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ASSESSING THE RESPONSE OF TYPE B PACKAGES TO MARITIME ACCIDENT ENVIRONMENTS

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ABSTRACT

The transport of radioactive material, and especially spent fuel, high-level waste, and plutonium, by sea is a source of concern for many coastal states. For states that are not nuclear-states this transport is seen as a risk without benefit. For this reason it is incumbent on the nuclear states that engage in this transport to ensure and assure that it is carried out in the safest possible manner. Safe transport is ensured by packaging the radioactive material within robust containers designed to the requirements of the IAEA. Safe transport is assured through public communication efforts, IAEA meetings, and the performance of technical studies. One large international technical study was performed under the auspices of an IAEA Coordinated Research Project (CRP) and was documented in IAEA-TECDOC-1231. One part of the IAEA CRP involved the assessment of the structural and thermal accident conditions that a spent fuel package could experience during sea transport and comparison of those conditions to the ones imposed by the IAEA packaging standards. This paper will provide an overview of the work on accident conditions. It will include discussions on impact accidents, crush accidents, and shipboard fires. The study concluded that the accident environments associated with sea transport are no more severe than those associated with land transport, and that the existing packaging standards provide for designs that have a very high probability of remaining leak-tight following even the most severe maritime accidents.

INTRODUCTION

The severity of accident conditions that might take place during the sea transport of radioactive materials was investigated at Sandia National Laboratories as part of the U.S. contribution to an IAEA Coordinated Research Project [1] on sea shipments of radioactive materials. Specifically, the mechanical accident environment that exists during ship-to-ship collisions and the thermal accident environment that exists during ship fires were calculated. These accident environments were compared to the resistance of the packages used to transport spent fuel and vitrified high-level waste and to the IAEA hypothetical accident environment of TS-R-1 [2]. The impetus for this study was the concern by non-nuclear nations that the IAEA hypothetical accident conditions were not severe enough to assure the safety of maritime shipments.

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SHIP-TO-SHIP COLLISIONS

The collision between another ship and a small (1675 tonne) charter freighter carrying spent fuel or vitrified high-level waste packages was considered [3]. A series of finite element analyses was performed using different masses and velocities for the striking ship and two loading cases for the charter freighter; a single package and a series of packages. For all of the analyses the geometry of the striking ship was identical to that of the charter freighter, but the mass was varied from equal to 10 times the mass of the charter freighter. The impact speed for the striking ship was 5.14 m/s (10 knots) for the case with equal mass and up to 15.6 m/s (30 knots) for the case with 10 times the mass. In all of the analyses the struck ship had no initial velocity and the resistance to sideways motion provided by hydrodynamic forces was modeled by increasing the inertia of the ship by 40%. The striking ship was assumed to be rigid, so all of the energy absorption is in the struck ship. The simulated RAM packages were modeled as rectangular elastic bodies, and were intended to act as force transducers in the analyses. No attempt was made to model the response of the packages. Figure 1 shows the geometry of the ship collision.

