SAND97-0865C

SAND--97-0865C

CONF-980507--

SEARAM: A DOE EVALUATION OF MARITIME ACCIDENT RISK ASSESSMENT DATA AND METHODS

J. L. Sprung, D. J. Ammerman, and J. A. Koski

Sandia National Laboratories*, Albuquerque, New Mexico, USA

INTRODUCTION

The SeaRAM Program conducted for the US Department of Energy by Sandia National Laboratories has developed estimates of

- the frequencies of occurrence of ship fires and ship collisions,
- the fraction of all ship fires and ship collisions that might be sufficiently severe to challenge the integrity of a Type B spent fuel transportation cask,
- the magnitude of the radioactive source terms that might be released from a Type B spent fuel transportation cask due to loss of cask integrity, and
- the magnitude of the radiological consequences that might be caused by the radioactive release.

Estimates of the frequencies of ship collisions and ship fires were developed by analysis of 15 years of Lloyd's casualty data and 2 non-contiguous years of Lloyd's port call data. Estimates of the fraction of all ship collisions that might be severe enough to challenge the integrity of a Type B RAM transport cask carried on the struck ship were developed (a) by analyzing the depth of penetration into the hull of the struck ship using Minorsky's correlation of collision damage with collision energy and (b) by performing finite element calculations that showed that crush forces were most likely to be dissipated by collapse of ship rather than cask structures. Estimates of the fraction of all fires that might be severe enough to both spread to the RAM hold and there burn hot enough and long enough to damage a Type B cask were developed by performing shipboard fire tests, by modeling those tests, and by constructing simple models of the spread of fires through a ship bulkhead and through a series of ship holds. Estimates of maritime accident source terms were developed by modeling aerosol and

---

* Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin company, for the United States Department of Energy under contract DE-AC04-94AL85000.

DISCLAIMER

vapor transport through a Type B RAM transport cask. Finally, estimates of maritime accident radiological consequences were developed by performing illustrative consequence calculations.

MARITIME ACCIDENT STATISTICS

Analysis of 15 years of Lloyds' casualty data and 2 non-contiguous years of port call data allowed ship collision frequencies to be developed per port call for high, medium, and low traffic ports, and per nautical mile sailed for 19 congested ocean regions, for all coastal waters not in these congested regions, and for the open ocean (Bespalko et al., 1997). Tables 1 and 2 presents selected results from this analysis. The analysis also developed fire frequencies per nautical mile sailed and per port call (a sailing into and then out of a port).

Table 1. Distances Sailed, Ship Collisions, and Collision Frequency for 8 of 21 Ocean Regions

Region	Distance Sailed (nautical miles)		Collisions	Collision Frequency
	1988	1993	1979-1993	(per nautical mile)
East Coast of Japan	4,169,250	4,497,723	120	$1.9x10^{-6}$
North Sea	48,945,873	46,676,760	134	$1.9x10^{-7}$
English Channel	21,879,012	20,479,594	33	$1.0x10^{-7}$
Agean Sea, Bosphorus	6,979,278	7,521,944	59	$5.4x10^{-7}$
Approaches to Singapore	30,056,459	43,928,308	41	$7.4x10^{-8}$
Suez Canal, Red Sea	30,562,346	30,397,942	17	$3.7x10^{-8}$
Coastal Waters	80,737,497	97,489,242	252	$1.9x10^{-7}$
Open Ocean	655,875,934	709,598,653	70	$6.8x10^{-9}$

Table 2. Port Calls (1988) and Port Collision Frequencies (per port call)

Port	Port Collisions (1979-1993)	Port Calls (1988)	Collision Frequency (per port call)
	High Traffic Ports		
Singapore	18	27129	$4.4x10^{-5}$
Rotterdam	11	26153	$2.8x10^{-5}$
Panama Canal	2	11058	$1.2x10^{-5}$
Port Said	13	8936	$9.7x10^{-5}$
All High Traffic	93	199609	$3.1x10^{-5}$
	Medium Traffic Ports		
New York	12	5144	$1.6x10^{-4}$
Marseilles	2	4238	$3.2x10^{-5}$
All Medium Traffic	174	254121	$4.6x10^{-5}$
	Low Traffic Ports		
All Low Traffic	422	656989	$4.3x10^{-5}$

