Plutonium Ocean Shipment Safety Between Europe and Japan

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Introduction

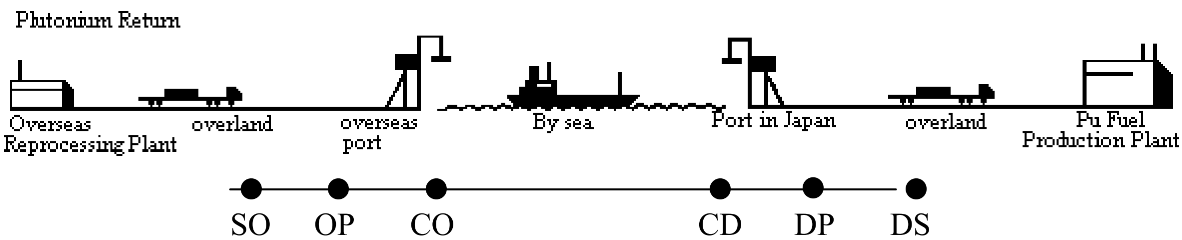
Sandia National Laboratories (SNL) and Japan Nuclear Cycle Development Institute (JNC) have conducted an extensive emergency response planning study of the safety of the sea transport of plutonium for JNC [1]. This study was conducted in response to international concerns about the safety of the marine transport of PuO2 powder that began with the sea transport of plutonium powder from France to Japan in 1992 using a purpose-built ship.

This emergency response planning study addressed four topics to better define the accident environment for long-range sea transport of nuclear materials. The first topic is a probabilistic safety analysis that evaluates the technical issues of transporting plutonium between Europe and Japan. An engine-room fire aboard a purpose-built ship is evaluated as the second topic to determine the vulnerability and safety margin of radioactive material packaging for plutonium designed to meet International Atomic Energy Agency (IAEA) standards. The third topic is a corrosion study performed for generic plutonium packaging to estimate the time required to breach the containment boundary in the event of submersion in seawater. The final study topic is a worldwide survey of information on high-value cargo salvage capabilities from sunken ships. The primary purpose of this overall emergency response planning study is to describe and analyze the safety of radioactive material transportation operations for the international transportation of radioactive materials by maritime cargo vessels.

Synopsis of Part I: Probabilistic Safety Analysis of Plutonium Transport from Europe to Japan

An evaluation of the probability of a severe transportation accident during marine transport for three separate routes from Cherbourg, France to Tokai, Japan was analysed for conventional cargo vessels and their accident histories to estimate the probability of accident occurrences. The accident probabilities developed in this study provide a conservative bounding estimate of the probabilities for accidents involving purpose-built ships.

Figure 1 is a schematic that shows the ocean shipment phases of OP, CO, CD, and DP for this study:



SO = Shipment Origin
OP = Origin Port
CO = Origin Coastal Waters Boundary
CD = Destination Coastal Waters Boundary
DP = Destination Port
DS = Shipment Destination

OP-DP = Ocean Shipment Segment
SO-OP = Origin Overland Shipment by Railroad or Rail
DP-DS = Destination Overland Shipment by Road or Rail
OP, DP = Site Location, Origin Port or Destination Port

Figure 1. Transportation Schematic.

This study relied on examination of transportation information sources, principally the Lloyd's Casualty Register that contains marine casualty information dating from 1979 through 1995 [2]. Specified transportation segments for the nuclear fuel cycle in Japan are analysed. Reprocessing operations are conducted in either the United Kingdom at the Magnox Reprocessing Plant at Sellafield or at the COGEMA reprocessing facility at La Hague, France. For this study, the origin port is assumed to be Cherbourg, France. The destination port is assumed to be Tokai port, a private port near Hitachi, Japan.