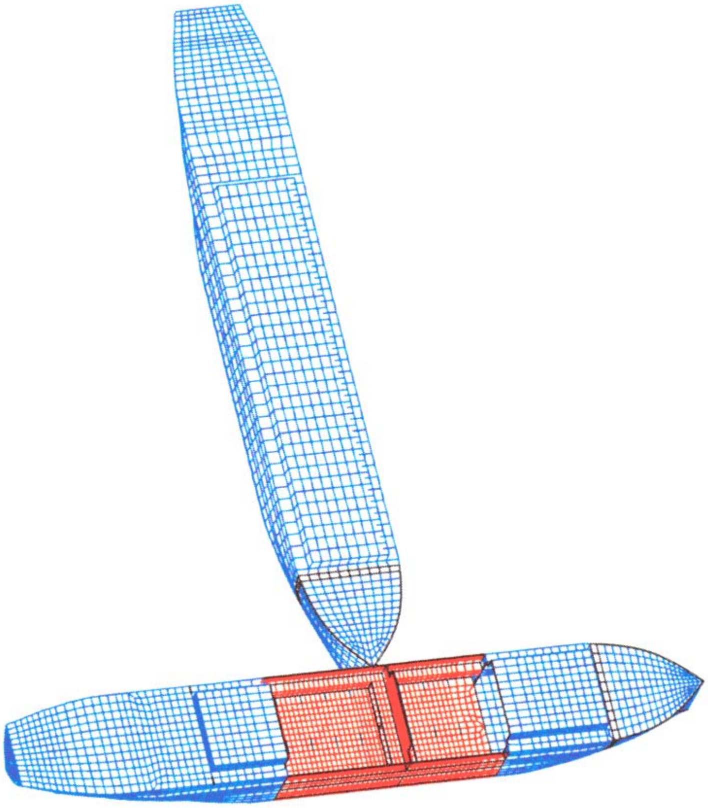

Figure 1 - Finite element model and geometry of ship-to-ship collision

For the cases with only a single RAM package the penetration of the striking ship was never sufficient to result in crush loading on the package. It is certain that the magnitude of the impact load that can result from a ship-to-ship collision is less than that from the hypothetical accident conditions because the impact velocity is generally less and never much greater and the rigidity of a ship bow is much less than the “essentially rigid” target required for the hypothetical accident. For the cases with multiple packages the analyses assumed they were stowed in a manner that spanned 90% of the width of the charter freighter. In these cases the magnitude of the crush force applied to the packages was limited by the strength of the ship hull. The row of packages is pushed against the back of the ship and the hull is pushed outward until it eventually fails. Figure 2 shows the damage for the 15.6 m/s impact with striking ship mass equal to 10 times the charter freighter mass. Note the packages (shown in yellow) being pushed through the hull at the bottom of the figure. In this view the distinction between the individual packages, which are stowed side-by-side longitudinally, cannot be seen.

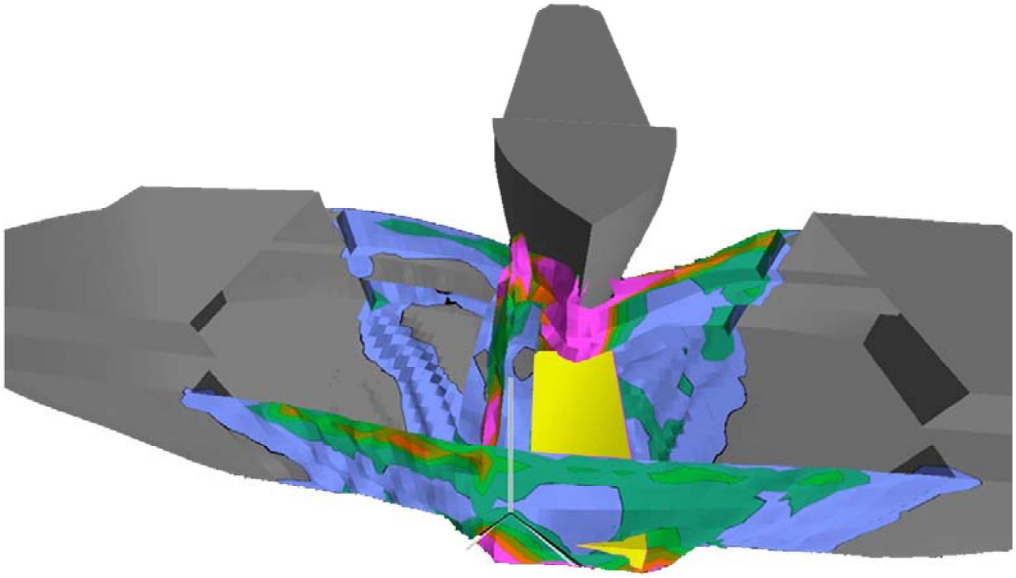

Figure 2 - Damage to a 1675-tonne charter freighter with a row of RAM packages caused by the collision of a 16,750-tonne rigid ship at 15.6 m/s.

