Annex 5

STUDY OF ACCIDENT ENVIRONMENT DURING SEA TRANSPORT OF NUCLEAR MATERIAL: ANALYSIS OF AN ENGINE ROOM FIRE ON A PURPOSE BUILT SHIP

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OBJECT

The program goal was to show the IAEA safe transport regulations adequately cover the thermal effects of an engine-room fire on plutonium transportation packages stowed aboard a purpose built ship. The packages are stored in transportation containers located in a cargo hold of the ship. For this study, it was assumed that the package in No. 5 hold adjacent to an engine room could be subject to heating due to a fire in the engine room. The No. 5 hold is separated from the engine room by a water-filled bulkhead. This study addressed the heat transfer from an engine-room fire that could heat and evaporate water out of the water-filled bulkhead and the resulting temperature conditions around the packages and inside the packages near their elastomeric seals.

This study was performed by joint research between Power Reactor and Nuclear Fuel Development Corporation (PNC) and Sandia National Laboratories (SNL). The study was designed to estimate the thermal response of a plutonium package in the hold of a purpose built ship during a shipboard fire. And furthermore, to confirm the sufficiency and adequacy of the current IAEA transport regulation.

ACTIVITY

Description of purpose built ships

Purpose-built ships for nuclear transport were designed to provide enhanced protection for the ships, crews, and their cargo, thus increasing the safety and reliability of transportation operations. The ships are constructed with a double hull. The inner shell that embraces the cargo space is formed by watertight, transverse bulkheads. The structure and subdivision of the hull are designed so that the vessel will stay afloat after it has sustained damage. Wing tanks formed by this construction are used for normal ballast and trimming requirements except for the tanks abreast of No. 5 hold, that are allocated for holding bilge water. The wing tank space is also structurally stiffened against impact damage that could be sustained by packages within the holds in the event of a collision with another vessel.

Wing space is also used to provide all-weather passageways on both sides of the ship, immediately below deck level for access to the holds and forward plant rooms. Subdivision of the hull is preserved throughout the passageways by the use of watertight doors.

Cargo handling

The transport packages are loaded into the available holds in ISO-containers. These transportation containers are ~2.4 × 6 × 2.6 m, are stacked transverse to the ship axis (their long dimension faces the bulkheads between the holds). The No. 5 hold is large enough to be loaded with three rows of ISO-containers stacked three high. Each ISO-container can hold 10 plutonium packages.

Segregation between the cargo space and the normally occupied space is provided by radiation shielding in the form of a water tank extending the full width and depth of the cargo hold at the aft end of No. 5 hold. The tank is formed by two transverse bulkheads (each 40-mm thick) that are separated by 750-mm of water space. Radiation shielding is extended forward from the bridge by concrete overlaid on the deck and beneath the hatch covers.

Ambient temperature in the cargo holds can be controlled within the limits of -40°C to +38°C. This has been achieved by providing two forced circulation air chillers in each hold, which reject the heat directly to sea. The chilled air is ducted to distributors low down in the hold and extracted at a high level using axial flow fans.

Each air chiller consists of two independent refrigerator units sharing a common air-circulating duct. Actual loading conditions can usually be met by running only one refrigerator. The heat is rejected to sea directly by sea water circulating pumps. All essential components of the systems are duplicated.

Even upon complete failure of the hold air cooling systems, the packages will reach an acceptable thermal equilibrium at all outside ambient air temperatures. In a conservative analysis of a thermal heat transfer due to an engine room fire, the active cooling will be assumed to be inoperable during the fire.

Cargo

Plutonium is transported in packages designed and approved in accordance with regulations of the International Atomic Energy Agency (IAEA). This study was done using a PNC surrogate plutonium package instead of an FS-47 package. The surrogate plutonium package was typical of packages approved for transporting uranium oxide, plutonium oxide and mixed uranium and plutonium oxide powders packed in storage cans.

Ship thermal characteristics

The double hull structure, overhead radiation shielding, and water-filled bulkhead need to be taken into account when developing a model for thermal analysis of heat transfer from a fire aboard ship. In the simulation, heat was allowed to flow from the holds through the double hull structure, the wing tanks, and passageways to an ambient temperature outside of the ship. Heat was also allowed to flow through the deck, the ship fuel storage areas between the deck and hull to an ambient temperature below the ship. The overheads are connected to outside ambient air through their concrete shielding.

