SANDIA NATIONAL LABS/U. S. DEPARTMENT OF TRANSPORTATION FIRE RESEARCH PROGRAM*

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ABSTRACT

A program has been established to develop technology that will support the design and licensing of Nuclear Material Transportation Systems. One component of the technology program is a task that seeks to gain a better understanding of the parameters that influence the thermal response of shipping casks to fire environments. Tests involving exposure to torch and engulfing pool fire environments have been conducted. Issues related to the response of a shipping cask to torch fires as well as the repeatability of and thermal flux generated by open pool fires are addressed.

INTRODUCTION

As part of its nuclear materials transportation research and development activities, the Sandia National Laboratories Transportation Technology Center (SNL/TTC) has been investigating the parameters that influence the thermal response of shipping casks to fire environments. The two fire environments being evaluated in this program are: (1) exposure to a torch fire and (2) exposure to an engulfing pool fire. This program has been conducted as a joint research effort between the SNL/TTC and the United States Department of Transportation Federal Railroad Administration (DOT/FRA). Funding was provided by the DOT/FRA as part of an overall effort to assure a high level of safety during the rail transport of hazardous materials. As part of these activities, the DOT/FRA has conducted a multi-phases research program designed to ensure the structural and thermal integrity of various bulk hazardous materials containers/tank cars under a number of accident scenarios. This effort was expanded, through SNL/TTC involvement, to include investigations of the thermal response of shipping casks used to transport nuclear materials.

This paper will review the joint SNL/TTC-DOT/FRA fire research program. The program was conducted in two phases: Phase I - Torch Fire and Phase II - Engulfing Pool Fire. During Phase I, full scale experimental measurements of the thermal effects of torch fires on a large spent nuclear fuel shipping cask were obtained. The measured temperature data in the various materials of the multilayered cask are unique since no torch tests have been previously conducted on a cask. These data were obtained during a series of four torch tests that simulate a situation in which the relief valve of a hydrocarbon fuel tank railcar has been ruptured during an accident and the contents are vented and ignited so that the resultant torch impinges on the cask. In the Phase II portion of the program, full scale measurements were made of the thermal effects of an engulfing pool fire on a large body which is fully engulfed by the fire. The purpose of this phase of the program was to determine if open pool fires can be used to provide a repeatable test environment and to determine the thermal heat flux incident on a large body situated in such an open pool fire.

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Phase I - Torch Fire

As a result of its concern with torch fire type accidents, the U. S. DOT has obtained experimental data on torch fires and has incorporated the results into regulations for tank car design.[1] In these accidents, a hydrocarbon fuel torch fire emanating from the damaged tank car impinges on an adjacent tank car. It should be emphasized that the DOT regulations apply only to tank cars and that there are currently no regulations requiring the exposure of shipping casks to torch fire environments. This phase of the program was strictly a research effort aimed at establishing the response of a shipping cask to a torch fire environment.

The torch type fire involves high heat transfer over a localized area, and the SNL/TTC efforts have centered on investigating the localized heating effects on shipping casks. The torch fire program has been developed in two segments; analytical and experimental.

Because of the expense and time involved in designing and fabricating a special cask for experimentation, existing casks were surveyed, and based upon availability an existing cask was selected for testing. The Hallam Nuclear Power Facility (HNPF) cask was made available for testing by the Department of Energy (DOE). Since the HNPF cask is of an older design, it did not have a neutron shield or impact limiters. Because contemporary casks do incorporate these features, it was necessary to modify the HNPF cask by designing and fabricating a neutron shield and steel/wood impact limiters to be added to the HNPF cask. These features were designed to meet the transportation requirements specified by the U. S. Nuclear Regulatory Commission,[2]. The HNPF cask was modified as shown in Figure 1 by Stearns-Roger Mfg. Co., Denver, Colorado.

The analytical portion of the program, conducted by Ridihalgh, Eggers and Associates (REA), Columbus, Ohio, consisted of the following tasks: (1) provide the design basis for the modifications of the HNPF cask, (2) develop an analytical model that would predict the thermal response of the modified cask to torch fire environments, and (3) refine the existing analytical model, based upon the experimental results, to produce a model that could then be used to predict the response of other casks to torch fire environments. In addition, REA provided technical support to the experimental portion of the program, both prior to and during the actual testing.

