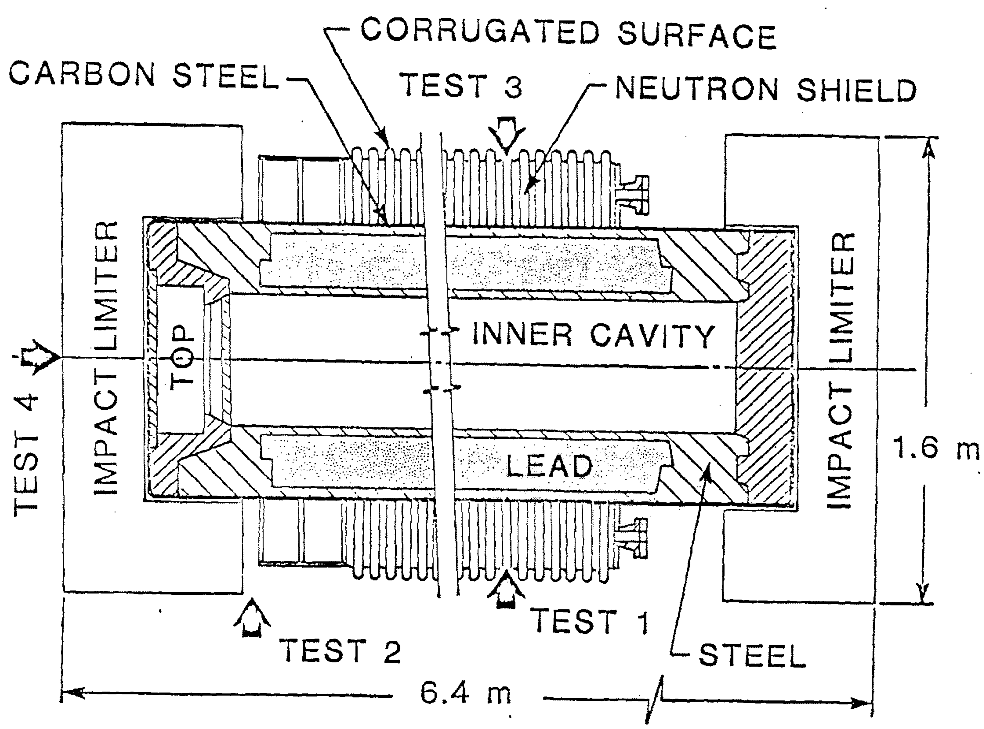


Fig. 4. Schematic of the modified HNPF tested in the torch tests.

**Test Facilities, Environments and Instrumentation**

*Railcar/Cask Pool Fire Test Facility*

The fuel pool was constructed specifically for this test. It measured 0.9-m deep, 9.1-m wide and 18.3-m long. JP-4 (jet) fuel was continuously piped into the pool to maintain a 15-cm layer of fuel above 60-cm of water. The cask/railcar combination was reassembled over the large fuel pool, supported on concrete pedestals. The cask/railcar and the wheel trucks that had become disengaged during the preceding impact test were positioned as they had been following the impact with the barrier as shown in Figure 5. Extensive thermocouple monitoring of the flame and the cask was undertaken during the test. The thermal-shielded “trees” for the thermocouples leading from the edge of the pool into the cask can be seen in Figure 5.


Fig. 5. Cask/railcar assembled over fuel pool prior to testing.

*Truck/Cask Pool Fire Test Facility*

The fuel pool that had been used for the railcar/cask pool fire test described above was also used for the truck/cask pool fire test. The casks that – as described previously – had been exposed to the structural tests were relocated into the tested trailer, and cask/trailer system was then positioned over the fuel pool as shown in Figure 6, for the thermal test.

Fig. 6. Placement of SNM cask in tested trailer over fuel pool.

The trailer included the sides and the top of 0.8 cm (0.31 in) thick mild steel plating; however, because the front end of the trailer was severely damaged in the impact test, it was fully removed for the thermal test. One tear occurred in the trailer deck during the impact test, which showed a weakness in the design and the design was corrected for actual use to prevent such damage from happening in an actual accident. Therefore the tear in the deck was repaired prior to the thermal test.