The probability of occurrence of transportation accidents in the accident categories was evaluated using the history of actual marine transportation events recorded in the Lloyd's Casualty File (Table 1). For a given Casualty Grouping, the Casualty Frequency per ship-year is calculated by dividing the casualty frequency per year by the total ship population (e.g. for collisions; 34.3 collisions per year divided by 14,820 ships per year or 2.32E-03). The Casualty Rate per ship mile is the casualty frequency per ship year divided by the average annual mileage per year (e.g. 2.32E-03 casualties per ship year divided by 60,000 nm per ship year or 3.86E-08). The Lloyds of London Casualty Categories are Category 1, Foundered; Category 2, Wrecked/Stranded; Category 3, Contact; Category 4,Collision; Category 5, Fire and Explosion; Category 6, Missing Vessel; Category 7, War Loss/Damage during Hostilities; Category 8, Hull/Machinery Damage; and Category 9, Miscellaneous.

Table 1. Casual Frequency and Casualty Rates
(Based on serious casualties for 1990 through 1995 worldwide for general cargo ships of 500 Dwt and above)

Casualty Grouping	Average Number of Casualties per year	Casualty Frequency (Per Ship-Year)	Casualty Rate (Per Ship-Mile)
Collision	34.3	2.32E-03	3.86E-08
Contact	17.7	1.23E-03	2.04E-08
Foundered	44.0	2.97E-03	4.95E-08
Fire & Explosion	25.3	1.71E-03	2.85E-08
Hull/Machinery	144.2	9.73E-03	1.62E-07
Missing Vessel	1.3	9.00E-05	1.50E-09
Grounding/Stranding	62.0	4.18E-03	4.65E-07
Miscellaneous	2.0	1.35E-04	2.25E-09
Total	331	2.24E-02	7.68E-07

Note: Ship population =14,820 ships
Average annual mileage per ship = 60,000 nm
Average annual coastal mileage per ship = 9,000 nm

The probability of an accident occurring during marine transportation can be evaluated for three zones. The first zone is the coastal waters near a large land mass. The second zone is the approach water in the origin port or the destination port. The third zone is the open ocean (termed global commons). Accident occurrences in coastal and port waters are more likely because of vessel traffic congestion. Lloyd's Register and other information were used to estimate the probability of collisions per port call.

These collision statistics were coupled with accident event trees to formulate the probability of occurrence of different categories of accidents. These accident probabilities were used in conjunction with the phenomenology of cask response for severe spent fuel transportation accidents to estimate the probability of a release of radioactive contents due to a severe accident. Figure 2 presents an example of the Accident Event Tree for Category 3 and 4 Accidents. Category 4 accidents were estimated to be on the order of 1.4×10^{-6} per vessel movement on the route. A Category 5 accident probability of occurrence was estimated to be on the order of 1.2×10^{-9}. A Category 6 accident was estimated to be on the order of 1.3×10^{-10}. The probability of a severe cargo vessel transportation accident in a port that might release radioactive material ranged from 10^{-9} to 10^{-10} per ship movement. These probability estimates can be used to estimate the health effects of such accident occurrences. None of the features of a purpose-built vessel were invoked in this study and one conclusion is that the probability of a release of radioactive material from a nonpurpose-built ship is on the order of one-in-one-billion. Invoking the special features of a purpose-build ship would further reduce the probability of the occurrence of such an accident.

