SeaRAM: An Evaluation of the Safety of RAM Transport by Sea[*]

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INTRODUCTION

SeaRAM is a multi-year Department of Energy (DOE) project designed to validate the safety of shipping radioactive materials (RAM) by sea. The project has an ultimate goal of developing and demonstrating analytic tools for performing comprehensive analyses to evaluate the risks to humans and the environment due to sea transport of plutonium, vitrified high-level waste (VHLW), and spent fuel associated with reprocessing and research reactors. To achieve this end, evaluations of maritime databases and structural and thermal analyses of particular severe collision and fire accidents have been and will continue to be conducted.

Program management for SeaRAM is based at the DOE's Office of Environmental Restoration. Technical activities for the project are being conducted at Sandia National Laboratories (SNL). Several private organizations are also involved in providing technical support, notably Engineering Computer Optecnomics, Inc. (ECO). The technical work performed for SeaRAM also supports DOE participation in an International Atomic Energy Agency (IAEA) Cooperative Research Program (CRP) entitled *Accident Severity at Sea During Transport of Radioactive Material*. This paper discusses activities performed during the first year of the project.

Radioactive material is packaged in accordance with national and international regulations. The transport of RAM by sea is conducted under the terms of IAEA, INO, and INF regulations. The transport regulations ensure safety through the integrity of the packaging regardless of the mode of conveyance. However, there has been speculation that maritime accidents are more severe than surface transport accidents and that the regulations may not adequately account for such loadings in packaging design. The premise of this project is not that these regulations are inadequate to ensure the safety of RAM transport by sea. Rather, the aim of SeaRAM is to substantiate the regulations and hence confirm the safety of RAM sea transport. This will ultimately entail quantification of the risks involved in RAM sea transport since no other recognized methodology can provide a definitive measure of safety. Detailed risk assessments of the safety of RAM transport by other conveyances, namely, truck, rail, barge, and air, have been performed. Significantly, these studies have

repeatedly demonstrated that pertinent regulations and packaging designs ensure that the transport of RAM by these means is within the bounds of acceptable risk.

The *Sea*RAM project is divided into four interrelated activities: systems studies, structural analyses, thermal analyses, including fire tests, and risk analyses of ship accidents with database evaluations.

The systems studies activity serves, among other functions, to coordinate and integrate the other activities. This activity includes evaluation of applicable regulations and codes, quality assurance, and overall program management.

Structural analyses will determine the response of ships transporting RAM to accidents involving collisions with other ships or resulting from impacts with stationary objects or structures. The loads imparted to RAM packagings onboard such ships will subsequently be calculated to determine the response of the packagings as a result of the various accidents analyzed (selected based upon historic accident events identified in maritime casualty databases). The RAM package responses will be compared to regulatory loading conditions.

The thermal analysis activity will develop an understanding of possible fire environments on ships that transport radioactive materials. Shipboard fire scenarios will be identified, methods for accurate thermal analysis developed, and the analysis methods verified through fire test experiments within actual ship holds. Thermal analyses will quantify thermal environments of selected severe shipboard fires, again based upon historic accidents identified from maritime databases, involving a postulated ship with RAM cargo. Thermal boundary conditions on RAM packages resulting from these fire environments will be compared to regulatory conditions. The analyses and experiments will determine typical hold temperatures, RAM packaging surface heat fluxes, and other fire conditions to permit estimates of the performance of RAM packagings during fires.

The database / risk assessment activity will evaluate maritime accident databases to define the wide range of scenarios that may impact the integrity of RAM packagings transported by ships. Information from the databases will identify accident scenarios to be used for the structural and thermal analyses and will be the source of input for development of event trees for risk assessments. Database analyses will structure existing data in a format useful to the international RAM transportation community for assessment of accident localities, frequencies, and probabilities, and for identification of representative severe accident scenarios.