The thermal characteristics of the fire and the thermal response of the cask and trailer during the fire test were monitored with 106 thermocouples. This included monitoring temperatures inside the cask, on the cask and trailer surfaces, on towers located at the four corners of the trailer, and on 21 calorimeters. The details of the locations and measurements taken are provided in Reference [8].

*Cask Torch Test Facility*

The torch tests [9 - 11] were performed at the New Mexico Institute of Mining and Technology/ Ballistics Research Laboratory (BRL) Torch Facility in Socorro, New Mexico, USA. The design characteristics of the torch include a 1204$^{o}$C flame temperature at the point of discharge, 1.22 m impinging flame diameter, 3.7 m distance between the torch point of discharge and the cask, and a 30-minute exposure time[12].

Four tests to different exposure conditions were performed. The four exposure conditions were:

- side of the cask at the centre with the neutron shield intact (i.e., filled with water), with the torch impinging perpendicular to the axis of the cask;
- side of the cask near the closure (i.e. seal) end with the neutron shield intact, with the torch impinging perpendicular to the axis of the cask;
- opposite side of the cask at the centre with the neutron shield voided of water, with the torch impinging perpendicular to the axis of the cask; and
- directly on the impact limiter at the head end (i.e. closure end), with the torch impinging parallel to the axis of the cask.

Temperature and pressure data were collected during both the heating and cool-down phases, for a total of 90 minutes. Temperatures were measured in the torch, at the external surface of the cask, and at various internal locations in the cask including the neutron shield water, the outer carbon steel cylindrical shell, and the inner stainless steel shell. The details of the locations and measurements taken are available in published documents [9 – 11].

## Test Results

*Railcar/Cask Pool Fire Test*

Prior to undertaking this test, it was agreed that the test would continue beyond the regulatory 30-minute requirement until damage to the cask was detected. Such detection would depend upon measured temperatures of the cask and visual observations.

Once the pool fire was ignited, the cask and railcar generally remained engulfed in the fire; although during minor wind gusts (fluctuating between 0 and 2 km/h) parts of the structure would momentarily be exposed from the flames, as shown in Figure 7. Despite these difficulties, the average flame temperatures ranged from 980 to 1200$^{o}$C [5], well above the 800$^{o}$C specified in the Transport Regulations.