Engine room fire scenarios

In this study, fuel was assumed to leak from local storage tanks and cover the entire deck of the engine room. The fuel ignites and the fire reaches up to the overhead covering the full area of the water-filled bulkhead, resulting in maximum heat transfer into the No. 5 hold.

A pool fire with sufficient oxygen will have a fire temperature of approximately 982°C [1]. Such a pool fire will consume fuel with a linear recession rate [2] of 4.7mm/min for large pool fires — those with characteristic sizes of 3 m or greater. Fuel in the engine room is stored locally in service and settling tanks. For this analysis, a fire might be fed from the primary service tanks and settling tank, which contain approximately 50 m^3, or 50 000 liters of fuel. In the event of an engine-room fire, this fuel might be spilled across the deck of the engine room, supplying enough fuel for a two hour fire.

An engine room fire

In the fire scenario, there is a fire in the engine room adjacent to the water-filled bulkhead, and the cooling system in the No. 5 hold is off. Such a fire was assumed to quickly engulf the full surface of the bulkhead, heating it uniformly over its surface. Under these conditions, the water in the bulkhead would be heated from 38°C (the ambient regulatory temperature) to 100°C in ~64 minutes. Over a period of two hours the water level in the water filled bulkhead would be decreased by 1 meter if the water were lost due to heating and evaporation.

The thermal heat transfer process into the No. 5 hold can be evaluated in two stages:

Stage 1: heat transfer through the water-filled bulkhead during heating of water from 38°C to 100°C.
Stage 2: evaporation of the water in the water-filled bulkhead with heat transfer below the water line with the water at 100°C and higher temperatures above the water line.

From these assumptions a set of thermal boundary conditions can be established. The water-filled bulkhead starts at 38°C temperature and is heated to 100°C by the engine-room fire. As the fire continues and the water evaporates, the bulkhead area above the water-line will be heated to a much higher temperature (~508°C) providing a higher temperature heat-transfer process over an increasing bulkhead area in the No. 5 hold.

Fuel for an engine-room fire could come from a rupture in a service tank or settling tank or a fuel line leading to or from a tank. If the leaking fuel forms a pool on the deck of the engine-room, this fuel ignites, and there is sufficient oxygen present, the fire would reach up to the overhead in the engine-room. For this analysis we conservatively assume the fire quickly covered the entire surface of the bulkhead. The fuel would cover the engine-room deck, approximately $10.6 \times 9.1 m^2 = 96.5\ m^2$. The resulting fire would rise to a height near that of the overhead, fully engulfing the area of the water-filled bulkhead in the engine-room.

Derivation of bulkhead temperatures

An open pool fire with a readily available oxygen supply was assumed for these simulations. From this heat source, an equilibrium temperature can be determined for the bulkhead on the far side of the water-filled bulkhead. While water is present in the water-filled bulkhead, the bulkheads in contact with the water would be at a maximum temperature of 100°C where the thermal properties of water at standard pressure and temperature are assumed to apply.

When no water is present, an equilibrium temperature for the far-side bulkhead can be derived by assuming steady state conditions. Consider the scenario with a fire in the engine room adjacent to the water-filled bulkhead.

Assume the following: a fire temperature of 982°C with a fire emissivity of 0.9, that the bulkhead between the No. 5 hold and the No. 4 hold (referred to here as bulkhead 3) is at 38°C, that the space between two bulkheads comprising the water-filled bulkhead and the bulkhead between holds No. 5 and No. 4 is a transparent medium, and that the thermal gradients through the bulkheads are small. For two infinitely large, parallel plates with a uniform temperature (a reasonable assumption for this conservative analysis), a steady state radiative heat transfer analysis predicts that the water-filled bulkhead on the No. 5 hold side would be heated to 508°C. Therefore, the No. 5 hold-side of the water-filled bulkhead above the water in Stage 2, will have a temperature of approximately 508°C.

Stage 1: Heating of the water-filled bulkhead

A water-filled bulkhead separate the engine room from No. 5 hold, comprised of two, 40-mm thick steel bulkheads separated by 750 mm. The space between these bulkheads is filled with water. This steel and water barrier provides both radiation shielding between the cargo area and the crew area of the ship and a thermal barrier in the event of a fire. The 40-mm bulkheads extend the full breadth of the ship, and are approximately 15.6 m wide and 8 m high (extending from the lower hull up to the upper deck). The cargo and engine room are, however, approximately 8.5 m wide, due to the double hull.

When water is present in the water-filled bulkhead, the bulkhead temperatures below the water line will be at their initial uniform temperature due to the high thermal conductivity of the water. This bulkhead is conservatively assumed to initially be at 38°C.