The results of the ship collision analyses demonstrated that the crush force that could be applied to a RAM package was limited by the strength of the hull of the RAM-carrying vessel. More detailed analyses of the package/hull interaction were conducted to better quantify the magnitude of this force [4]. In these analyses, a RAM package was pushed through a section of the hull bounded on both sides by bulkheads and at the top and bottom by decks. Two cases were considered, one with the RAM package in an end-on orientation (the most likely orientation during transport), and one with the package in a side-on orientation. The RAM package was modeled as an elastic solid and the ship hull and stiffeners were modeled with shell elements. Figure 3 shows the results for the side-on orientation analysis. At the beginning of this analysis the package is in contact with the hull. The package was given a constant velocity outward. The magnitude of the contact force between the package and the hull is initially limited by the buckling of the hull stiffeners at a load of about 20 MN. After the stiffeners all buckle, membrane tension in the hull and stiffeners leads to a peak contact force of about 105 MN before the hull tears. The conservatisms in the way the ship hull was modeled in this case assures that the actual contact force required to push a package of this size through the hull would be less than 105 MN. While it is not possible to directly compare crush forces from ship collisions to inertial forces present during the regulatory hypothetical accident condition test, it is instructive to compare the magnitudes of these forces. The 105 MN force acting on a 22-tonne cask is equal to an acceleration of 487G. Peak accelerations during cask side drops are typically about this same level. Therefore, it is expected the package would not be damaged as it is pushed out through the ship hull in a side-on orientation. Figure 4 shows the results for the end-on orientation. For this case there is only one stiffener interacting with the cask, and the force required to buckle that stiffener is less than 1 MN. The membrane force that is generated pushing the cask through the hull is only about 9 MN, much less than the side-on orientation. In these analyses it was assumed there was no other cargo in the hold with the RAM package, as would be the case for transportation in the charter freighter analyzed in the ship collision analysis. A case with other cargo present in the hold with the RAM package was also analyzed [5].

