EXPERIMENTAL SHIP FIRE MEASUREMENTS WITH SIMULATED RADIOACTIVE CARGO

J. A. Koski (1), M. Arviso(1), J. G. Bobbe,(1), S. D. Wix(1), and D. E. Beene, Jr. (2), J. K. Cole(1), G. F. Hohnstreiter (1), M. P. Keane (3), S. D. Wix (1)

(1) Sandia National Laboratories*, PO Box 5800, Albuquerque, NM 87185-0717
(2) United States Coast Guard, Research and Development Center, Groton, CT 06340-6096
(3) United States Department of Energy, Germantown, MD 20874-1290

SUMMARY

Results from a series of eight test fires ranging in size from 2.2 to 18.8 MW conducted aboard the Coast Guard fire test ship *Mayo Lykes* at Mobile, Alabama are presented and discussed. Tests aboard the break-bulk type cargo ship consisted of heptane spray fires simulating engine room and galley fires, wood crib fires simulating cargo hold fires, and pool fires staged for comparison to land-based regulatory fire results. Primary instrumentation for the tests consisted of two pipe calorimeters that simulated a typical package shape for radioactive materials packages.

INTRODUCTION

The safety of land transport of radioactive materials packages has been studied for many years. For example the "modal studies" (see Fischer, et al, 1987), conducted during the 1980s, considered truck and rail shipment of radioactive cargoes. Sea shipments of such cargoes, on the other hand, have not been studied to the same level of detail. In an effort to increase the knowledge of the possible fire exposure that a package might receive during sea transport, a series of eight shipboard fire experiments have been conducted aboard an actual break-bulk cargo ship. The tests were intended to measure a range of possible fire exposures for packages on ships, and give some basis for comparison to fires specified in current safety regulations. This paper presents some key results from the tests. More detail in a report format, including plots of all data collected, is available in Koski, et al, 1997.

Sea shipments of hazardous materials are governed by the International Maritime Dangerous Goods (IMDG), 1992 code. For radioactive materials packages, the Irradiated Nuclear Fuel (INF), 1995 regulations and the International Atomic Energy Agency Safety Series 6, 1985 (as amended 1990), regulations must also be followed. Together these regulations limit the types

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of fires that must be considered during sea shipments. For example, the IMDG code specifies that for break-bulk freighters, a watertight bulkhead must separate radioactive cargo from flammable liquid cargoes. Thus, the most likely fires on this type of ship are fires with flammable materials in adjacent holds such as engine rooms, galleys and crews quarters, and combustible cargo fires in the same ship hold.

Land based studies of fire accidents concentrate on the fully engulfing pool fire. This type of fire could occur, for example, if a truck transporting radioactive materials collided with a gasoline tanker truck with a resultant large gasoline spill. Packages for larger quantities of radioactive materials are designed and tested to withstand 30 minutes in a fully engulfing hydrocarbon fire. Filling a ship hold with flammable hydrocarbons with an adequate source of oxygen is a highly unlikely event, but for comparison to land based fires, a pool fire with a simulated package suspended over the pool was conducted as part of the test series to determine if in-hold shipboard pool fires differed from those conducted on land.

TEST DESCRIPTION AND SEQUENCE

The tests were conducted aboard the *Mayo Lykes*, a World War II Victory class cargo ship, maintained by the United States Coast Guard at Mobile, Alabama, specifically for the purpose of fire testing. Two holds, Holds 4 and 5, at the aft end of the ship were selected for the tests. Level 1 of these holds, immediately below the weather deck, was used for all fires and measurements. In all cases the fires were set in Hold 4. Steel pipe calorimeters representing simulated radioactive materials packages were placed in both Holds 4 and 5. Fires included ignited heptane sprays impinging on the steel bulkhead between Holds 4 and 5, and wood crib fires representing combustible cargo fires. The general experimental arrangement is shown in Figure 1.