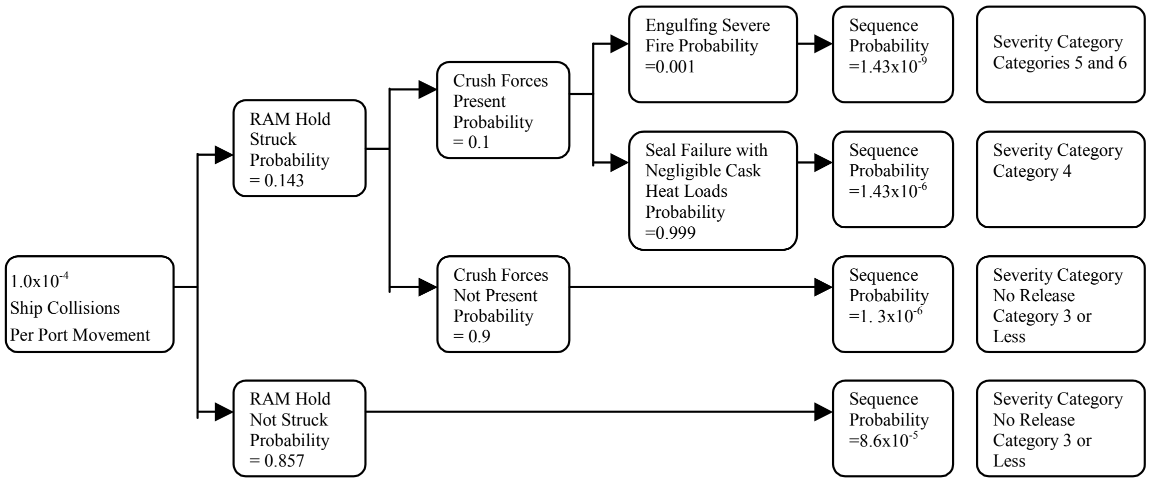


Figure 2. Accident Event Tree for Category 3 and 4 Accidents.

Synopsis of Part II: Analysis of an Engine-Room Fire on a Purpose-Built Ship

An engine-room fire aboard a purpose-built ship was evaluated to determine the vulnerability of radioactive material packagings designed to meet IAEA standards when it is stored in a cargo container and placed in the ship's hold. Plutonium is transported aboard purpose-built ships containing no other flammable cargoes that could provide fuel for an extended fire that could threaten the special packaging carrying the plutonium. The study, which used a number of very conservative assumptions, illustrated that even in the event of a two-hour engine-room fire; elastomer seal temperatures in a plutonium packaging would remain well below the design limits, thus ensuring packaging integrity. The goal of this investigation was to evaluate the IAEA safe transport container regulations concerning thermal effects of an engine-room fire on plutonium transportation packaging stowed aboard a typical 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 packages in a hold adjacent to an engine room, referred to as the No. 5 Hold, could be subject to heating from a fire in the engine room. A water-filled bulkhead separates the No. 5 Hold from the engine room. This study addressed the heat transfer from an engine-room fire that could heat and evaporate water from the water-filled bulkhead, and it calculated the resulting temperature conditions around the packages and inside the packages near their elastomer seals. A schematic depiction of this arrangement is shown in Figure 3.

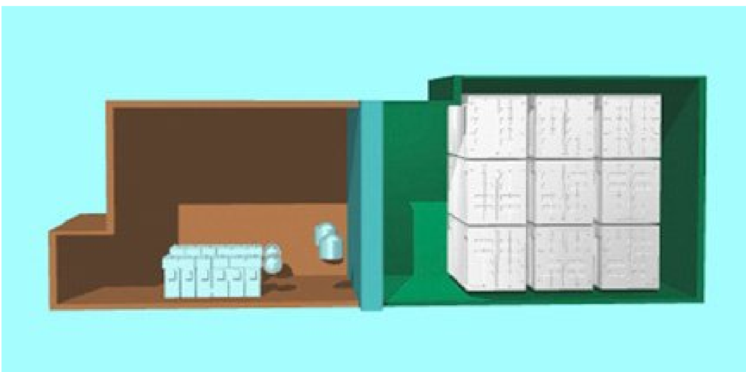


Figure 3. Schematic drawing of the engine room and No. 5 Hold separated by a water-filled bulkhead.

An engine-room fire was selected as the most likely fire scenario to occur. Purpose-built ships have a number of advanced safety features to provide protection against fire. In addition to statutory requirements, the typical ship considered was fitted with extensive fire detection and fire fighting systems, including the ability to flood the holds and machinery spaces with fire suppressant gases. However, in order to proceed with a conservative analysis, the above safety features were assumed inoperable. Furthermore, it was assumed that there was sufficient fuel oil and oxygen in the engine room to allow the fire to burn for two hours, taking into account the fuel oil quantity in the engine room of the purpose-built ship.