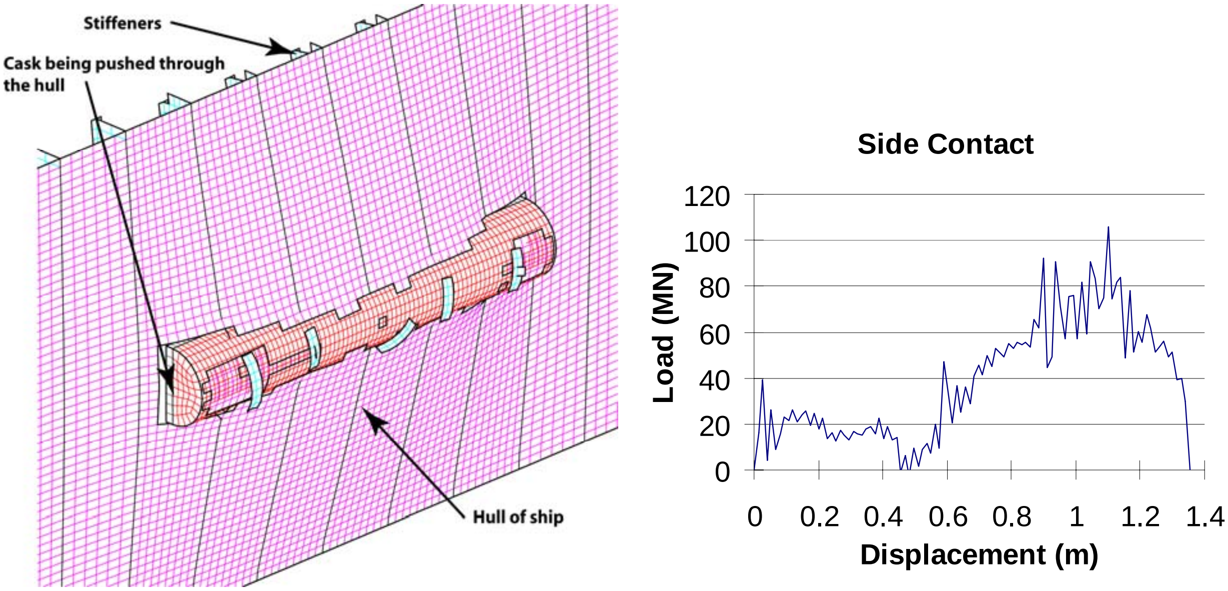

Figure 3 – Detailed model of 22-tonne RAM package being pushed through the hull of a charter freighter and contact force between the package and the hull.

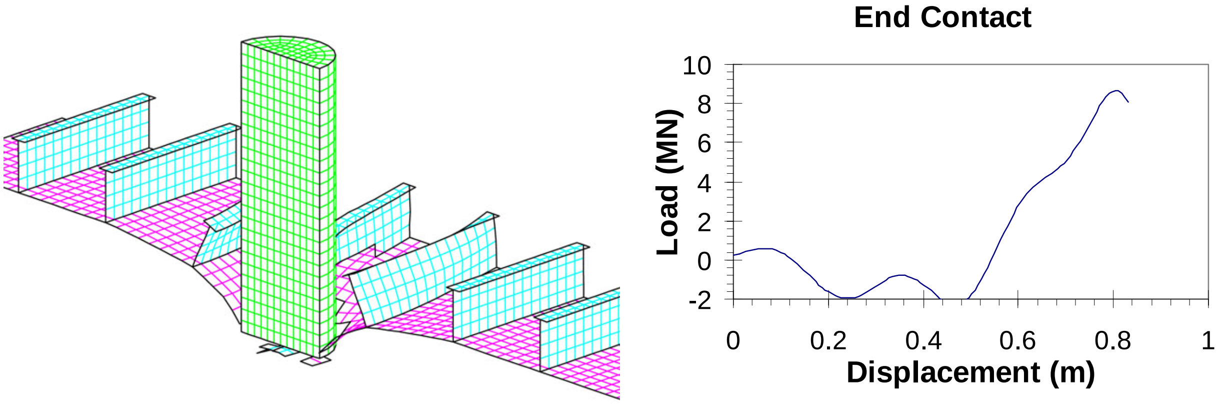

Figure 4 - Detailed model of 22-tonne RAM package being pushed through the hull in an end-on orientation.

The cargo was modeled as a homogenous crushable material. Three cases were considered, a crush strength of 13.8 MPa (2 ksi) and a shear failure strength of 13.8 MPa, a crush strength of 6.9 MPa (1 ksi) and a shear failure strength of 13.8 MPa, and a crush strength and shear failure strength of 6.9 MPa. These strengths are typical of relatively dense discrete cargo, such as lumber or automobiles. Light-weight cargo, such as consumer electronics, would have a much lower strength and would result in response that is not significantly different from the case with no cargo.

Figure 5 shows the force and deformation for the case with a cargo crush strength of 6.9 MPa and a shear strength of 13.8 MPa. For low displacements the response is controlled by the crushing and shear failure of the cargo. The cyclical response is due to each successive row of finite elements failing in shear. The force drops off and then increases while the next row of elements is crushed. This behavior continues up to a package displacement of about 1.5 meters, when all of the cargo has failed in shear. At this point the shear plug of cargo and the package are being pushed together through the distance of the hull stiffeners and it takes very little force to continue the displacement. When the cargo contacts the ship hull the force increases again until hull failure. In this case the force required for hull failure is about equal to the force required to crush the cargo. The force for hull failure with cargo present is nearly identical to that required for the end-on orientation with no cargo.