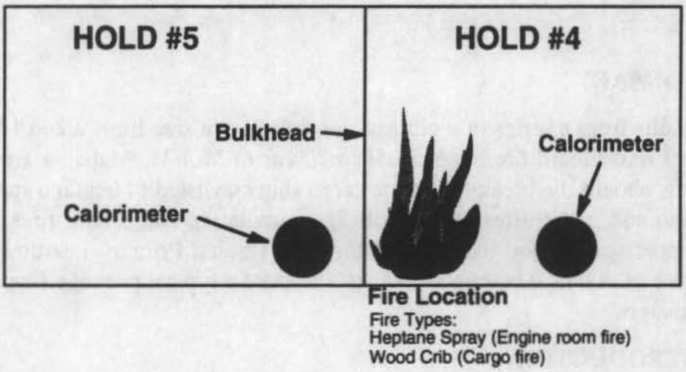

Figure 1. Fire test arrangement.

The sequence of eight fires conducted aboard the *Mayo Lykes* is shown in Table 1. A brief description of each type of fire and major fire characteristics follows. Hold 4 measures 17.6 m wide by 21 m long by 3.8 m high. Hold 5 dimensions are 17.6 m wide by 16 m long by 3.8 m high. For all tests the calorimeter in Hold 5 was located with its centerline 0.4 m above the deck and 2 m aft of the Hold 4-5 bulkhead. Detailed descriptions of the ship holds involved and instrumentation locations are included in Koski, et al, 1997.

To avoid potentially explosive conditions with the heptane spray and in-hold pool fires, adequate oxygen was supplied to Hold 4 via openings in the hull. Measurements indicate that oxygen levels in the vicinity of the fire were usually near normal atmospheric content. In sealed shiphold fires at sea, oxygen would be more limited, leading to smoldering fires with even lower heat flux levels than experimentally measured. The experimental fires reported here rep-

Table 1. Fire Test Sequence

Test Number	Date, Time and Duration	Type of Test	Peak Thermal Power, MW
5037	9/12/95 2:09 PM CDT 60 Minutes	2 burner heptane spray test	2.2
5040	9/14/95 9:13 AM CDT 20 Minutes	Wood crib fire test with 17 L heptane accelerant	4.1
5041	9/14/95 12:21 PM CDT 60 Minutes	2 burner heptane spray test with diesel fuel in drip pans for smoke	2.2
5043	9/15/95 8:26 AM CDT 20 Minutes	Wood crib fire test with 17 L heptane accelerant	4.1
5045	11/13/95 12:02 PM CDT 60 Minutes	4 burner heptane spray test	5.6
5046	11/13/95 2:46 PM CDT 60 Minutes	4 burner heptane spray test with diesel fuel in drip pans for smoke	5.6
5048	11/14/95 3:09 PM CDT 27 Minutes	Diesel pool fire in Hold 4	15.7
5049	11/15/95 2:20 PM CDT 32 Minutes	Diesel pool fire on weather deck	18.8

resent conditions more typical of a fire that could occur during ship loading or unloading in port.

Heptane Spray Tests

The heptane spray fires were intended primarily to simulate a fire in an adjacent ship compartment. For the first series of tests heptane in a pressurized reservoir was fed through nominal 3/8 inch stainless steel tubing to two nozzles located in Hold 4. Stainless steel BETE model P54 fine atomization spray nozzles were used to create a 90° cone shaped fog spray that was manually ignited with a propane torch. The nozzles were located 0.91 m to either side of the hold centerline. The nozzles were located 1 m above the deck, 1 m from the bulkhead between Holds 4 and 5, and were aimed at the bulkhead at an angle of 45° above horizontal. For the estimated 0.21 MPa pressure difference across each nozzle, a 0.024 kg/s mass flow rate was calculated. For heptane with a heat of combustion of 44.6 MJ/kg, this gives a thermal output of each nozzle for full combustion of 1.1 MW. The two nozzle configuration doubles this to a total thermal output of the fire to 2.2 MW.

After inspecting the calorimeter results from the first series of two-burner heptane spray tests, a second series with larger nozzles in a four-burner arrangement was conducted. For these tests, in addition to the nozzle locations 0.91 m to each side of the ship centerline, nozzles were located 3.05 m to each side of the centerline. As with the two burner tests, nozzles were 1 m above the deck, 1 m from the Hold 4 and 5 bulkhead, and aimed at the bulkhead at an angle of 45° above horizontal. For the test, the larger BETE P66 nozzles were used with a 0.55 MPa pressure maintained at the fuel reservoir. This gives an estimated nozzle pressure difference of 0.17 MPa and a flow from each nozzle of 0.031 kg/s. This yields an estimated power release of 1.4 MW for each burner, and a total release of 5.6 MW total for all burners.