The analysis showed that ship collision frequencies increase as the traffic density in the ocean region being sailed increases and range from about 7×10^{-9} per nautical mile sailed in the open ocean to 2×10^{-6} per nautical mile sailed in heavily congested ocean regions. The review also showed that the frequency of port collisions is relatively independent of port traffic densities being about 4×10^{-5} collisions per port call in low, medium, and high traffic ports, that the frequency of fires per port call is about 5×10^{-5}, and suggested that the frequency of ship fires depends only on distance sailed being about 1×10^{-7} per nautical mile sailed independent of where the sailing takes place.

The data in Tables 1 and 2 can be used to estimate the chance that a ship collision will occur if a specific voyage is sailed. For example, Table 3 presents the chance of a collision for a voyage from Charleston, SC, to Cherbourg, France, and also for each leg of that voyage.

Table 3. Collision Probabilities for a Voyage from Charleston, SC, to Cherbourg, France

Route Segment	**Depart Charleston**	**US Coastal Waters**	**Atlantic Ocean**	**English Channel**	**Enter Cherbourg**	**Entire Voyage**
Nautical Miles		**50**	**3375**	**197**		**3622**
Probability	**2.2×10^{-5}**	**9.5×10^{-6}**	**2.3×10^{-5}**	**2.0×10^{-5}**	**2.2×10^{-5}**	**9.5×10^{-5}**

Table 3 shows that the probability of a ship collision during a trans-Atlantic voyage is about 10^{-5} for each of the five legs sailed and about 10^{-4} for the entire voyage. In addition, because collisions are so unlikely in the open ocean and because decreased sailing speeds in ports mean port collisions are unlikely to challenge the integrity of a spent fuel cask, the risk of collisions that might fail a spent fuel cask occurs primarily while traversing congested regions or coastal waters.

SHIP COLLISION SEVERITIES

Minorsky's linear correlation of ship collision damage volumes (R_T, m^3) with collision energies (ΔKE, MJ) was revalidated and then modified to allow hull penetration depths to be estimated for single and double hull ships (Reardon and Sprung, 1996). With the correlation intercept, which represents the energy required to penetrate the shell of a single hull ship, constrained to a value estimated using a theoretical model of a wedge cutting a plate, the slope of the revalidated correlation was found to be almost identical to Minorsky's orginal slope (Minorsky, 1959). Thus, the slope of the revalidated correlation, $\Delta KE = (47.1 \pm 8.8) R_T = 28.4$, has a value of 47.1 MJ/m^3 while the value of the slope of Minorsky's original correlation is 47.2 MJ/m^3.

Illustrative application of the revalidated, modified correlation to break-bulk freighters showed that shell penetration is less likely for smaller freighters because more collision energy is expended pushing a small struck ship sideways through the water and less damaging ship structures than is the case for larger ships which slide sideways less easily. For small freighters, shell penetration occurs for about one collision in five while for large freighters it occurs in half of all collisions (Reardon and Sprung, 1996). However, for small ships, deep hull penetration and therefore application of crush forces to a RAM cask stowed at a hold midline is more likely simply because small ships are not as wide as large ships.

In order to determine collision penetration distances for ships with hull structures substantially different than those used by Minorsky to develop his correlation, a mechanistic treatment of the energy absorbed during shell penetration was developed, which reflects the structural properties of all of the important structures (hull, web frames, longitudinals) in the shell of the struck ship (Ammerman and Daidola, 1998). By combining this mechanistic shell penetration energy calculation with Minorsky's hull penetration energy calculation, the total energy absorbed during a ship collision can be estimated for ships with any type of side structure, including double hulls.