Illustrative risk calculations associated with shipping plutonium, VHLW, or spent fuel by sea will eventually be performed. Both incident-free and accident scenarios will be considered. The illustrative risk assessment will specifically evaluate consequences due to open sea, harbor, and coastal accidents. Incident-free and accident scenario risks for coastal shipments will be estimated using the *RADTRAN 4* risk assessment code to calculate population dose and health effects. Risks resulting from credible port accident scenarios will be estimated using the *MACCS* site-specific dose / health effects consequence code. Consequences of radiation dose that may be delivered via the marine food pathway following at-sea accidents will be estimated using the *MARINRAD* code. Probabilities of ship accidents and potential RAM package damage will be estimated using event tree methodology. The event trees will be developed through searches of maritime databases, review of the technical literature, and from the results of the structural and thermal analyses. A generalized method for estimating the possibility that ship accidents (structural and thermal) will damage RAM packagings, validated by comparison to data from a set of severe ship accidents and detailed finite-element ship calculations, will be

developed. Accident source terms, should it be determined that a release may occur, will be developed for PuO_2, VHLW, and spent fuel shipped in a variety of packagings. Radionuclide release fractions will be developed, in part, from the *MELCOR* thermal-hydraulic radionuclide transport compartment code. These calculations will determine the potential release of volatile radioactive species due to fires and the deposition of vapors and aerosols on surfaces. This approach is exactly analogous to that used in the United States in Environmental Assessments and Environmental Impact Statements to determine the risks associated with surface transport of radioactive material.

STRUCTURAL ANALYSES

A goal of the structural analysis task of *Sea*RAM is to model and analyze selected severe ship collisions that are based upon historic records within maritime databases. Ultimately INF Class 1 and 2 and perhaps Class 3 ships will be analyzed in the *Sea*RAM project. Analyses of collisions involving an INF Class 3 ship are not within the scope of the IAEA CRP, as currently defined, but will be performed in the *Sea*RAM project. (The INF *Code for the Safe Carriage of Irradiated Nuclear Fuel, Plutonium, and High-Level Radioactive Wastes in Flasks on Board Ships* categorizes ships as to the amount of radioactivity the ship is qualified to transport with requirements as to ship design, safety features, and administrative controls: INF Class 1 aggregate radioactivity less than 4000 TBq; Class 2 aggregate radioactivity less than $2x10^6$ TBq or, if carrying plutonium, an aggregate radioactivity less than $2x10^5$ TBq; Class 3 no restrictions on aggregate radioactivity.)

One purpose of structural analyses of ship collisions is to calculate the forces imparted to RAM packages onboard the struck ship allowing comparisons with regulatory conditions. Another purpose is to provide data required for input to event trees for which damage to RAM packages relative to regulatory package design for various realistic accident scenarios is required. (However, for the many scenarios that need be considered for construction of event trees, a simpler methodology for estimating damage to onboard RAM packages from collision events will be developed, based upon results of the finite element analyses, similar to the well-known "Minorsky" method [Minorsky 1959] of estimating damage to struck ships.) The structural analyses are not intended to model nor analyze a hypothetical worst-case accident scenario.

Analyses of an INF Class 2 ship have been conducted (Porter and Ammerman 1995). The ship modeled was based upon the design of a ship that has transported U.S.-owned research reactor spent fuel from Europe to the United States. These analyses are not considered definitive in terms of all possible accident scenarios to which ships that may transport RAM packages may be subjected. Nor are the analyses considered a worst-case hypothetical accident scenario. They do model, however, a severe accident, based upon records from maritime databases, to which a ship of a design that has actually transported RAM may conceivably be subjected.

The model used in the analyses assumed the following general characteristics: The striking ship varied in mass and in collision speed, but always collided with the struck ship at a right angle at its midpoint. The striking ship was assumed to have a zero bow rake angle. Hull stiffeners were not modeled. The finite element mesh was a relatively coarse 1-m square shell elements. The bow of the striking ship was treated as an essentially rigid elastic solid. All ship hatch covers were assumed to be rigidly attached to the top deck. The hydrodynamic force of the sea was not modeled but was considered as added mass to the struck ship.

The matrix of analyses performed always assumed the struck ship to have a mass of 1675 tonnes and the struck ship had zero velocity. The striking ship had an assumed mass of

either 1675, 10050, or 16750 tonnes. The 10050-tonne mass was selected based upon a historic collision between the *SS Howard Olsen* and the *SS Marine Leopard* in the North Pacific Ocean in 1956 in which the 21000-tonne *SS Marine Leopard* struck the 3500-tonne *SS Howard Olsen* at 16 knots. In this accident the striking ship had a mass six times that of the struck ship. This ratio was used to derive the 10050-tonne mass. The speed of the striking ship was varied from 10 to 30 knots. The struck ship was assumed to have a RAM cargo consisting either of one or of seven packages (similar to a 22.7-tonne truck RAM package). The transient dynamic finite element code *PRONTO3D* was used to perform the analyses.