The two steel bulkheads comprising the water-filled bulkhead, each 40-mm thick, have a total mass of 40 000 kg. The volume between the two thick bulkheads is 95.4 m^3. The total mass of the water is then 94 900 kg. Since the heat capacity of steel is 452 J/kg-K and that of water is 4175 J/kg-K, the energy required to heat the water-filled bulkhead from 38°C to 100°C is 2.7×10^{10} J. The time required to heat the water-filled bulkhead is then 63.9 minutes.

Stage 2: Evaporation of the water out of the water-filled bulkhead

The latent heat of evaporation of water is 2.255×10^6J/kg. The energy required to evaporate the water is then 2.14×10^{11} J. The time required to do this can be estimated again. The water-filled bulkhead would be at 100°C below the level of the water during this stage. Above that level, the bulkhead was assumed to be at 508°C. The heat flow from the fire into the water is determined by the vertical surface area of the water in contact with the bulkhead. Under the modeling assumptions used here, the evaporation rate will be constant, with the water level decreasing at a constant rate of 2.65×10^{-4} m/s.

Simulation model of an engine-room fire thermal heat transfer process

During an engine-room fire, heating the water-filled bulkhead from 38°C to 100°C would not generate a temperature increase of concern for packages in the No. 5 hold aboard ship. Elastomeric seals used in the construction of the packages are designed not to fail below 230°C [3, 4, 5] and higher under certain conditions [3]. The greatest possible heat transfer to the packages would be expected to occur sometime during Stage 2, in which the water in the water-filled bulkhead is evaporating and the bulkhead above the water level is reaching 508°C. Absorption of radiant energy by water vapor and steam cooling of the water-filled bulkheads are neglected in this conservative analysis.

To model Stage 2 in the engine-room fire scenario, a simulation with a state-of-the-art, time-dependent, 3D, thermal, computational fluid dynamics code is required. The hull, port and starboard bulkheads, and the bulkhead to the No. 4 hold are thermally connected to an ambient temperature sink. The overhead of each hold is covered with concrete, which would act as an insulator in this fire scenario, and the water-filled bulkhead would act as a thermal source. Heat transfer by convection would dominate at low temperatures on all ship, container, and package surfaces. As the upper portion of the water-filled bulkhead is heated to 508°C, radiation from this hot surface would become the dominant heat transfer mode to the first row of ISO-containers, which have a direct view of the hot bulkhead. Convective airflow established in this region would provide an additional heat transfer mode to all the containers and needed to be evaluated in detail.

For this simulation, the CFX code from AEA Technology is the best code currently available that incorporates all of the required heat transfer modes (conduction, convection, and radiation). For this study, the simulation was conducted in two parts. In the first part, the simulation concentrated on the heat transfer from the water-filled bulkheads to the ISO-containers. In the second, detailed heat transfer into a package was determined.

For the first simulation, the ISO-containers were modeled as two rows of containers: the row nearest the water-filled bulkhead was treated as a single unit and the two farthest rows were treated as a second unit. These assumptions allow evaluation of the radiative coupling to the first row of ISO-containers, while accounting for the thermal sink presented by the two farthest rows. A more detailed simulation also was performed to assess heat transfer to the packages in an ISO-container.

In the first model, the bulkheads, overhead, and deck were assumed to be 15-mm thick and made of carbon steel, except for the water-filled bulkhead, which is 40-mm thick. The water-filled bulkhead was treated as a heat source. The overhead, which is covered with concrete, was assumed to be an adiabatic surface. The deck, port and starboard bulkheads, and bulkhead between the No. 5 and No. 4 holds were assumed to be connected to an ambient temperature of 38°C. The ISO-containers and packages were assumed to be at 38°C in the simulation.

The hold is approximately 8.5 × 13 × 9.1 m. ISO-containers are ~2.4 × 6 × 2.6 m in three rows stacked three high and loaded transverse to the ship axis (their long dimension faces the water-filled bulkhead). The ISO-container walls are ~1.5-mm thick steel. Each container can have 10 packages in it. The surrogate plutonium packages have 1.5 mm stainless steel walls around a balsa layer.

The first row of ISO-containers were treated as a single volume and the packages were treated as a single surrogate package in order to understand the principle heat transfer mechanisms from the water-filled bulkhead, through the ISO-container walls, to the packages. The front surface areas of the ISO-container and packages facing the water-filled bulkhead were preserved in order to account for the dominant radiation heat transfer to these surfaces. The second two rows of ISO-containers were also treated as a single volume with a single surrogate package. The thermal mass and conductivity of the surrogate packages and lumped ISO-containers was designed to generate a good estimate of typical individual ISO-container and package temperatures from the simulation.