Wood Crib Fires

Wood cribs built from clear Douglas fir were used to simulate a cargo fire immediately adjacent to the simulated radioactive cargo. The general wood crib design is based on UL Standard 711, 1990, and is consistent with the size designated as 20-A in that standard. To estimate the heat release from the crib, equations were taken from Walton, 1988. Application of these equations gave a heat release of 2.4 MW. The UL standard also specifies that to initiate the fire, 17 L of heptane accelerant are to be ignited in a 1 m square pan under the crib. Observation of the experimental data indicated that this accelerant burned for about five minutes giving an experimental recession rate of 0.038 kg/(m^{2}s), and a corresponding output of 1.7 MW. Combining the heat release of the wood crib and the heptane accelerant gives an initial thermal output of 4.1 MW for the first 5 minutes of the fire, then a steady heat release of 2.4 MW as the crib alone burns. Inspection of the data for the calorimeter in Hold 4 indicates that the wood crib heat release decreased rapidly 15 minutes after ignition indicating that most of the wood had burned.

Pool Fires

For this test a 3 m x 3 m pool was constructed on the ship centerline at the aft end of Hold 4, and the steel pipe calorimeter moved to be centered above the pool in a manner consistent with land based regulatory testing.

During the test a 7.6 cm depth out of a total depth of 13 cm of diesel fuel was burned before overhead temperatures exceeded the previously agreed upon maximum of 540°C at 24 minutes into the test. At 27 minutes the fire extinguishment with foam was complete. From this information a fuel recession rate of 0.0443 kg/(m^2-s) was calculated. With a typical diesel heat of combustion of 42.75 MJ/kg this leads to an average heat release of 15.7 MW during the test.

For comparison to the in-hold fire test, a 3 m x 3 m pool was built on the weather deck of the *Mayo Lykes* on the port side amidships. The pool was constructed to closely follow the dimensions of the pool built in Hold 4. The calorimeter from Hold 5 was centered above the pool, 1 m above the fuel surface at the start of the test. A depth of 13 cm of diesel fuel gave a 32 minute burn, typical of a regulatory pool fire. Calculation of the recession rate for this fire led to an estimated average thermal output of 18.8 MW.

PIPE CALORIMETER DESIGN

The pipe calorimeters that simulated the radioactive cargo packages were constructed from two 1.52 m lengths of nominal 2 foot diameter Schedule 60 carbon steel pipe with an outside diameter of 0.61 m and a wall thickness of 0.0244 m. Nominal 1 inch (0.0254 m) thick circular carbon steel plates were bolted to form the ends of the calorimeters. Thermocouples were fastened to the pipe interior and exterior surfaces with thin capacitance-welded Nichrome metal strips. Calorimeters located in Holds 4 and 5 were identical in construction, with the side containing the larger number of thermocouples facing the bulkhead between Holds 4 and 5. A total of 24 type K thermocouples were attached in pairs with one interior and one exterior thermocouple at each location.

The calorimeter interiors were packed with commercial Kaowool insulation material to provide an insulated boundary condition for data analysis. The insulation also blocked thermal radiation and convection heat transfer inside the calorimeter cavity that would require the complicated interior geometry to be analyzed as part of the data reduction.

Absorbed heat fluxes to the calorimeter were determined with the use of the Sandia One-Dimensional Direct and Inverse Thermal (SODDIT) computer code described by Blackwell, et al, 1987. This code can be used to solve inverse heat conduction problems, i.e., rather than solving for the temperatures of an object given the boundary conditions, this code estimates the heat flux boundary conditions given object temperatures. As the name implies, the code assumes a one-dimensional geometry for cylinders, spheres or plates. This approach provides good estimates of the surface heat transfer as long as local peaking of the flux profiles does not produce significant two- or three-dimensional heat transfer near the peak.