The transport packages are loaded into the available holds in International Standards Organization (ISO) containers. These transportation containers are $2.4 \times 6 \times 2.6$ m, and are stacked transverse to the ship axis. 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. Plutonium is transported in packages designed and approved in accordance with guidance of the IAEA. This study was done using a generic plutonium package.

The double hull structure, overhead radiation shielding, and water-filled bulkhead were included to develop a model for thermal analysis of heat transfer from a ship fire. 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 and 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.

Fuel was assumed to leak from local service and settling tanks and cover the entire deck of the engine room. When the fuel ignites, 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. Such a pool fire will consume fuel with a linear recession rate of 4.7 mm/min for large pool fires — those with characteristic sizes of 3 m or greater. Fuel in the engine room is stored in local service and settling tanks. For this analysis, a fire was assumed to be fed from the primary service tanks and settling tank containing approximately 50 m^3, or 50,000 L, of fuel and is assumed spilled across the deck of the engine room, supplying enough fuel for a two-hour fire. These conditions are considered to be unlikely in the actual situation, and as such they constitute a conservative analysis.

For this scenario of a fire in the engine room adjacent to the water-filled bulkhead, the cooling system in the No. 5 Hold is assumed to be non-operational. Such a fire could quickly engulf the full surface of the bulkhead, heating it uniformly over its surface. The thermal heat transfer process into the No. 5 Hold was 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 was established. The water-filled bulkhead starts at 38°C temperature and is heated to 100°C by the engine-room fire. As the fire continued and the water evaporated, the bulkhead area above the water line would be heated to 508°C, providing a higher-temperature heat transfer process over an increasing bulkhead area in the No. 5 Hold.

These simulations assume that a sufficient air supply is available for the engine-room fire. From this heat source, an equilibrium temperature can be determined for the bulkhead on the far side of the water-filled bulkhead. When water is present, the bulkheads in contact with the water would be at a maximum temperature of 100°C. With no water present, the assumption of steady-state conditions allowed the derivation of an equilibrium temperature for the far side bulkhead.

During an engine-room fire, heating of the water-filled bulkhead from 38°C to 100°C would not generate a temperature increase of concern for the packages in the No. 5 Hold. Elastomer seals used in the construction of the packages are designed to perform satisfactorily at temperatures up to 230°C and higher under certain conditions. The greatest possible heat transfer to the packages would be expected to occur sometime during Stage 2, when water in the bulkhead evaporates and the bulkhead above the water level approaches 508°C.

To model Stage 2 in the engine-room fire scenario, a simulation with a state-of-the-art, time-dependent, three-dimensional, thermal, computational fluid dynamics code was utilized. The hull, port and starboard bulkheads, and the bulkhead to the adjacent 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. 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, providing an increasing heat flow into the No. 5 Hold and increasing radiant heat transfer to the ISO containers and packages. Results from the two stages were then used to establish boundary conditions on the ISO container for heat transfer to the plutonium package.

The air surrounding the generic plutonium package is modeled as a weakly compressible fluid with buoyancy. Conduction, convection, and radiation are modeled in this region. Two hours is the maximum length of fire duration considered for this simulation because 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.

The temperature of the inside of the generic transportation 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 generic package over longer time scales.

A one-dimensional model of the package 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, a package loaded with plutonium for transport will have an internal temperature near the seals of 90°C in steady state for normal transport. For a two-hour fire in the engine room, the temperature time-history of the inner surface of the generic plutonium package near the area of the containment vessel seals was calculated. The external surface increases in temperature by 36°C as a result of the fire, and the internal surface responds to this change but increases by only 4°C. Figure 4 shows a 16-hour calculated history of the plutonium package following a two-hour engine-room fire.