The simulation accounts for conduction through the bulkhead, deck, overhead, ISO-container walls, and package walls. It uses convective and radiative heat coupling to all surfaces, calculating the heat flow in detail at each node. And it models the airflow within the No. 5 hold, and inside ISO-containers around the surrogate packages.

The simulations were done separately for the two stages described above. In all stages, the water-filled bulkhead was treated as a temperature source. In Stage 1, it was assumed to start at 38°C and rise linearly with time to 100°C over 63.9 minutes.
In Stage 2, the water-filled bulkhead started at a uniform 100°C. As time progressed and the water level decreased in the water-filled bulkhead, the area of the bulkhead above the water level was changed to 508°C. This provided an increasing heat flow into the No. 5 hold and increasing radiative heat transfer to the ISO-containers and packages.

Results from the two stages were then used to establish boundary conditions on an ISO-container for heat transfer to a surrogate plutonium package.

Stage 1 simulation

In the Stage 1 simulation, the same model for the No. 5 hold, ISO-containers, and packages was used. During the time that the water in the water-filled bulkhead rose from 38°C to 100°C, the peak temperature from the simulation of the first row of ISO-containers was 52°C. From the same simulation, the surrogate package reached a peak temperature of 42°C. That temperature would not compromise the integrity of the seals in the packages even when taking into account the internal heat from the plutonium.

Stage 2 simulation

The ambient temperature for this simulation was assumed to be 38°C, since this temperature is described as ambient temperature in the IAEA regulations and provided a conservative simulation for the heat transfer.

The No. 5 hold was modeled with ~40,000 nodes and used millimeter grid spacing near all conducting surfaces. The airflow was treated as buoyant with a k-ε model for turbulent flow.

During the first half-hour of the simulation, the airflow in the No. 5 hold established a single large cell between the water-filled bulkhead and the first row of ISO-containers. The air flowed vertically upward near the water-filled bulkhead with varying velocities and downward near the first ISO-container model. The peak velocity at this time was approximately 0.6 m/s (rising to ~0.8 m/s at 2 hours). Note that there was a significant flow over the top of the ISO-containers.

After approximately 120 minutes as the area of the 508°C bulkhead increased, radiative heat transfer to the front of the ISO-containers established an upper level, hot, airflow cell, and a cooler, counter rotating air cell below that. This division in the airflow results in a larger convective coupling between the hot bulkhead and the upper level of the ISO-containers in contact with the upper cell than the convective coupling with the lower, cooler cell, an effect which would not be accounted for in a simpler analysis.

The temperature of the ISO-containers started at 38°C, the initial boundary conditions in the simulation, and within 5 minutes came up to 40°C, a level consistent with the water-filled bulkhead being at 100°C. Even if the engine-room fire continues for two hours, the surface temperature of the ISO-container which affects the environmental temperature of the surrogate package only increases to 89°C. Because there is no significant environmental temperature rise after extinction of the fire, the accident condition of 800°C for 30 minutes specified in the IAEA regulations is sufficient and adequate for a 2-hour engine-room fire.

Simulation model of a surrogate plutonium package in an ISO-container

The temperature change near the seals of a surrogate plutonium package was simulated in a more detailed model of a package aboard a purpose-built ship. This model included a surrogate plutonium package in an ISO-container. The transient boundary conditions for this model were obtained from the large-scale, No. 5 hold model described above. The model had ~20 000 nodes and used millimeter grid spacing near all conducting surfaces. The airflow was treated as buoyant with a k-ε model for turbulent flow. Details of the surrogate plutonium package, its properties, and initial conditions were obtained from PNC. The initial surface temperature for the surrogate plutonium package was 38°C. The temperature at which the package would be if it were not loaded with plutonium, which fuel acts as an internal heat source. The simulation was run with these initial conditions, and the resulting temperature changes determined during a two-hour engine room fire. The result for packages with fuel was then determined by the principle of superposition [6] adding the temperature changes obtained in the simulation to those determined in the PNC analysis of the surrogate plutonium package for normal conditions of transport.