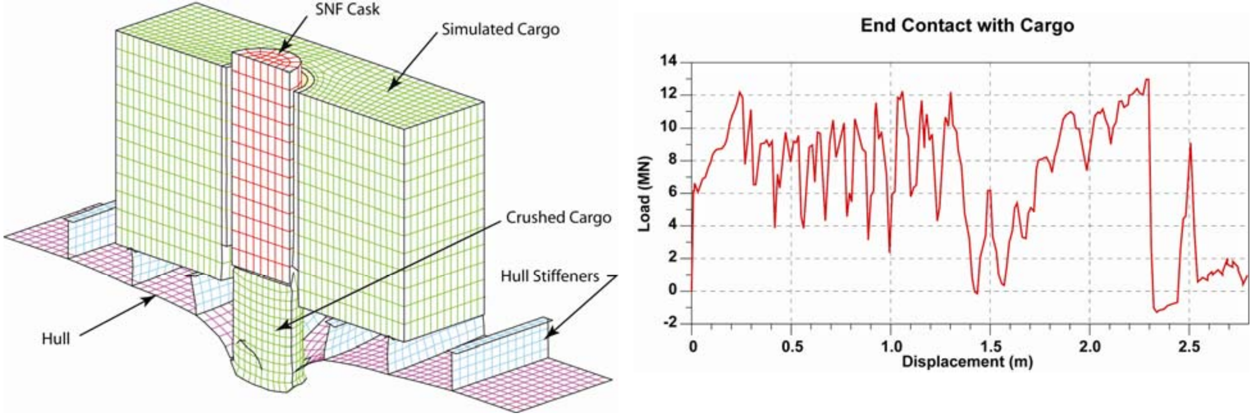

Figure 5 - Crushing force for a RAM package when other cargo is in the hold with the package.

SHIPBOARD FIRES

The thermal environment experienced by RAM packages during shipboard fires was investigated primarily by conducting experiments onboard a U.S. Coast Guard ship at their research facility in Mobile, Alabama [6]. The experiments included simulated engine room fires, simulated cargo fires, and pool fires. In each test, a pipe calorimeter that was approximately the size of a truck transport spent fuel package was used to measure the heat flux. The engine room fire was simulated by having the flame from four heptane spray burners impinge on a bulkhead. The calorimeter for this test was on the opposite side of the bulkhead. The cargo fire was simulated by having a standardized wood crib fire adjacent to the calorimeter. The pool fire was conducted by having a pan of diesel fuel burning in a hold adjacent to the calorimeter. The pipe calorimeter used for these tests was made from Schedule 60 (2.62cm wall thickness) steel pipe 1.52 meters long and 0.61 meters in diameter with 2.54 cm thick circular steel plates bolted to the ends and packed with Kaowool insulation. The total mass of the calorimeter was 719 kg (1585 lbs).

The fire duration for the heptane spray test was one hour. The total heat output for the four heptane torches was approximately 5.6 MW. Figure 5 shows the heat flux at four locations on the pipe calorimeter. The maximum heat flux is less than 1 kW/m^2, much less than the 55 kW/m^2 heat flux due to radiation from the regulatory fire. During this test the temperature of the calorimeter increased approximately 25°C. For the simulated combustible cargo test, the wood crib was constructed from clear Douglas fir and was built to size 20-A of UL Standard 711 [7]. The burning of this crib was initiated by the use of 17 L of heptane. The thermal output of this fire is approximately 4.1 MW for the first five minutes while the heptane is burning and 2.4 MW for the remaining 15 minutes of the fire. Figure 6 shows the heat flux at four locations on the pipe calorimeter that was 1.1 meters away from the edge of the wood crib. The maximum heat flux is about 22 kW/m^2. During this test the temperature of the calorimeter increased by about 200°C. In the case of the in-hold pool fire, the fire duration was 27 minutes. To prevent a possibly explosive condition during this test, the hold with the pool fire was vented. This condition simulates a fire that may occur in port when the hatch covers of the hold are open. While at sea the holds are generally sealed, which would result in a reduced oxygen supply to the fire and lower fire temperature. The pool fire had a heat output of approximately 15.7 MW. Figure 7 shows the heat flux at four locations on the pipe calorimeter that was in the neighboring hold. The maximum heat flux is about 1.5 kW/m^2.