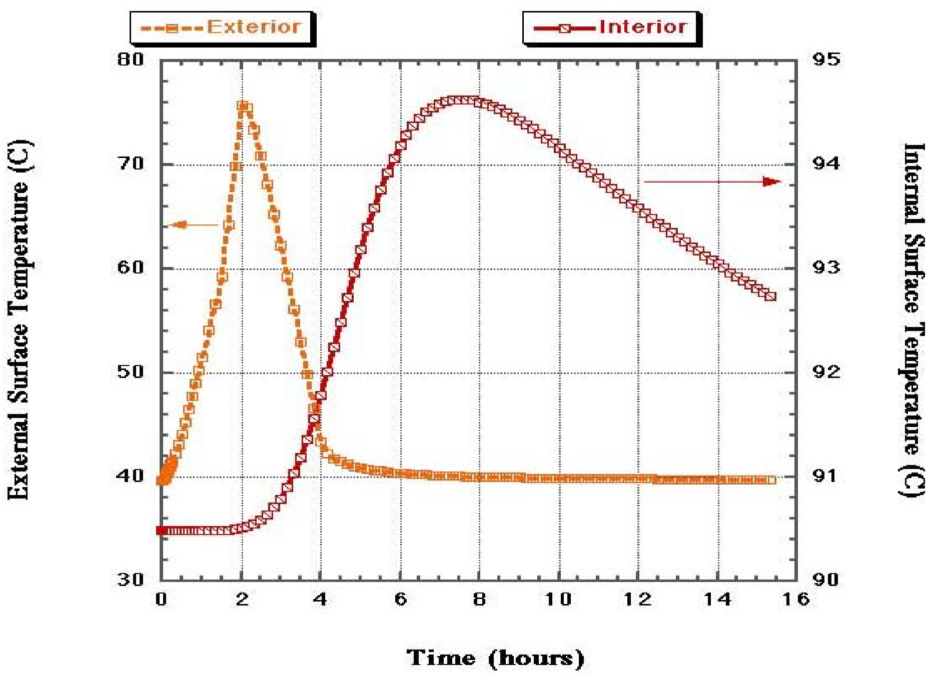


Figure 4. Plutonium package temperature response for a two-hour engine-room fire.

Thermal analysis of the generic plutonium package shows that the peak temperature in the seal region occurred approximately 6.5 hours after the start of the fire, reaching a maximum temperature of 94.6°C. In this conservative two-hour fire environment, the seal area inside the package stays below 230°C, the manufacturer's recommended limit for the operating range for elastomer seals.

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 one-dimensional 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 manufacturer's recommended lifetime for elastomer seals at a constant 142°C is over 1000 hours. Therefore the thermal environment even in this conservative scenario did not threaten the integrity of the seals.

The thermal findings can be summarized as follows: The well-planned construction of purpose-built ships provides excellent protection for sea transport of plutonium dioxide 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 two-hour engine-room fire. The surface temperature of the ISO container, which affected the environmental temperature of the generic package, increased only to 95°C after a two-hour fire. Seals of the generic plutonium package transported in the No. 5 Hold stayed well within their design temperature range as a result of a two-hour engine-room fire, despite a number of conservative assumptions.

Synopsis of Part III: A Corrosion Susceptibility Assessment of a Plutonium Transport Container in Seawater

A corrosion study was performed for generic transportation packagings to estimate the time it takes to breach a typical containment boundary in the event of submersion in seawater for the unlikely possibility that the ship was sunk. The migration time of plutonium out of the packaging following containment breach was not estimated. This study was made to determine an estimate of the length of time available to recover the packaging if it is not feasible to abandon the material on the sea floor because of safety, security, environmental or political reasons.