Minorsky's correlation does not predict how crush forces, caused by penetration into the hull of the struck ship by the bow of the striking ship, will be relieved. Because striking ship masses can be large, collision energies can also be very large. This leads to a concern about the safety of RAM transport by sea. Specifically, whether large collision kinetic energies assure cask damage when hull penetration is deep enough to apply crush forces to the cask. Even though ship velocities are relatively small (usually less than 13.4 m/s), because striking ship masses can be very large, ship collisions may involve kinetic energies much larger than those generated by the regulatory impact test. For this reason, the possibility of damaging a cask during collisions that lead to deep hull penetration was investigated. Initially, a set of collisions between two small charter freighters was modeled using finite element methods (Porter and Ammerman, 1995; Ammerman and Ludwigsen, 1998). In these calculations the mass of the striking ship ranged from 1.7 to 17 ktons and impact velocities up to 30 knots were considered. The coarseness of the finite element mesh required for these analyses made it impossible to accurately determine the loads imparted to the cask, but an upper bound of 130 MN for the load was calculated.

Penetration by a striking ship to the location in the hold of the RAM transport ship where the RAM cask is stowed may not cause the cask to be damaged by the collision. At first contact with the RAM cask, there will be an initial impact load. Since the impact velocity that produces this load is nearly always less than the impact velocity from the regulatory test, and because the bow of the striking ship is always less rigid than the unyielding target used in the regulatory test, the forces imparted to the cask from the impact are less than the forces imparted during the regulatory drop test. After the initial impact causes the cask tie downs to break (tie-downs are designed to fail at relatively low loads), the cask will be pushed across the deck until it meets an object massive enough and stiff enough to stop it from sliding. For shipments where there is no other cargo in the hold with the RAM cask, sliding of the package across the deck will continue until the package is pushed up against the struck ship's shell on the side of the ship away from the collision. Finite element analyses initiated at that point in time indicate that the magnitude of the crushing force imparted to the cask is limited by the strength and stiffness of the shell structure of the struck ship. But the shell structures of typical single hull break-bulk freighters are not strong enough to cause the cask to be subjected to crush forces larger than the inertial crush force seen during the regulatory drop test. Smaller ships have even weaker shell structures, and therefore lower crush forces will be imparted to the RAM cask. Consequently, as Figure 1 shows, crush forces are likely to be relieved by collapse of the shell on the far side of the struck ship, which may allow the RAM cask to spill into the sea.

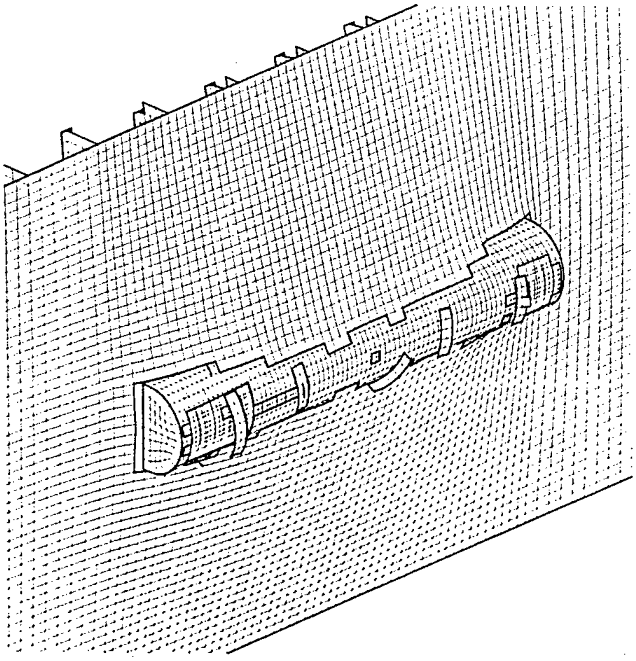

Figure 1. Penetration of the Far Shell of the Struck Ship by the RAM Cask

If the hold containing the RAM package also contains other cargo, it is possible for the other cargo to be pushed up against (compressed about) the RAM cask thereby subjecting the RAM cask to crushing forces before the cask contacts the far shell of the struck ship. Finite element analyses have been performed to determine the maximum crush force that can be imparted to the cask during this scenario (Ammerman and Radloff, 1998).