The torch for these tests was provided by Ballistics Research Laboratory. The torch had a nozzle exit diameter of 9.5 mm and used a propane/air mixture for fuel. A flow rate of 50.3 /min was required and a nozzle exit velocity of 64.4 km/hr was produced.

The thermal torch tests included exposure of the modified cask to a 0.5-h, 1200 C, 1.22-m-diam. torch fire at the following cask locations, as illustrated in Figure 1:

Test 1. Side of cask, neutron shield intact.

Test 2. Side of cask near closure (seal) end, neutron shield intact.

Test 3. Opposite side of cask to Test 1, neutron shield voided.

Test 4. Head-on impact limiter, neutron shield voided.

The torch tests were performed at the New Mexico Institute of Mining and Technology/Ballistics Research Laboratory Torch Facility in Socorro, New Mexico.

Eighty-three stainless-steel-sheathed, Type K (Chromel/Alumel) thermocouples and two piezo-resistive pressure transducers were installed on the cask. Thermocouples were positioned in circumferential and horizontal arrays on the outer corrugated stainless steel surface (0.74-m radius), the outer steel shell (0.47-m radius), and the inner steel surface (0.23-m radius), as shown in Figure 2. The heavy dots in Figure 2 indicate typical thermocouple locations. In addition to those measurements on the cylindrical surfaces, thermocouples were placed in similar vertical and horizontal arrays on the exterior flat surface of the impact limiter. The high-temperature, pressure transducers (0 to 1.7 MPa) were mounted at opposite ends of the neutron shield cavity to measure water pressure. Only two of the thermocouples failed during testing, and all the others performed satisfactorily.

A more complete description of the cask instrumentation and test details can be found in References 3 & 4.

Surface temperature measurements in the vicinity of the torch fires were made to determine the extent of thermal penetration and spreading of heat from the torch. Table I lists the maximum measured temperatures:

1. on the outer jacket surface (T_{os})
2. within the neutron shield (T_{ns})
3. on the carbon steel shell (T_{cs})
4. on the stainless steel inner cask cavity (T_{ic}) for each of the four torch tests.

The temperature of the stainless steel inner cask cavity prior to the torch test (T_{ci}), as well as the maximum temperature rise (DT_{ic}) of the inner cavity for each of the four torch tests, is also presented in Table I.

TABLE I

Cask Temperatures

Test Number	Maximum Temperature (°C)					
	T_{os}	T_{ns}	T_{cs}	T_{ic}	T_{ci}	DT_{ic}
1	421	138	127	40	9	31
2	514	93	88	65	12	53
3	938	492	330	105	25	80
4	974	89	96	44	31	13

Results of these tests indicated that the surface temperatures for the cask with a voided neutron shield were about twice as high as those for a cask having a neutron shield filled with water. The wood in the impact limiter effectively prevented thermal penetration, limiting the temperature rise of the inner cavity surface to only 13 c. The maximum temperature rise of the inner cavity surface, which occurred in test 3 with the neutron shield voided, was 80 C. More detailed results of the torch fire phase are presented in Reference 4.

Phase II Engulfing Pool Fire

Containers which are used to transport radioactive materials (RAM) are governed by stringent regulations. Any Type B RAM transport packaging which has received Nuclear Regulatory Commission (NRC) license certification must have demonstrated by