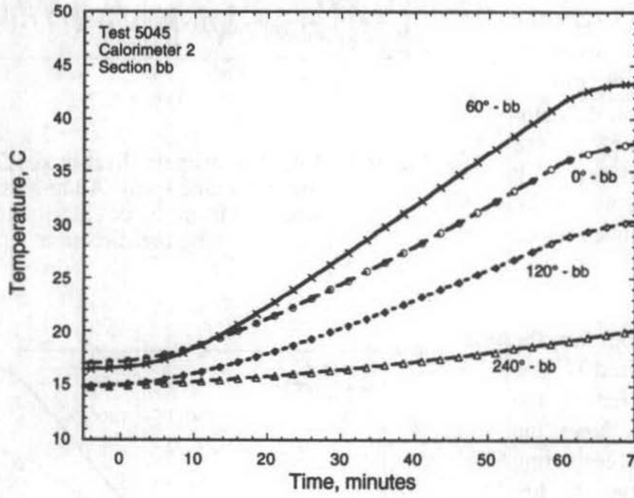

Figure 2. Hold 5 calorimeter temperatures for four-burner heptane spray. All angular locations shown are measured from the top of the calorimeter with 90° location facing toward fire.

EXPERIMENTAL RESULTS

Heptane Spray Fires

Temperature and heat flux results for the first four-burner heptane spray test designated test 5045 are given in Figures 2 and 3. These results are typical of the one-hour four-burner heptane spray fires conducted. For these tests the calorimeter located in the adjacent compartment, Hold 5, was heated about 25°C during the one hour duration of the test as shown in Figure 2. SODDIT, with use of both inside and outside thermocouples at each angular position shows maximum heat fluxes of about 0.8 kW/m^2 on the side of the calorimeter facing the hot bulkhead between Holds 4 and 5 (see Figure 3).

Wood Crib Fires

Results for the calorimeter located immediately adjacent to the burning wood crib (Calorimeter 1) for the first wood crib test designated as Test 5040 are shown in Figures 4 and 5. During this test the calorimeter increased in temperature about 200°C. The initial rapid temperature increase at the start of the test is caused by the heptane accelerant used to start the fire. This initial transient results in an initial peak of about 25 kW/m^2 on the calorimeter surface (see Figure 5) as estimated with SODDIT with the use of the interior thermocouples only.

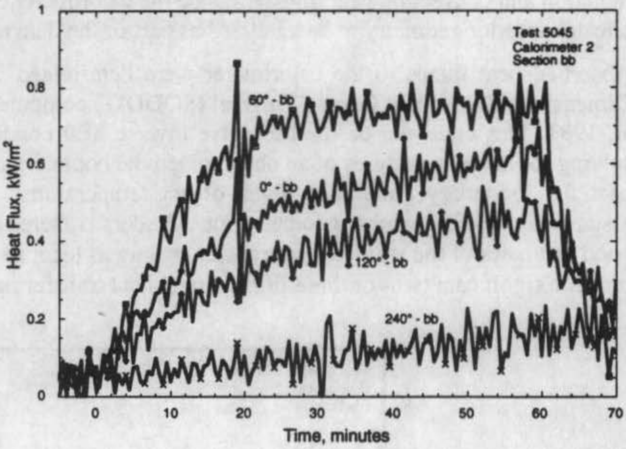

Figure 3. Hold 5 calorimeter heat fluxes for four-burner heptane spray. All angles are measured from top of calorimeter, with 90° location facing fire direction.

Pool Fires

For the in-hold pool fire, the calorimeter in Hold 4 was completely engulfed by the pool fire flames. Near the end of this test, cables strung on the deck above the fire hold were damaged, resulting in erratic data swings. The heat fluxes to the calorimeter in Hold 5 adjacent to the fire compartment remain at about the 1 to 1.5 kW/m^2 level as shown in Figure 6. At about 24 minutes, a decision to extinguish the fire was made to avoid damaging the deck immediately above the fire zone.

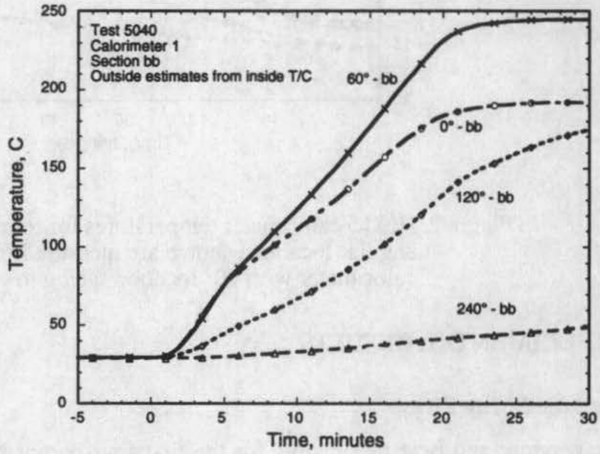

Figure 4. Typical Hold 4 calorimeter temperatures for wood crib test.