The analyses graphically demonstrated the severe damage to ship hulls resulting from collisions of this nature due to the enormous kinetic energies involved ranging from 22.1 MJ for the analysis for which the striking ship was assumed to have a mass of 1675 tonnes and a speed of 10 knots to 2038 MJ for a mass of 16750 tonnes and a speed of 30 knots. The penetration of the striking ship into the struck ship was significant although mitigated somewhat by the fact that the collision was modeled to have taken place near the lateral midship bulkhead of the struck ship.

The time of the highest load coincided with the initial impact to the RAM package(s) by the bow of the striking ship. Subsequent crushing forces occurred when the package(s) contacted the back hull, and they were significantly lower than the initial impact forces. For the scenario for which a 30 knot 16750-tonne ship struck a ship containing seven RAM packages, the maximum compressive force on the packages was 370 MN. Later in the event the packages experience crush forces as they were in contact with both the striking ship bow and the back hull of the struck ship. The crush forces are lower, however, on the order of 100 MN. The initial impact was at a lower velocity and with a less stiff target than associated with a regulatory 9-m impact that RAM packages are designed to withstand.

Additional structural analyses will be performed with other ship designs and collision scenarios. A simpler technique will be developed to allow estimation of damage to struck ships and forces on RAM packages for a wide range of ship designs / sizes, velocities, impact angle, and so forth, for input to event trees.

THERMAL ANALYSES

Experimental data and analyses are needed to define actual shipboard fire environments in terms of temperatures and duration and heat fluxes imparted to RAM packages. Comparison of shipboard fire environments and regulatory open pool fire conditions are necessary to assess the response of RAM packages subjected to shipboard fires in terms of regulatory criteria. The elements of the thermal analysis activity are to identify, model, and analyze selected shipboard fires. Severe accidents events related to the database records shall be selected for analyses. This is to quantify heat fluxes that RAM packages may experience if subjected to severe thermal environments onboard ships. Ultimately a simpler method of assessing the severity of fires onboard ships will be developed to provide the thermal information required for the multitude of event tree scenarios. Fire tests onboard actual ships will be performed to provide benchmark data to validate finite volume thermal analyses. Both the analyses and the actual fire test data will be compared with regulatory conditions to which RAM packages are designed to withstand.

Modeled were holds within the *SS Mayo Lykes*, an INF Class 1 "Victory"-class break bulk freighter that is used by the U.S. Coast Guard (USCG) for fire research tests at their Mobile Bay Fire & Safety Test Detachment. The thermal analysis calculations were performed using AEA Technologies *CFX*™ code, which was developed to model thermal-

fluid conditions including convective, conductive, and radiative heat transfer (Koski et al. 1995). The analyses are to be correlated to fire test conditions aboard the *SS Mayo Lykes* for code and model validation. The initial volume modeled was from the front bulkhead of a hold that contained a RAM package to a furnace wall and from the centerline of the hold to the end of a simulated RAM package. A constant wall temperature of 15°C was applied to all bulkheads in the model except the front bulkhead where a fire in the adjacent hold was assumed to exist. A uniform heat flux of 30 kW/m^2 was applied uniformly across the surface of this bulkhead. Additional models of the entire ship hold are in progress.

The results of the analyses were evaluated in terms of fluid flow streamlines and velocities, fluid temperature, and RAM package temperature. The analyses of the thermal response of the ship hold indicated that fluid flow in the hold becomes fully developed between 300 and 600 seconds from the onset of a hold fire. A convection cell forms between the RAM package and the front wall indicating that the RAM package (and presumably any other cargo within the hold) influences the fluid flow field. Four convection cells developed within the flow field. The maximum and average fluid velocities were 2.4 m/s and 0.5 m/s, respectively. The RAM package slowly rose in temperature, although much more slowly than during an open pool fire. The maximum temperature of the RAM package after 900 seconds was 59°C, well below the regulatory temperature restrictions for RAM packages. An extrapolation of the RAM package temperature rise suggests a temperature of only 200°C after 1.5 hours.