A generic containment system designed for land-based transportation of reprocessed plutonium dioxide was analysed for corrosion susceptibility in seawater. In this generic container, most of the components are assumed constructed from stainless steel. In the event that a shipping accident occurred and the container is inundated in seawater, corrosion becomes a concern. The expected corrosion behavior of exposed components was characterized and time to failure was estimated. Because stainless steel is known to exhibit susceptibility to corrosion in seawater, and because of the wide variability of environmental conditions and physical configuration of test samples, little directly relevant quantitative corrosion rate information is available. As such, only bounding estimates of time to failure could be made.

Several aspects of the environment must be considered when determining corrosion susceptibility and rates. Properties of the seawater itself can affect corrosion processes. Primary effects include oxygen concentration, temperature, and salinity. Of prime importance is the influence of oxygen concentration. Because the corrosion reaction of steel is controlled by the supply of oxygen, its higher concentration results in a higher corrosion rate. Similarly, corrosion decreases when steel is buried in sediments where the environment is colder and the oxygen concentration is lower. Secondary environmental factors include the presence or absence of biological factors, sediment interactions, and salinity of the seawater.

The study on corrosion susceptibility formed several conclusions and recommendations: The primary concern is crevice corrosion under a main closure O-ring seal in open seawater. The consequence is cask breach that could occur sometime between six months and seven years after the accident. To obtain a more precise estimate, better characterization of the lateral crevice corrosion rate and a reasonable definition of effective cathode to anode area are needed. Failure caused by pitting of the body should be much slower. After a period of three to 17 years, the outer wall would perforate, exposing a typically thick grout layer. Such grout material has been shown to have excellent stability in seawater. Once the seawater permeates the grout and contacts the inner cask wall, it would take an additional 7+ years for pitting to perforate the inner wall.

The secondary concern is failure of a possible sampling port cover (spring or O-ring) with the resulting in exposure of the sampling port itself. Multiple failure mechanisms exist for springs. The time to failure cannot be estimated if stress corrosion of a spring is the failure mechanism. Relative to general corrosion, cadmium plating will provide protection for more than three months and the total time to failure should exceed two years. Failure from crevice corrosion under the O-ring is estimated to be between four months and four years. Detailed information concerning the construction of the sampling port itself is design dependent. Therefore, an equivalent evaluation of the subsequent susceptibility of that component to corrosion failure could not be made.

Synopsis of Part IV: Ocean Salvage Capabilities

A survey was conducted to evaluate commercial recovery capabilities for salvage of high-value cargoes from sunken ships. SNL, JNC and the Applied Physics Laboratory of the University of Washington compiled information on worldwide capabilities for salvage of "high value" cargoes from sunken ships. As unlikely as a sinking of such a modern vessel under heavy surveillance may be, the probability is not zero. Therefore, this survey addresses salvage modes from harbour depths to the deepest ocean trenches. Military and research organizations have been at the forefront in developing deep-diving techniques and manned submersibles for deep ocean-depth excursions. Although these techniques have been used under a variety of circumstances, commercial salvage companies do not use them routinely because the costs usually outweigh the benefits. Ship or cargo salvage in protected harbours to depths of 600 m could be started by a number of companies, including diving companies, in a fairly short time (on the order of days), in many parts of the world. Ship salvage, if performed by a commercial company in the open ocean beyond the continental shelf, would probably be under the management of a major contractor with worldwide offices and resources. These major contractors are primarily involved with petroleum or mineral recovery from the ocean and have available specialized tools for their work. With the current natural resource recovery depths that extend to 900 m, many remotely operated vehicle (ROV) systems are available that can operate in these depths for initial survey and to provide tools to attach lift lines. Due to the versatility required of these ROVs, many are built for rapid reconfiguration aboard ship and can interchange tool devices even at depth.