Because the on-deck outdoor pool fire was conducted during a strong wind, these data are not directly comparable to typical regulatory outdoor pool fires conducted under low wind conditions. For this reason, these data are not presented here. A complete summary of the data is provided in Koski, et al, 1997

DISCUSSION AND CONCLUSIONS

The fire tests yielded several results support the beliefs held prior to testing. First, the overall heat flux level in typical adjacent-hold and combustible-cargo ship fires is considerably below the initial 65 kW/m^2 heat flux levels implied by regulations such as Safety Series 6, 1990. Even for the in-hold pool fire, initial heat flux levels to the calorimeter over the fire were comparable to values measured in land-based regulatory fires (see Gregory, et al, 1989). For Hold 5, adjacent to the fire hold, the heat fluxes to the calorimeter never exceeded 1.5 kW/m^2, even with the large 15.7 MW pool fire near the Hold 4-5 bulkhead in Hold 4..

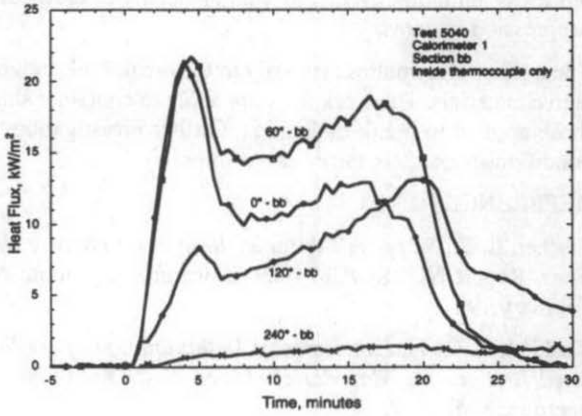

Figure 5. Typical Hold 4 calorimeter heat fluxes for wood crib test.

For both the heptane spray and wood crib fires, analysis of the calorimeter heat flux plots shows that the absorbed heat fluxes are much higher on the side facing the fire. This indicates that thermal radiation is the dominant heat transfer mechanism since convection would lead to a more uniform heating with hot gases flowing around the entire circumference of the calorimeter. Accurate fire simulations with computer models will aid in determining the partitioning of the heat transfer mechanisms involved.

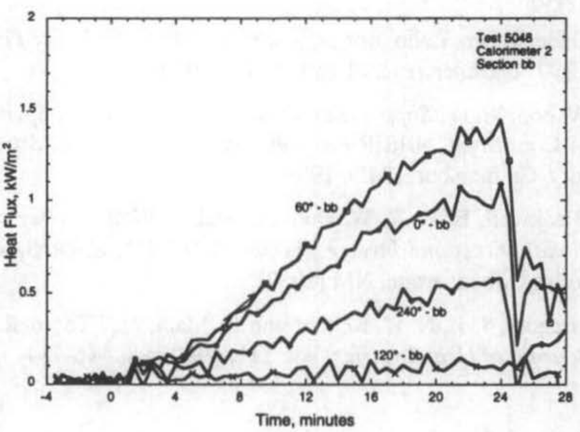

Figure 6. Hold 5 calorimeter heat fluxes for in-hold pool fire test.

Analysis of the data does not indicate that shipboard fires are likely to lead to increased heat transfer when compared to land based regulatory fires. In general, the heat transfer seems to be lower than for the fully engulfing pool fire considered for land based accidents. This leads to the consideration of the duration of shipboard fires, a study that may be better based on historical data or engineering analysis than on experiment.

These experimental results are primarily intended to serve as a means of confirming and refining analytical heat transfer models of shipboard fires. No general conclusions regarding the adequacy or inadequacy of regulatory tests as applied to the shipboard fire environment can be drawn directly from the tests. Any risk assessment model of fires must also include the probabilities of initiating events, as well as details of crew response and allowances for use of fire suppression systems.

The testing here applies primarily to the break-bulk freighters typically used to transport radioactive materials. The work does not apply to container ships, where the IMDG rules differ from those applied to break-bulk ships. Further investigations are in progress to assess typical fire conditions aboard container cargo ships.

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SESSION 10.2

Criticality and Shielding