SHIP FIRE SEVERITIES

The size and duration that fires must have to support hold-to-hold fire spread and to damage a RAM cask were investigated by performing shipboard fire tests (Koski, Arviso, et al., 1998; Koski, Bobbe, et al., 1997; Koski, Hohnstreiter, et al., 1998), by modeling those tests (Cole et al., 1998; Koski, Cole, et al., 1997; Wix et al., 1998), and by constructing simple models of the spread of fires through a ship bulkhead and through a series of ship holds (Sprung et al., 1998). A series of eight highly instrumented fire tests simulating both cargo fires and engine room or galley fires were conducted aboard a break-bulk freighter, the *Mayo Lykes*, at the US Coast Guard's fire test facility at Mobile Bay. Cargo fires were simulated by burning a wood crib. Heptane spray and pool fires were used to simulate engine room and galley fires. During each test, heat loads on instrumented cylindrical pipe calorimeters (one in or next to the fire and one on the other side of a bulkhead close to the fire) were measured. These measurements indicate that the test fires generated heat fluxes no larger than those characteristic of the regulatory 800 C, 30 min fire used to certify casks.

Three of the fire tests, the wood crib fire and two heptane fires, were simulated using the CFX computational fluid dynamics (CFD) code. As Figure 2 illustrates, in general, good agreement between experimental results and the computer simulations was found.

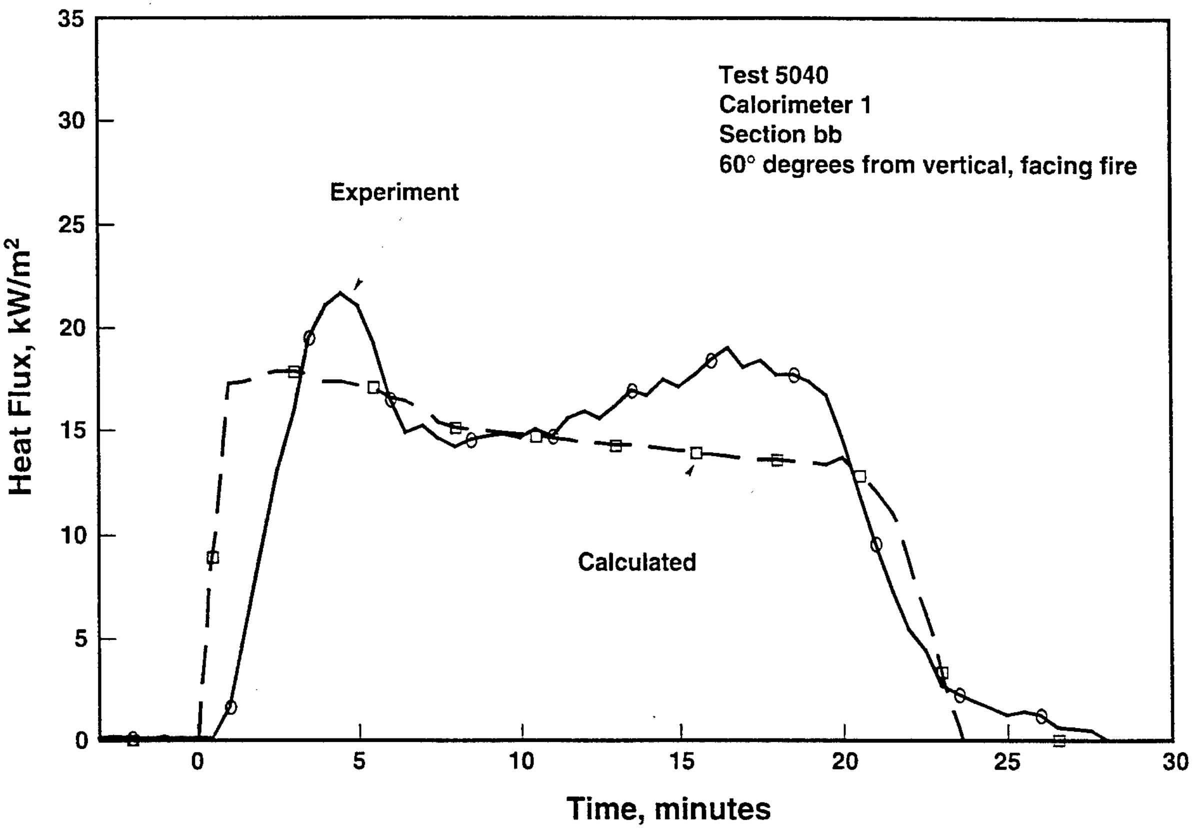

Figure 2. Comparison of calculated vs. experimental heat fluxes to a pipe calorimeter adjacent to a wood crib fire in a ship hold