CFX model description

CFX was used to model the surrogate plutonium package in an ISO-container. The top ISO-container nearest the water-filled bulkhead received the greatest heat flux from an engine room fire and was the one modeled in this conservative simulation. The ISO-container was modeled with a single surrogate plutonium package near a plane of symmetry. The walls of the ISO-container are stainless steel with an emissivity of 0.8. The front, back, and side walls, and the top of the ISO-container each have time-dependent temperatures obtained from the No. 5 hold simulations. The floor of the ISO-container modeled is treated as an adiabatic surface since it is resting on another ISO-container in the No. 5 hold.

The surrogate plutonium package model

The balsa layer of the surrogate plutonium package was modeled in this simulation, as was the air between the package and the ISO-container walls. The inner surface of the balsa layer is conservatively treated as an adiabatic surface boundary. The critical area of the container seals is near the upper lip of the balsa region. The time-dependent temperature history of this area is presented in detail in the full report.

The air surrounding the surrogate plutonium package is modeled as a weakly compressible fluid with buoyancy. Conduction, convection, and radiation are modeled in this region. The simulation accounted for conduction through the ISO-container and package walls. It used convective and radiative heat coupling to all surfaces and it modeled the airflow within the ISO-containers around the package.

The time-dependent temperatures of the ISO-container walls were obtained from the No. 5 hold simulations. The heat from the walls was coupled to the surrogate plutonium package via radiation and convection. It then flowed into the package by conduction, with the temperature dependent conduction obtained from earlier PNC studies.

Simulation results

At five minutes into an engine room fire adjacent to the water-filled bulkhead, the surrogate plutonium package/ISO-container model temperatures and the airflow are minimal. The surface temperatures were fairly uniform at this time. The peak airflow velocity was ~0.07 m/s (rising to ~0.22 m/s 2 hours into the simulation). At 15 minutes into an engine-room fire, gradients in temperature began to appear and the left-hand side of the package appears warmer than the right. At 30 minutes, the temperature gradients are clear. Approximately one hour into an engine-room fire near the water-filled bulkhead, the water in the bulkhead reached 100°C and began to boil off. The bulkhead above the water line then reached temperatures above 100°C, and significant heat transfer from this warmer bulkhead was by way of radiation.
At this point in the simulation, the surface temperatures inside the upper ISO-container are obvious. The ISO-container wall on the left side and the left side of the package are clearly at a higher temperature than the right. Two hours after the start of the engine room fire, there is a 10°C temperature difference from the left to right external surface of the package.

This is the maximum length of fire considered for this simulation of a fire in the engine room near the water-filled bulkhead. It is unlikely that there would be sufficient fuel to burn this long or that a fire would continue unabated for so long a period on a purpose-built ship.

Internal temperatures in a surrogate plutonium package

The external surface temperatures provide a picture of the environment a package might be exposed to in the case of an engine room fire. This detailed simulation also provided information on heat flow into the package. The temperature of the inside of the surrogate package changes little during the two-hour engine-room fire. The temperature information from this heating portion of the simulation can be used to determine the maximum temperature near the seals in the surrogate package over longer time scales.

A 1-D model of the package, using PATRAN/Pthermal from MacNeal-Schwindler Corporation, was developed for determining the temperature increase near the area of the seals over long time scales. This model assumed that the package contained a 100 W internal heat load from the plutonium that resulted in a uniform, internal heat flux. For an ambient temperature of 38°C, the radial temperature distribution through the package near the area of the seals was obtained for normal conditions of transport. A package loaded with plutonium for transport will have an internal temperature near the seals of 90°C in steady state.

Seal area temperatures

To determine the temperature change near the seals, the 1-D model was run with the ISO-container wall increasing in temperature from 38°C to 82°C in accordance with the 3-D simulation results. Heat flowed from this surface to the package through radiation, convection and conduction.

For a two-hour fire in the engine room, the temperature time-history of the inner surface of the surrogate plutonium package balsa near the area of the containment vessel seals was obtained (Fig. 1). The left-hand curve is the temperature history of the warmest region of the external surface of the surrogate plutonium package. The right hand curve is the corresponding temperature response of the internal surface near the seal area. The external surface increases in temperature by 36°C as a result of the fire. While the internal surface responds to this change, increasing by only 4°C.