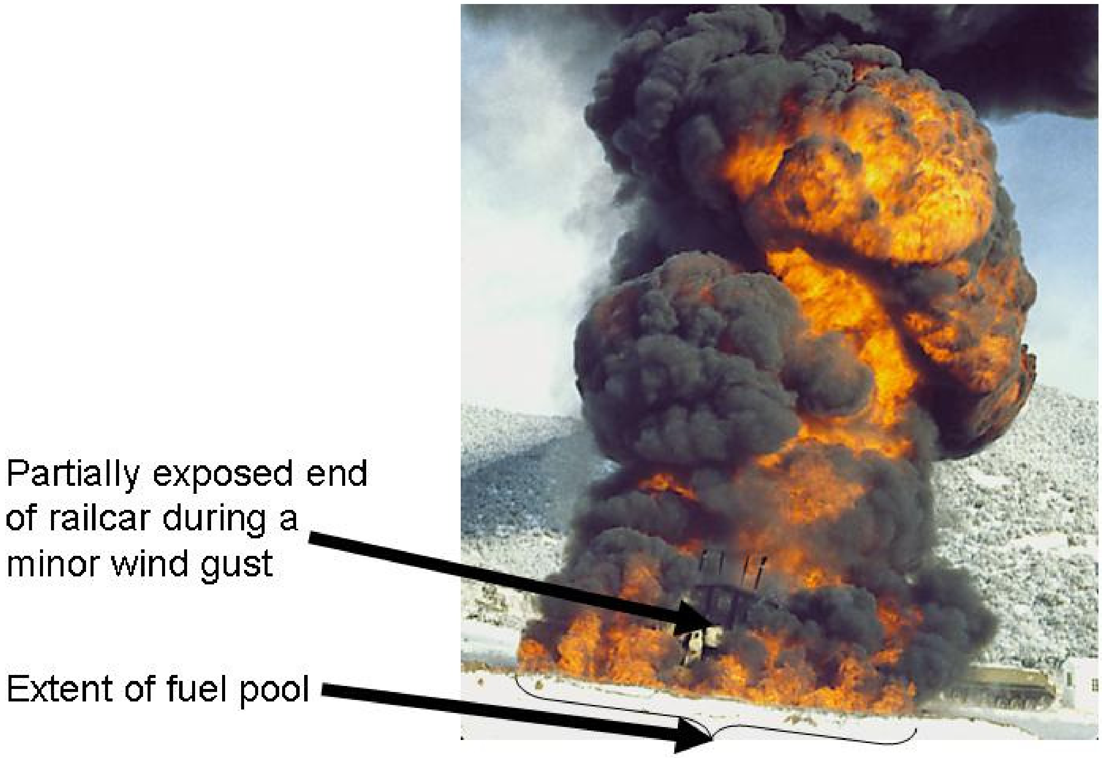


Fig. 7. Cask/Railcar during thermal test.

During approximately the first 90 minutes of the test, the cask temperature response followed a relatively mild response, following which the rate of temperature rise increased more rapidly. At approximately 100 minutes, a white cloud of smoke was visually detected emanating from the cask. At this time the supply of fuel to the pool was terminated, but the fire continued to burn until all fuel was consumed. Due to the weakening of the concrete and metal supports and the metal railcar, the railcar still containing the cask toppled onto its side at approximately 122 minutes, severing all thermocouple connections. The fire self-extinguished at 125 minutes. The final position of the railcar/cask following fire exposure is shown in Figure 8.

Fig. 8.  Cask/Railcar following exposure to fire for 125 minutes.

Figure 9 depicts the cask from a top view, showing the general wind direction and the maximum measured surface temperature at various locations.  Temperatures were higher on the top than on the on the bottom, and on the windward side than on the leeward side.

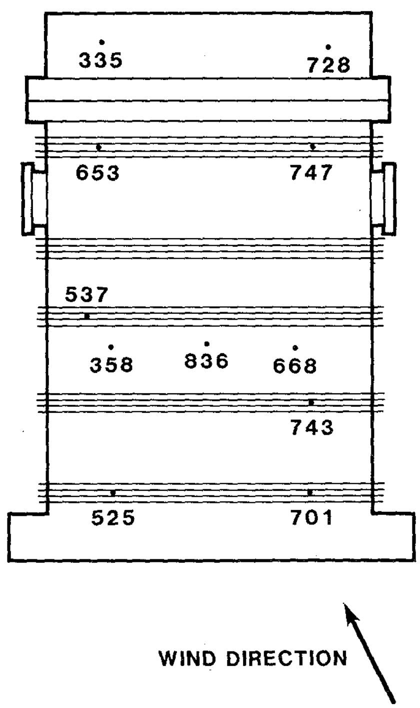


Fig. 9.  Schematic of cask showing maximum surface temperatures (in $^{o}$C) after 60 minutes exposure.

A detailed assessment of the results of this thermal test is provided in Ref. [5]. This included summarizing both pre-test predictions and post-test modelling; the latter performed with a view to obtaining a better understanding of the parameters involved in such fire exposures. This paper concluded that "*the computer analysis of this test configuration proved to be difficult, not because of the cask model, but because of the definition of the boundary conditions.*" The effects of variations with time of the absorptivity of the cask and the reduction of heat input to the cask from intervening structure were addressed in these analyses. The paper concluded that the "*present regulatory criteria appear to properly account for the wide range of environments a package might be exposed to in a severe accident.*"

A thorough post-mortem inspection of the tested cask was undertaken [13] to assess the modes of failure resulting from this extensive thermal exposure. This detailed disassembly and metallurgical analysis of the cask showed "*the presence of two macrofissures in the outer cask shell. The first, lying within a stainless steel seam weld fusion zone, is believed to be a hot crack which resulted from elevated temperature stressing of the cask. The second crack, located within the stainless steel base metal, appears to originate at a copper-stainless steel dissimilar metal weld joint during manufacture, with final propagation thru the outer cask shell occurring during the fire-exposure.*"

It is noteworthy that the cask was initially designed to incorporate empty volumes next to the lead shield to accommodate lead expansion should it melt. However, the post-mortem examination showed that the pathways from the lead gamma-shield to the expansion volumes were not opened during fabrication. Based on this finding, Reference [13] concluded that "*neither macrofissure would have formed if (a) the fire test temperature had not been excessive, that is exceeding the Nuclear Regulatory Commission (1075$^{o}$K – 30 min.) regulation, (b) appropriate lead expansion volumes had been provided, and (c) appropriate procedures, e.g., a Ni filler wire and low heat input, had been used during welding of the copper fins to the stainless steel outer wall*". Thus, with the advance in metallurgical technology and the imposition through regulations of more stringent quality assurance during fabrication, the problems encountered after the obsolete 67-tonne cask had been exposed to the fully engulfing fire for about 90 minutes could have been avoided.