The shipboard fire tests demonstrated that, in the vicinity of a hot bulkhead, heat transfer is dominated by thermal-radiation with only minor contributions due to convection and conduction. This result suggests that a simple bulkhead fire spread model needs to treat only thermal radiation between hot bulkheads and adjacent cargoes. An initial implementation of such a bulkhead fire spread computer code is complete, and testing is in progress.

More recently, tests with ISO standard shipping containers were conducted to determine the fire environment inside such a container during a ship fire. Analysis of these data have been initiated.

SOURCE TERMS

Transport of aerosols and fission product vapors, released to the interior of a Type B TN-125 cask, from the cask interior to the environment was modeled (Sprung et al., 1998) using the MELCOR code. The calculations indicate that cask-to-environment release fractions increase as cask leak areas increase. This is to be expected since, after pressurization due to the failure of fuel rods, cask depressurization times decrease as cask leak areas increase. Thus, a large leak area means a short depressurization time, little time for fission product deposition to cask interior surfaces, and consequently large cask-to-environment release fractions. Figure 3 presents the results of this study and shows that the seal failure areas expected for credible impact, crush, or fire accidents will lead to cask-to-environment release fractions of order 10^{-2}.

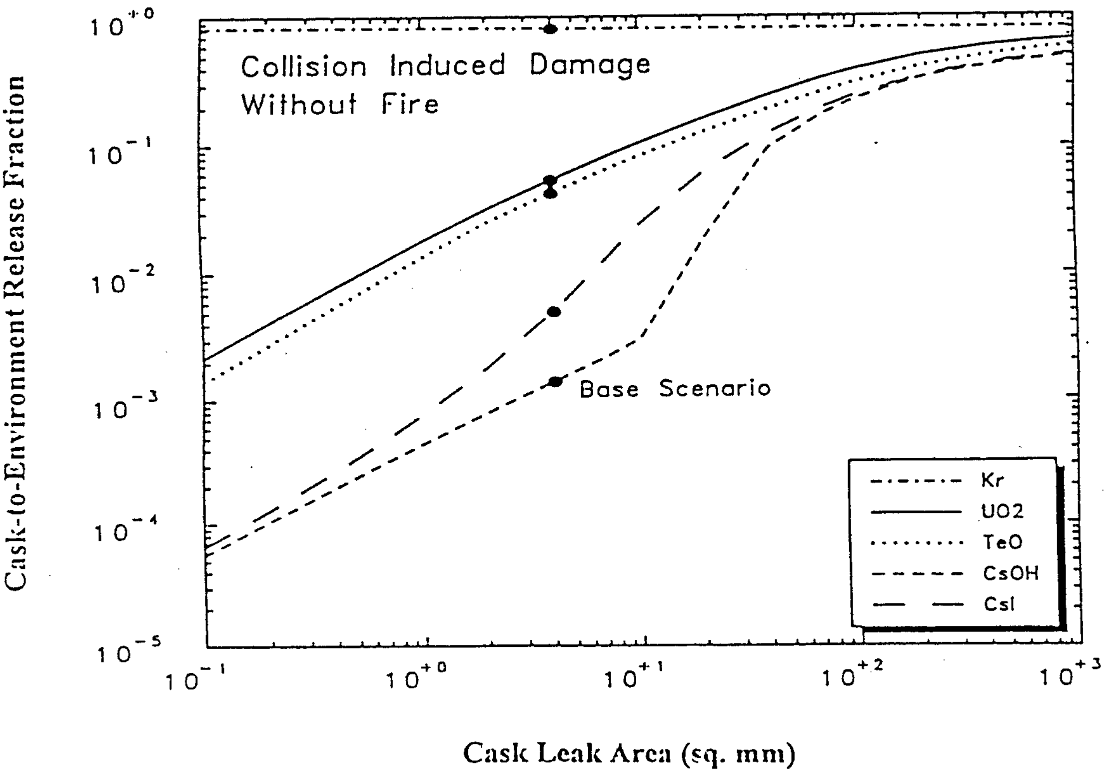

Figure 3. Dependence of Cask-to-Environment Release Fractions on Cask Failure Area