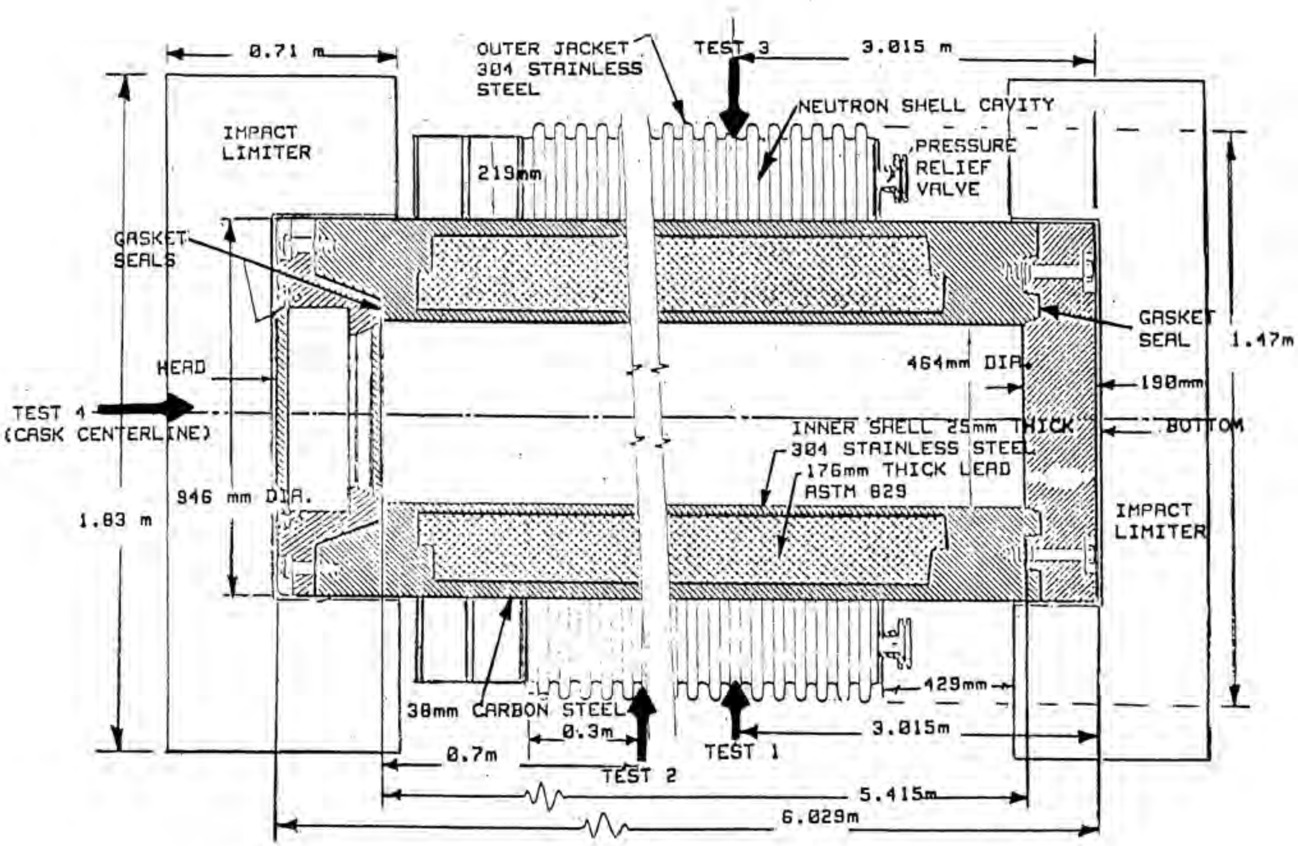

Figure 1. Modified HNPF Cask

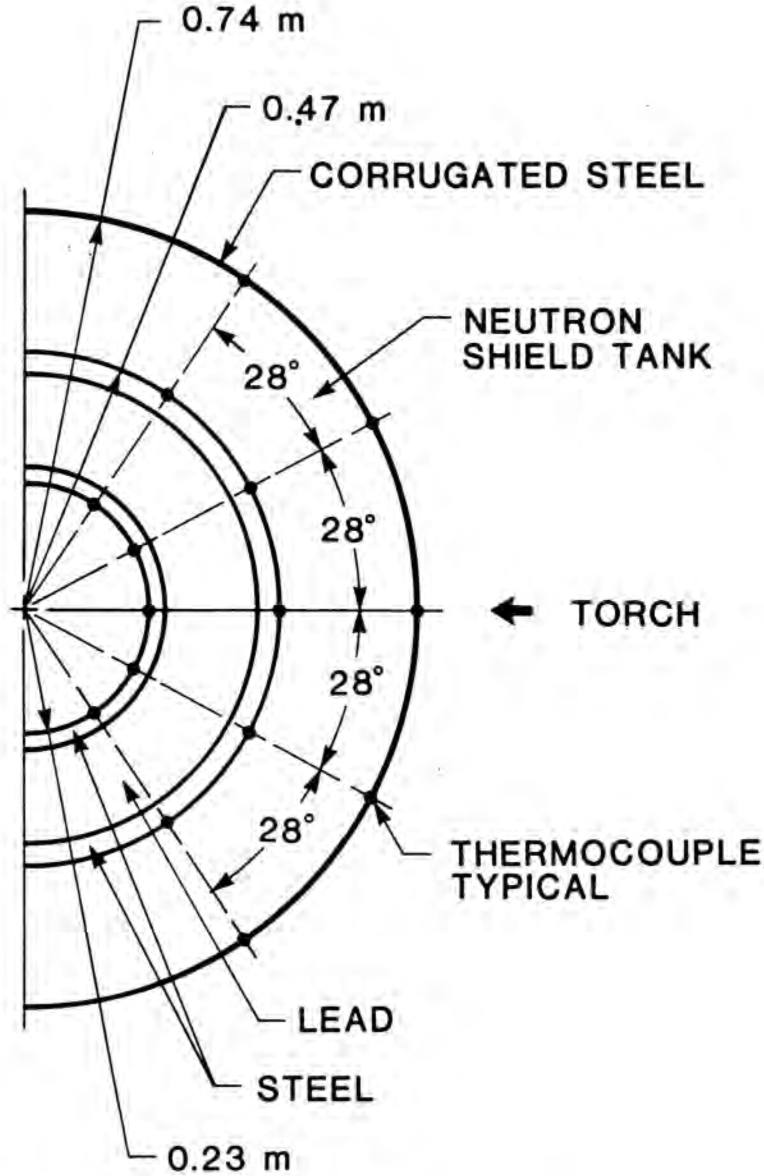

FIGURE 2 TYPICAL CASK INSTRUMENTATION

analysis and/or testing that it can maintain specified containment integrity during both normal transport and hypothetical accident conditions. NRC hypothetical accident conditions entail subjecting the package to free drops, puncture, thermal assaults and water immersion[2]. For example, NRC Regulation 10CFR71 specifies thermal hypothetical accident conditions consisting of "exposure to a thermal test in which the heat input to the package is not less than that which would result from exposure of the whole package to a radiation environment of 1475 F for 30 minutes with an emissivity coefficient of 0.9, assuming the surfaces of the package have an absorption coefficient of 0.8". This NRC regulatory thermal specification is easily applied in computational analysis, but does not define experimental test conditions and procedures which ensure that the required "exposure" is attained. Since the NRC does not provide guidance for experimental open pool fire testing, some experimenters look to the International Atomic Energy (IAEA) for direction. Guidance for satisfying IAEA regulatory experimental testing in open pool fires is described in IAEA Safety Series No. 37[5] which states that the package "shall be supported so that its bottom is 1 meter above the initial level of the fuel" and further "that all sides of the specimen are exposed to a luminous flame not less than 0.7 meters and not more than 3 meters thick". It also states that the supporting structure should not "prevent direct exposure" of the package to the fire and that the package should be oriented "so that maximum damage will result". Additional recommendations describe the desired thermo-chemical properties of the fuel to be used. However, since unspecified variables such as wind direction and velocity, barometric pressure, humidity and surrounding terrain may significantly influence the testing conditions, even strict adherence to the guidelines presented in IAEA Safety Series No. 37 will not guarantee (a) that each test performed in the open pool fire will be similar, or (b) that the thermal regulations established in NRC Regulation 10CFR71 have been satisfied. In order to investigate the experimental open pool fire test, a Department of Transportation (DOT) funded project has been undertaken at Sandia National Laboratories. The major objectives of the engulfing open pool fire program are: (a) the determination of open pool fire reproducibility, and (b) the quantification of the thermal input from an engulfing open pool fire to a package. While the objectives are easily stated, it is difficult to define the basis for assessing reproducibility and the methodology for thermal input quantification. However, considering the original application of open pool fire testing of RAM packages for purposes of certification, it was decided for this study that reproducibility of engulfing open pool fires should be assessed from test-to-test comparisons of thermal inputs from the open pool fires to the engulfed packages. It was with respect to this interpretation that a test plan was established to accomplish the program objectives. The experimental segments of the program are discussed in the following sections.