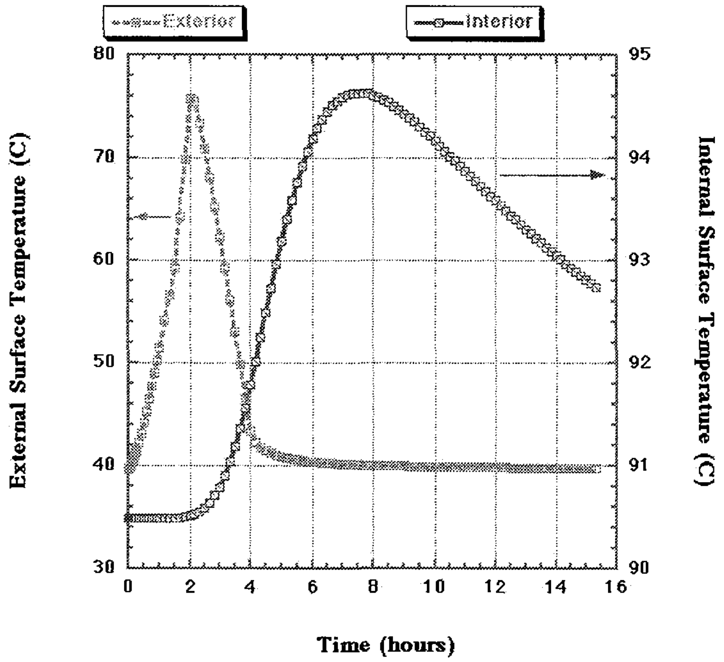

FIG 1. Surrogate plutonium package temperature response for a two-hour engine-room fire.

Thermal analysis of the surrogate plutonium package shows that the peak temperature of the seal region of the surrogate plutonium package occurred approximately 6.5 hours after the start of the fire reaching a maximum temperature of 94.6°C.

It is clear that even in this case, the seal area inside the package stays below the 230°C manufacturer's limit for the operating range for the elastomeric seals for this 2-hour fire duration.

The water in the water-filled bulkhead, however, will cool down slowly. Therefore the ISO-container wall will continue to be heated for a longer period of time. A 1-D model for the package with its internal heat source and an ISO-container wall fixed at 100°C was developed. This model simulated the scenario in which the No. 5 hold was heated by a two-hour engine-room fire, and the hold remained at 100°C for an extended period of time. Analysis of this model showed that the peak temperature near the seal area would only reach ~142°C approximately 50 hours after the start of the two-hour engine-room fire. This simulation provided an upper limit for the temperature of the seal area. The recommended lifetime for elastomeric seals at a constant 142°C is over 1000 hours [3]. Therefore the thermal environment even in this conservative scenario did not threaten the integrity of the seals.

CONCLUSION

The well-planned construction of purpose-built ships provides excellent protection for sea transport of plutonium oxide powder in packages from an engine-room fire thermal event.

This study indicated that the fire accident condition of 800°C for 30 minutes specified in the IAEA regulations is sufficient and adequate for a 2-hour engine-room fire. The surface temperature of the ISO-container which affected the environmental temperature of the surrogate package only increased to 95°C after a 2 hour fire, or 142°C in the case where the No. 5 hold remains at 100°C for an extended period of time. Seals of the surrogate plutonium package transported in the No. 5 hold stayed within their design temperature range after a 2-hour engine-room fire.

The seal integrity was maintained in spite of the following conservative assumptions:

1. Ambient temperature was 38°C for the local air temperature, ship hold temperature, and the initial water-filled bulkhead temperature, and the refrigeration units in the No. 5 hold were off during the engine-room fire.
2. Spilled fuel from a settling tank and two service tanks was available for supporting a two-hour fire.
3. There was sufficient oxygen resulting in a fire temperature of approximately 982°C.
4. The engine-room fire adjacent to the water-filled bulkhead engulfed its full surface and heated it uniformly over its exposed surface.
5. When no water is present, an equilibrium temperature for the far-side bulkhead can be derived by assuming steady state conditions, with the bulkheads treated as infinitely large, parallel plates with a uniform temperature.
6. The space between two bulkheads comprising the water-filled bulkhead and the bulkhead between holds No.5 and No.4 is a transparent medium and absorption of radiant energy by water vapor and steam cooling of the water-filled bulkheads are neglected.
7. Thermal gradients through the bulkheads are small.
8. The overhead, which is covered with concrete, and the inner surface of the balsa layer were adiabatic surfaces.

During the stage of a fire in which water in the water-filled bulkhead is being heated, packages in the No.5 hold will not rise in temperature beyond the seal operating temperature since the water can only be heated to 100°C.

For an ongoing engine-room fire, two convection cells would be established in the No.5 hold in this model, posing changing thermal heat transfer modes to upper and lower ISO-containers; the upper ISO-containers are subject to the highest heat flux. The seal area will remain within its temperature-operating region for the two-hour fire.

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