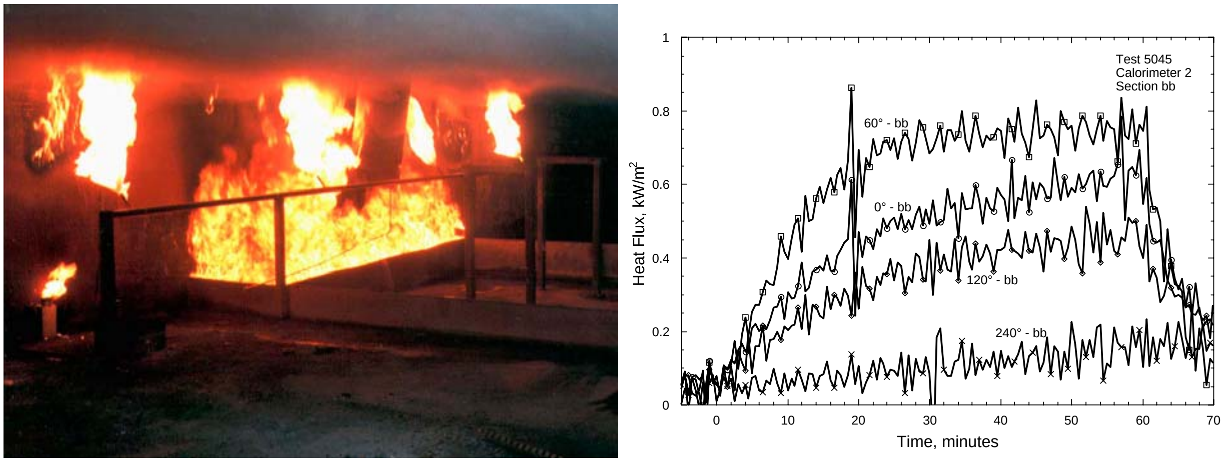

Figure 6 – Heat flux on calorimeter for a 60-minute simulated engine room fire (in addition to the four heptane spray fires there is a pan of burning diesel fuel). The calorimeter was in an adjacent hold on the other side of the bulkhead on the left side of the figure.