Using data from Figure 3 and results from this and prior studies (Wilmot, 1984; Sandoval et al., 1991; Sprung et al., 1996), source terms can be constructed for two bounding ship accident scenarios, a ship collision that leads to a small seal failure, and a much more severe collision that leads to a double failure of the cask and also initiates a fire that spreads to the hold where the spent fuel cask is stored, and there engulfs the cask and burns hot enough and long enough to significantly increase the release of radioactive material from the spent fuel to the cask interior. Table 4 presents the release fractions estimated for these two bounding ship accident scenarios. Using these release fractions and the inventory (Ii) for radionuclide i in a TN-125 cask after cooling for three years, source terms were calculated using the following equation for the two bounding ship accident scenarios: $M_i = I_iF_i = I_iF_{mci}F_{cei}$, where F_{mci} is the spent fuel-to-cask interior release fraction and F_{cei} is the cask-to-environment release fraction.

Table 4. Release Fractions for Two Bounding Ship Accident Scenarios

Chemical Element Class		Scenario					
Name	Symbol	Collision-Only (1 hole)			Collision-plus-Fire (2 holes)		
		F_{mci}	F_{cei}	F_i	F_{mci}	F_{cei}	F_i
Noble Gases	Kr	0.2	0.8	0.16	0.2	1.0	0.2
CRUD	Co	0.3	1×10^{-2}	3×10^{-3}	0.3	1.0	0.3
Cesium	Cs	2×10^{-6}	1×10^{-2}	2×10^{-8}	1.6×10^{-3}	1.0	1.6×10^{-3}
Ruthenium	Ru	2×10^{-6}	1×10^{-2}	2×10^{-8}	1.6×10^{-6}	1.0	1.6×10^{-6}
Particulates	Part	2×10^{-6}	1×10^{-2}	2×10^{-8}	2×10^{-6}	1.0	2×10^{-6}

ACCIDENT CONSEQUENCES

In agreement with past maritime accident EAs and EISs, illustrative consequence calculations show (Sprung et al., 1998) that the small source terms likely to be released as a result of maritime accidents lead to expected (mean) values for population dose and cancer fatalities that are significantly smaller than normal background doses and the normal rate of occurrence of cancer fatalities. For example, Table 5 presents consequence estimates for the two bounding ship accident scenarios just described assuming that these accidents occur in the ports of Newark and Charleston.

Table 5. MACCS Predictions of 50 Year Population Dose and Cancer Fatalities for Port Accidents

Site	Source Term	Probability (per port call)	Population Dose (Sv)	Cancer Fatalities
Charleston	**Collision-Only (1 hole)**	**1.1×10^{-7}**	**63**	**3**
	Collision-plus-Fire (2 holes)	**1.3×10^{-12}**	**699**	**30**
Newark	**Collision-Only (1 hole)**	**1.0×10^{-6}**	**857**	**37**
	Collision-plus-Fire (2 holes)	**4.0×10^{-12}**	**2.4×10^{4}**	**1.0×10^{3}**
	50 Year Background Dose		**$> 1.8\times10^{6}$**	
	50 Year Cancer Fatalities			**$> 1\times10^{5}$**
	Exposed Population		**$\sim 1\times10^{6}$**	

Table 5 shows that the normal background radiation doses and normal rates of cancer deaths among the population exposed to radiation as a result of these hypothetical ship accidents exceed the MACCS predictions of mean population dose and cancer fatalities among the same population for these two bounding port accident scenarios by factors of about 10^2 to 10^5.

CONCLUSIONS

Ship collisions depend on traffic density, ship fires don't.

Ship collisions are unlikely to damage a spent fuel cask; any crush forces applied to the cask will be relieved by collapse of ship structures, not cask structures.

Fire start in a RAM hold is unlikely; so is fire spread to RAM hold; and should a fire spread to the RAM hold, it is very unlikely to burn there hot enough and long enough to contribute significantly to the release of radioactivity to the environment.