Ship hold fire tests have been performed primarily to benchmark the thermal analyses and to experimentally determine typical surface heat fluxes and temperatures for RAM packages exposed to fires in ship holds. The fire tests were not related to a specific ship fire event within the databases, but they were considered realistic and conceivable, comparable to fires in engine rooms, galleys, or cargo space. The fire tests monitored thermal conditions within holds and thermal response of simulated RAM packages for fires within the RAM hold and for fires in an adjacent hold. The objectives of the fire test were to:

- Measure shipboard fire environments in holds with simulated RAM transport packages present. The fire scenarios were:
  - Engine room fires within and adjacent to the RAM hold
  - Cargo fires within and adjacent to the RAM hold.
- Use experimental results to benchmark and validate the thermal analysis methodology.
- Provide data useful for the construction of event trees.

The fire tests were conducted in September 1995 and were witnessed by an international contingent of governmental and industry representatives. Four fire tests were conducted: two heptane fires, utilizing two 1.2 MW spray nozzles, representing engine-room fires or fuel-line break fires, and two 2.4 MW wood-crib fires representing combustible cargo fires within or adjacent to the RAM hold. (Additional fire tests, including fully engulfing pool fires, were conducted in November 1995.) Pipe calorimeters simulated the RAM packages. Two pipe calorimeters were employed, one in the hold with the fires and the other in the adjacent hold. Thermocouples were strategically placed within the holds as were flow probes, radiometers, and video equipment.

Data analyses of the fire tests are not yet complete. A significant preliminary result of the tests, however, is that maximum measured heat fluxes on the simulated RAM packages, approximately 2.6 kW/m^2 and 22 kW/m^2 for the heptane and wood-crib fires, respectively, lower than IAEA Safety Series 6 regulatory values (approximately 62 kW/m^2 at 60°C) for

all tests conditions. A preliminary conclusion is that the vast majority (if not all) fires on ships transporting RAM packages are of a severity below which RAM packages are designed to withstand. Comparisons with the analytical thermal model are in progress, which will allow benchmarking of the thermal code. This is essential for evaluating thermal conditions for a wide range of fire accident scenarios identified by database evaluation in order to provide input for the construction of event trees for risk assessments.

DATABASE EVALUATIONS

A primary objective of the *Sea*RAM project is to evaluate the safety of RAM transport by sea in terms of risk to humans and the environment. (This is not, however, a specific objective of the IAEA CRP, which is focused on evaluating severe accidents such as collisions and fires to assess the impact on RAM packages in terms of regulatory requirements.) A broader objective of this task is to demonstrate methodologies for assessing the risk of RAM sea transport. Risk assessment methodologies have been utilized at SNL for risk evaluations for Environmental Assessments and Environmental Impact Statements for the sea transport of U.S.-owned foreign research reactor spent fuels. Components of a risk assessment methodology include:

- Constructing ship accident scenarios.
- Identifying the data required to estimate the probabilities of the events that comprise each accident scenario.
- Calculating accident scenario probabilities.
- Categorizing accident scenarios.
- Determining the mechanical and thermal environments that characterize each accident category.
- Calculating RAM package release fractions for each accident category.
- Performing consequence calculations to estimate radiological consequences of possible ship collision accidents.
- Calculating risks associated with sea transport of RAM.

Considerable information from maritime databases regarding accident scenarios and estimates of damage to RAM packages resulting from either collisions, groundings, and/or fires is required.

Risk is the product of probability of an event (such as a ship collision) times the consequence of that event (such as a release of radioactivity). For radiologically relevant scenarios, consequences of an accident are a function of the source term, which is the product of radioactive inventory times the release fraction, dilution, and exposed population. Accident scenario probabilities are estimated by constructing events trees from which scenario probabilities are derived as the product of all event probabilities on the scenario path (e.g., a ship has a collision, the hull is breached, the RAM package is impacted, a radiological release occurs, etc.). Accident probabilities will be determined primarily from information available mainly from the Lloyds database. Crush forces that may adversely affect RAM packages onboard ships will be calculated from specific finite element analyses and via an estimation technique.

The probability of a ship collision is the ratio of the number of collisions per a geographic region to the number of ship transits. Regions of interest and of significant probabilistic significance are open seas, coastal waterways, and ports (channels, dockside). Radiological consequence calculations will be based upon the region for which an accident

is assumed to have occurred. In port *MACCS* will be employed; along coastal routes *RADTRAN*; and at sea *MARINRAD*.