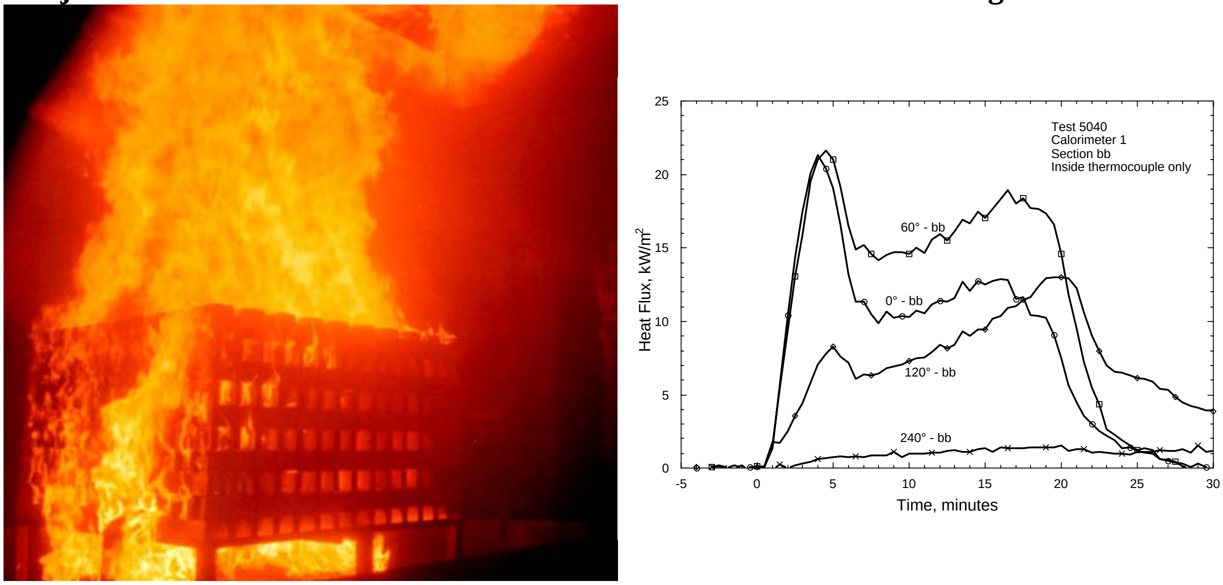

Figure 7 - Heat flux on calorimeter for a simulated cargo fire. The calorimeter was located 1.1 m away from the edge of the wood crib.

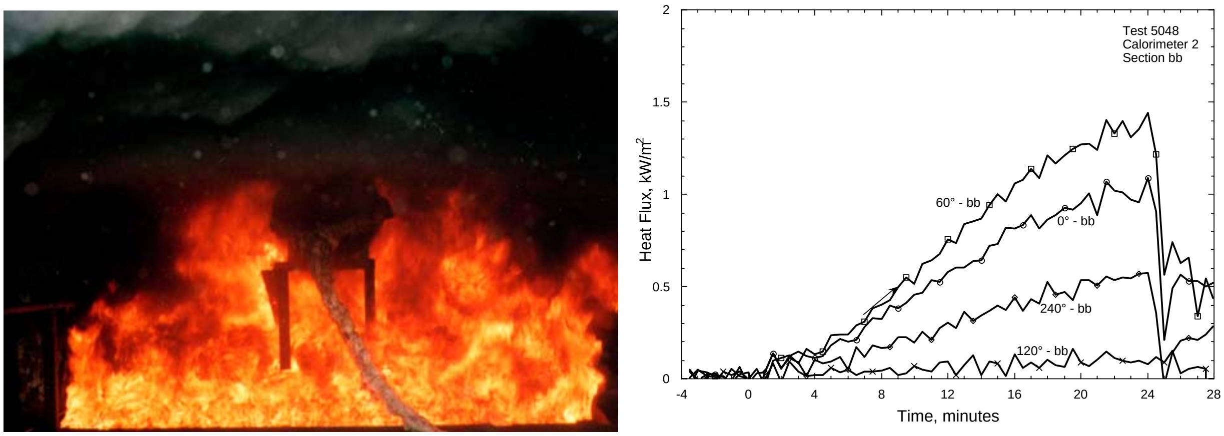

Figure 8 – Heat flux on calorimeter for a pool fire in an adjacent hold. The data shown on the right side of the figure are for a calorimeter in an adjacent hold. The calorimeter seen in the photo was used to provide characterization of the fire.

CONCLUSIONS

This investigation demonstrates that the mechanical and thermal accident environments associated with ship-to-ship collisions and onboard fires is not more severe than the hypothetical accident environment of TS-R-1. Even the most severe ship-to-ship collisions cannot generate impact or crush forces on a package that are higher than the impact forces from the certification impact test. The International Maritime Dangerous Goods (IMDG) Code [8] prevents the transportation of flammable materials and RAM in the same hold. This means that a pool fire is very unlikely to occur in the same hold as a RAM package, but only in an adjacent hold. For pool fires or even spray fires directly onto a bulkhead, the bulkhead acts as a very good radiation shield and limits the heat flux to a RAM package in an adjacent hold. Combustible cargo may be transported in the same hold as a RAM package, but the heat flux from a combustible cargo fire adjacent to a package is less than for the certification fire.

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