The experimental program consisted of three 30 minute open pool fire tests. To avoid scaling problems in the fire environment, large calorimeters, which are dimensionally comparable in external size to large shipping casks, were employed for these tests. A separate, but identical calorimeter was used for each of the three calorimeter burn tests. The open pool employed for these tests is located at the Lurance Canyon Burn Site at Sandia National Laboratories. The physical dimensions of this pool are 9.14 by 18.29 m (30 by 60 ft). with a depth of 91 cm (3 ft.). Elevated tanks containing water and fuel feed the pool through a pipe and manifold system. During a burn test, approximately 61 cm (2 feet) of water covers the bottom of the pool while 5 to 15 cm (2 to 6 inches) of fuel floats on top. JP-4 fuel, which satisfies the thermochemical properties described in IAEA Safety Series No. 37, was used as the pool fire fuel. The pool was instrumented for all tests with twenty eight 1.6 mm (1/16 in.) Type K, grounded, Inconel sheathed thermocouples emplaced at fourteen stations, which provided temperature mapping of the pool at two distinct elevations. Twelve of these stations were positioned at six locations along both sides of the calorimeter axis. The final two stations were positioned near the ends of the calorimeter.

One of the large calorimeters used for the tests is shown in Figure 3. They were fabricated from 137 cm I.D. carbon steel pipe (ASTM A517) with a 3.18 cm wall thickness and a length of 6.4 m. Several existing 15.2 cm wide by 7 cm thick welded ribs were evenly spaced on the external pipe wall at axial increments of 61 cm. The internal pipe wall was insulated with 3 layers of 2.5 cm thick blanket which had a density of 128.2 kg/m^3. Insulated cover plates have been bolted onto both ends effectively sealing the interior of the calorimeter. The calorimeters were instrumented at 14 different thermocouple stations with fifty six 1.6 mm Type K, grounded, Inconel sheathed thermocouples. Four stations, located at 90 circumferential intervals, at each of three axial positions (indicated by arrows in Figure 4) established twelve of the calorimeter stations. Each of these twelve stations had 3 thermocouples positioned along a radial line: one embedded 2.5 cm into the insulation from the pipe wall-insulation interface, one at the pipe wall-insulation interface, and the final one at a radial position located 7 cm from the pipe's outer diameter (at the height of the welded ribs). Redundant thermocouples were installed at some of the internal calorimeter thermocouple positions. The final two stations were located at the center point of the two end cover plates. Each of these stations was instrumented at the three radial thermocouple positions as discussed earlier for the other twelve stations.

Prior to the burn tests, the calorimeter was centered in the pool and positioned at a 1 m height above the fuel surface using a specially designed support foundation. This supporting structure was designed to minimize interference between the open pool fire and the calorimeter by positioning most of the supporting pedestal below the fuel-water level. The portion of the pedestal remaining above the fuel level was wrapped with blanket insulation to minimize warpage and ensure that the same support structure could be employed for all three calorimeter burn tests.

Prior to conducting the tests, one criterion must be satisfied. As prescribed in the test plan, the wind velocity, because of its transient nature and its potential for disrupting the test reproducibility, had to be less than 1 m/s before the test could be initiated.

It was estimated that approximately 38,000 of JP-4 fuel were consumed during each 30 minute test. A photograph taken during one of the tests is shown in Figure 5.