With mineral recovery now possible at 1,800-m depths, worldwide ROVs may soon operate even at these depths. Heavy lift platforms are available to make the actual recovery, although few recoveries have been made to date because of the high cost. One insurance underwriting company representative stated that if the cargo is not worth 80 to 100 million dollars or is not an ecological disaster, sunken vessel recovery in the deep ocean is not economically feasible. Since 98% of the world's ocean area is 6,000 m deep or less, commercial ROV manufacturers use that as the maximum depth. The use of drill-string-supported tooling allows heavy, complex, and powerful equipment limited only by cost that can work on a salvage project in the 6,000-m depth range. Ship salvage in depths from 900 to 6,000 m should be considered a job for military resources or large military contractors who would develop the resources for the job over a mobilization period of months, probably at costs in the hundreds of millions of dollars. Ship salvage beyond 6,000-m depths is not realistic, even for advanced military systems. A few research ROVs and manned submersibles from other countries have the depth capabilities to function at these depths but not the tools to salvage a ship. The Japan Marine Science and Technology Center (JAMSTEC) organization has a manned submersible capable of 6,500-m depth and an ROV for submersible salvage that has operated at a depth of 10,911 m. These assets are at the call of the Japanese government but are scheduled primarily for research work around the world.

Work in shallow water (down to 30 m) can be done by a large number of contractors worldwide, and new methods usually refer to larger traditional equipment such as lift barges, derricks, hoisting equipment, and tugboats. The next depth increment of underwater manned intervention involves mixed-gas diving operations that go to 100 m and are performed by commercial dive companies. An ROV may be used to aid the diver. When water depths exceed 600 m, all operations will have to be done through a man-machine interface, usually consisting of a video presentation and manipulators. The special needs of heavy salvage are generally beyond the ability of even the heavy work ROVs. For special applications it is necessary to use a drill ship/platform and its hoisting hardware combined with unique deep-water tools that have been made for the specific job. Recently a consortium of large international underwater firms built and operated a salvage system to recover silver from a sunken World War II Liberty ship offshore from Oman in 2600 m deep water. This is the deepest use known of the traditional “smash and grab” technique. The Glomar Explorer used the drill ship/drill pipe method to do recovery work on a sunken Soviet submarine over 20 years ago. The *Joides Resolution* drill ship, which does scientific deep ocean drilling, has lifted a 70-ton package at 5,400 m depth. Deep submersibles from Russia (*Mir* I and II), France (*Nautile*), U. S. (*Alvin*, *Sea*, *Cliff*), and Japan (*Shinkai 6500*) are the deepest diving manned submersibles at 6,000 m and have manipulators, but they are primarily designed for observation, inspection, and small sample collection.

Other Studies

In addition to the material presented here, SNL conducted extensive studies for the U. S. Department of Energy (DOE) concerning the safety of plutonium shipments by sea [3]. These studies included a probabilistic risk assessment of the overall safety, source term evaluations, finite-element-structural-dynamics calculations to determine ship-to-ship collision effects on nuclear material containers, and the effects of ship fires on transport packaging as determined by actual fire experiments conducted on board a test ship. These previous studies, together with this report, form a technical basis that encompasses the overall safety of plutonium transport by sea between Europe and Japan.

Conclusions

Based on this complete set of technical analyses, transport of nuclear materials by sea in Type B packaging, as approved by the Nuclear Regulatory Commission (NRC), Japanese regulations and the IAEA and carried in nonpurpose-built ships with adequate surveillance, represent a very high degree of safety. Thus, land transport mode regulations provide safety when applied to sea transport accident conditions. Transportation in the newer purpose-built ships that have the redundancy in safety features provides an exceptionally high degree of safety for all of the accident failure modes.

References

[1] *Safety Report for the Ocean Shipment of Plutonium Between Europe and Japan*, J. D. Pierce, G. F. Hohnstreiter, J. D. McClure, J. D. Smith, R. J. Dukart1, J. A. Koski, J. W. Braithwate, N. R. Sorenson, K. Yamamoto*, T. Kitamura*, K Shibata*, Y. Ouchi*, T. Ito,* Sandia National Laboratories, Albuquerque, NM; Japan Nuclear Cycle Development Institute, Tokai-mura, Japan*, draft SAND report, Sandia National Laboratories, Albuquerque, NM, 2003.

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