*Truck/Cask Pool Fire Test*

The time for performing the test was selected to provide as near-optimal weather conditions as possible. The velocity varied from 0 to no more than 8 km/h (5 mph). Once the fuel was ignited, flames quickly engulfed the trailer/cask system. A study of the films of the test showed that, during the 72 minutes of the fire, the system was totally engulfed for 69 minutes (i.e. for 96 percent of the time). The tested system, following termination of the fire exposure is shown in the photograph provided in Figure 10.

Temperatures in the fire were measured and the means of the temperature time averages at four heights in the fire were developed for 30 and 60 minutes for the four locations surrounding the cask/trailer test system. Similarly, the means of the temperature time averages for the cask surface, the cask tie-downs and the trailer were developed for 30 and 60 minutes. The means of the temperature time averages are summarized in Table 1.

Fig. 10.  Photograph of cask/trailer system following fire exposure.

Table 1. Mean temperature at various heights in the 72-minute, fully engulfing fire test of the PNC SNM package

| Location | Mean of the temperature time average at 30 minutes (°C) | Standard deviation of the temperature time average at 30 minutes (°C) | Mean of the temperature time average at 60 minutes (°C) | Standard deviation of the temperature time average at 60 minutes (°C) |
|---|---|---|---|---|
| In fire at 2.3 m height | 1040 | 20 | 1050 | 6 |
| In fire at 2.9 m height | 1050 | 40 | 1060 | 30 |
| In fire at 3.5 m height | 1000 | 40 | 1010 | 50 |
| In fire at 6.1 m height | 720 | 90 | 700 | 80 |
| Cask surface | 440 | 180 | 600 | 170 |
| Cask tie-downs | 180 | 50 | 370 | 60 |
| Trailer | 750 | 180 | 850 | 140 |

The data in Table 1 illustrate that:

(a) the mean flame temperatures in the areas surrounding the cask/trailer test system were consistently on the order of 1000 to 1050 °C, well above the 800°C required by the regulatory test standards;

(b) the mean flame temperatures cooled as would be expected at heights well above the location of the cask, to a value of 720°C at a height of 6.1 m;

(c) the cask surface temperatures varied significantly over the surface as indicated by the standard deviation of these values;

(d) the trailer temperatures also varied significantly;

(e) the temperatures of the hardware increased with time; and

(f) on average, the trailer was hotter than the cask and the cask was hotter than the tie-downs at any given time.

As expected, the front end of the cask tended to heat faster than the rear of the cask, because the front end of the trailer had been removed following its damage in the preceding impact test. This fully exposed the front end of the cask directly to the fire environment. The maximum mean axial temperatures for the cask were 870°C at the front of the cask, decreasing to 660°C at the centre of the cask, and then increasing somewhat to 759°C at the back of the cask.

The cask was examined in detail following exposure to the fire test. It was not possible to remove the outer head of the cask after the thermal test because of structural damage incurred during the preceding impact tests. Thus, the examination included leak rate testing of the seals and physically sectioning the package for visual examination. The results of the examination are as follows:

(a) The post-fire leak rate test exhibited no detectable leak;

(b) Temperature sensitive labels on the inner head showed maximum temperatures of only 205°C to 210°C;

(c) Much of the balsa wood was charred (approximately 90 percent on the upper half and 70 percent in the lower half, with some local areas having been completely charred);

(d) The maximum surface temperatures of the cask exceeded 600°C, and were thus well above the temperatures measured on the inner head (slightly above 200°C). Thus, the charring of the balsa wood can be viewed as a thermal protective mechanism, creating a low-conductivity porous structure that limited the heat transfer to the cask interior; and

(e) Since the temperatures at the front of the cask where the trailer was open to the fire were higher than those at the rear of the cask where the trailer walls were intact, it was concluded that the intervening structure of the trailer served as an effective thermal shield.