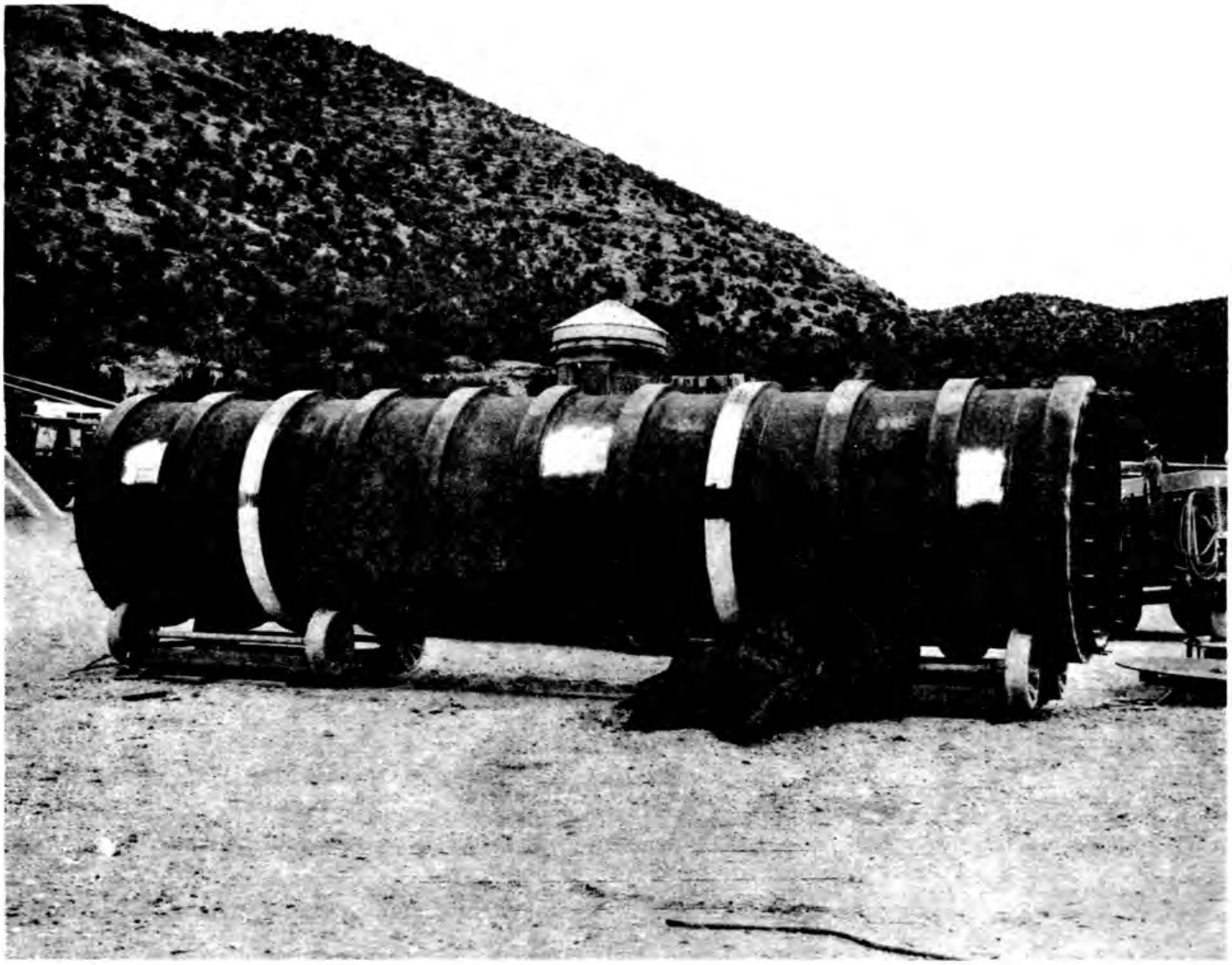

Figure 3. Photograph of Calorimeter

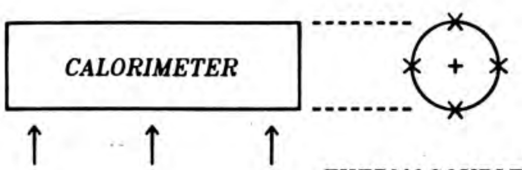

Figure 4. Thermocouple Stations for Calorimeter

Figure 5. Photograph of Open Pool Fire Test

Thermocouple time-temperature data were obtained for both the calorimeter and the pool during the experimental testing phase. However, this data cannot be used directly in raw form. A thermal input, or equivalently a net heat flux, is required to meet the program objectives. The calculation of a net heat flux from time-temperature data is referred to as the inverse heat transfer problem.

An inverse heat transfer code, SODDIT[5], will be used to compute the net heat flux from the time-temperature data obtained during the three calorimeter-engulfing open pool fire tests. Net heat flux results for all fourteen thermocouple stations of the calorimeters will be obtained as output. Open pool fire reproducibility will then be assessed by comparison of the net heat flux data from the similar calorimeter stations for the three burn tests over all fourteen stations.

Data reduction for the Phase II portion of the program has been completed. Current efforts involve verification of the data and interpretation of the results. At this time, the data analysis has not progressed to the point where any conclusions regarding pool fire repeatability or thermal flux incident on the calorimeter can be drawn. Since the analysis is still in a preliminary stage, the results cannot be presented until a later date.

CONCLUSIONS

A DOT funded study at SNL concerned with investigating torch and pool fire environments has been outlined. Results of the torch fire experiments have produced the conclusion that the torch fire represents a relatively benign thermal environment for large shipping casks used to transport nuclear material. Engulfing pool fire experiments have been conducted, and this phase of the program has been described. However, the data from the tests is currently being analyzed so that results regarding pool fire repeatability and thermal flux measurements cannot be presented at this time.

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