To date the *Sea*RAM project has focused on accident scenario development. Model event trees are under construction using SNL's event tree code *SANET* to represent ship accident scenarios. The majority of efforts to date have been directed to gathering the data needed to establish the event tree accident scenarios (tree "branches") and for estimating the probabilities of occurrence of the individual events that contribute to accident scenarios. Accident scenarios probabilities will be estimated from the product of the probability of an accident times the severity probability. Accident probability will be obtained by determining site-specific accident frequencies. The severity probability requires data obtained from accident descriptions in databases and models of collision and/or fire damage (finite element or the simpler estimation technique).

The maritime database evaluations entailed a review of available data to determine what type of data was available . All pertinent maritime databases publicly available have been surveyed and evaluated. They include:

- USCG *Marine Safety Management System Casualty Database.*
- USCG Vessel Casualty Case Files.
- Lloyds Casualty Files and Maritime Shipping Records.
- International Maritime Organization Vessel Casualty Database.
- U.S. Army Corps of Engineers Waterborne Commerce Database.
- U.S. National Transportation Safety Board Maritime Casualty Database.
- *Fairplay*© publications and miscellaneous public documents.

These databases were scrutinized to identify ship accidents in terms of numbers of collisions and fires, frequencies of accidents (which requires data regarding nonaccident transits and port calls), accident locations, ship sizes and classes, ship speeds, climatic conditions, and accident severity.

The Lloyds maritime casualty file records were found to be most useful and have become the primary source of data for the *Sea*RAM project (years 1978 - 93 of the Lloyds database are under review). The data records in the Lloyds database provide much the same information as in the USCG *Marine Safety Management System Casualty Database*, but the Lloyds records contain data for more serious collisions and fires. Lloyds data are also very accurate in terms of identifying the location of vessel accidents throughout the world. For the *Sea*RAM project, data on accident severity is important for the construction of event trees, particularly information regarding ship damage resulting from collisions and groundings and fire temperatures and durations. Also required are data on vessel velocities, collisions (data on ship speeds within coastal areas and ports and data regarding specifics of recent severe ship collisions are being collected by ECO), and mass. Such data are difficult to locate from any database, particularly in the detail required for statistical confidence.

To date over 40000 records have been examined, primarily from the Lloyds and USCG databases. The majority of collisions, fires, and collisions with fires have been evaluated (> 2000, 2547, ≈ 50, respectively). Relevant preliminary conclusions from the database evaluations include:

- The vast majority of ship collisions occur near ports and in coastal areas, not surprising since those are locations in which ship traffic is heaviest. Ninety percent of collisions occur within 100 km of the vicinity of ports.
- Specific locations for which numerous ship collisions and accidents occur have been identified. Collisions tend to occur within an extremely small area of the world's waterways.
- If there is a ship accident, there is a 90% probability that it will be in port or in coastal water (locations at which there are highest densities of human populations).
- Limited visibility appears to be a contributing factor in approximately 25% of all collisions.
- There is only approximately a 25% chance that a striking ship will penetrate a hold of the struck ship.
- The risk of fire is proportional to the time spent at sea.
- Fire locations are widely distributed and are not as geographically concentrated as are collisions.

Additional data are being evaluated, particularly port-call data, speeds within ports, and port-to-port transits.

FUTURE ACTIVITIES

Future activities of the *Sea*RAM project will include additional structural and thermal analyses, ship fire tests, and development of ship accident event trees for illustrative risk assessments of the transport of RAM by sea. All analyses shall be available to the international RAM sea transport community and shall be presented at future IAEA CRP meetings. Interested parties are invited to contact the SNL authors for input and discussions related to the scope of the *Sea*RAM project.

REFERENCES

Koski, J.A. et al. *Estimates of Fire Environments in Ship Holds Containing Radioactive Packages*, Proceedings of The 11th International Conference on the Packaging and Transportation of Radioactive Materials (PATRAM '95), Las Vegas, NV (1995).

Minorsky, V.V. *An Analysis of Ship Collisions with Respect to Protection of Nuclear Power Plants*, Journal of Ship Research, Vol. 3, No. 1 (1959).

Porter, V.L. and Ammerman, D.J. *Analysis of a Ship-to-Ship Collision*, Proceedings of The 11th International Conference on the Packaging and Transportation of Radioactive Materials (PATRAM '95), Las Vegas, NV (1995).