In summary, it was concluded that the containment integrity of the cask was not impaired by the preceding three impact test or the subsequent 72 minute fire test.

*Cask Torch Tests*

A photograph of one of the torch tests is shown in Figure 11.

Fig. 11. Photograph of modified HNPF cask being exposed to torch environment at the side of the cask in the centre.

For the torch tests of the modified HNPF cask, the response at various locations was monitored, and the maximum temperatures in these locations was determined. Table 2 summarizes those results. The temperatures reported in this table are:

- the temperature on the outer shell ($T_{os}$),
- the temperature within the neutron shield ($T_{ns}$),
- the temperature on the carbon steel shell between the neutron and gamma shielding ($T_{cs}$), and
- the temperature on the inner surface of the stainless steel inner containment shell ($T_{ic}$).

The final two columns in the table show the initial temperature of the inner containment shell, and the maximum temperature rise experienced by the inner containment shell, respectively.

Table 2. Summary of maximum temperatures measured during the torch testing of the modified HNPF cask.

| Type of test | Maximum temperature in °C | | | | Initial temperature in °C | Maximum temperature rise in °C |
|---|---|---|---|---|---|---|
| | $T_{os}$ | $T_{ns}$ | $T_{cs}$ | $T_{ic}$ | $T_{ic}$ | $\Delta T_{ic}$ |
| Side of cask, neutron shield intact | 421 | 138 | 127 | 40 | 9 | 31 |
| Side of cask near closure end, neutron shield intact | 514 | 93 | 88 | 65 | 12 | 53 |
| Opposite side of cask, neutron shield voided | 938 | 492 | 330 | 105 | 25 | 80 |
| Head on the impact limiter at the head end | 974 | 89 | 96 | 44 | 31 | 13 |

The table shows that each test was initiated with a different starting temperature in the cask cavity, ranging from 9 °C to 31 °C. This resulted from changes in the ambient conditions during the test program, and residual heat in the cask from preceding tests. These data show that exposure to the torch environment does not significantly threaten the containment system. Specifically:

(a) the presence of water in the neutron shield adds thermal mass and allows the heat to be spread throughout the cask structure, limiting temperature rise in the containment system to no more than 53 °C;

(b) when the neutron shield has been voided, localized heating near the torch impingement area allowed a greater increase in the inner containment system to a maximum of 80 °C; and

(c) when the torch impinged on the impact limiter, the maximum temperature rise of the inner containment system was only 13 °C.

From this, and associated analyses [14, 15], it was determined that the torch environment was much less severe than the regulatory fully engulfing thermal test, and that even if the cask were damaged and the neutron shield were lost, the temperature rise of the inner containment system would still be well within acceptable bounds. In addition, the temperature rise in the neutron shield would not have been sufficient to cause it to release its contents due to overpressure.

## CONCLUSIONS AND DISCUSSION

A review of these three thermal test programs, establishes that the two older cask designs and one new cask design have the ability to survive environments that were different from (the torch environments) or more severe than the environment specified by the existing thermal test requirement in the Transport Regulations. These results can be extrapolated to apply to modern casks that generally have more robust designs as well as better quality assurance applied during the manufacturing process. From this, it would appear that the existing thermal test requirement in the Transport Regulations provides a very robust specification for evaluating package designs to many of the environments that could be expected in a transport accident involving fire.

For pool fire exposures, both the railcar/cask and truck/cask tests exposed the casks to longer duration, fully-engulfing fires. The temperatures measured in the flames of both exceeded the flame temperature required by the Transport Regulations; yet the obsolete 67-tonne cask survived at least 90-minutes of exposure without apparent failure, and the Japanese SNM cask survived more than one-hour of fire exposure while retaining its containment integrity.

For the exposure of the modified HNPF cask to four different torch environments, the integrity of the containment system was retained, the temperature increase was not sufficient to cause the seals to fail, the pressure within the neutron shield did not increase sufficiently to cause loss of the water shield, and the relative temperature increases within the cask were well within acceptable limits and were well below the values that could be expected if the cask were exposed to the Regulatory thermal test.

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