Most radioactive species released to cask interior will deposit on interior cask surfaces; so cask retention fractions will almost always be large and cask-to-environment release fractions will almost always be small.

Consequently, the risks of maritime transport of spent fuel are most likely very small.

REFERENCES

D. J. Ammerman and J. C. Daidola, *An Improved Model for Determining Penetration Distances during Ship-to-Ship Collisions*, Proceed. 12th Intl. Conf. on the Packaging and Transportation of Radioactive Materials (PATRAM '98), May 10-15, 1998, Paris, France.

D. J. Ammerman and J. S. Ludwigsen, *Crush Loadings to Radioactive Material Transportation Packages during Ship Collisions*, International Journal of Radioactive Materials Transport, Nuclear Technology Publishing, Kent, England, 1998.

D. J. Ammerman and H. D. Radloff, *The Effect of Cargo on the Crush Loading to Radioactive Material Transportation Packages in Ship Collisions*, Proceed. 12th Intl. Conf. on the Packaging and Transportation of Radioactive Materials (PATRAM '98), May 10-15, 1998, Paris, France.

S. J. Bespalko et al., *Variation of Ship Fire and Ship Collision Frequencies with Ocean Location,* Intl. J. Radioactive Materials Transport, 1998 (accepted for publication).

J. K. Cole et al., *Calculation of the Effects of a Cargo Fire in a Hold of a Ship*, Proceed. 12th Intl. Conf. on the Packaging and Transportation of Radioactive Materials (PATRAM '98), May 10-15, 1998, Paris, France.

J. A. Koski, M. Arviso, et al., *Experimental Ship Fire Measurements with Simulated Radioactive Cargo,* Proceed. 12th Intl. Conf. on the Packaging and Transportation of Radioactive Materials (PATRAM '98), May 10-15, 1998, Paris, France.

J. A. Koski, J. G. Bobbe, et al., *Experimental Determination of the Shipboard Fire Environment for Simulated Radioactive Material Packages*, SAND97-0506, Sandia National Laboratories, Albuquerque, NM, March 1997.

J. A. Koski, J. K. Cole, et al., *Calculation of Shipboard Fire Conditions for Radioactive Materials Packages with the Methods of Computational Fluid Dynamics*, SAND 97-2182, Sandia National Laboratories, Albuquerque, NM, September, 1997.

J. A. Koski, G. F. Hohnstreiter, et al., *Experimental Measurement of Shipboard Fire Environments for Simulated Radioactive Material Packages on a Break-Bulk Freighter*, Intl. J. Radioactive Materials Transport, 1998 (accepted for publication).

V. L. Porter and D. J. Ammerman, *Analysis of a Ship-to-Ship Collision*, Proceedings of PATRAM 95, Las Vegas, NV, 1995.

P. C. Reardon and J. L. Sprung, *Validation of Minorsky's Ship Collision Model and Use of the Model to Estimate the Probability of Damaging a Radioactive Material Transportation Cask during a Ship Collision*, Proceed. SNAME/SNAJ Intl. Conf. on Designs and Methodologies for Collision and Grounding Protection of Ships, San Francisco, CA, August 22-23, 1996, p. 5-1, 1996.

R. P. Sandoval et al., *Estimate of CRUD Contribution to Shipping Cask Containment Requirements*, SAND88-1358, Sandia National Laboratories, Albuquerque, New Mexico, January 1991.

J. L. Sprung et al., *Radiological Consequences of Ship collision that Might Occur in U.S. Ports During the Shipment of Foreign Research Reactor Spent Nuclear Fuel to the U.S. in Break-Bulk Freighters*," SAND96-0400, Sandia National Laboratories, Albuquerque, New Mexico, August 1996.

J. L. Sprung et al., *Data and Methods for the Assessment of the Risks Associated with the Maritime Transport of Radioactive Materials: Results of SeaRAM Program Studies*," Sandia National Laboratories, Albuquerque, New Mexico, 1998 (to be published).

E. L. Wilmot, *Transportation Accident Scenarios for Commercial Spent Fuel*, SAND80-2124, Sandia National Laboratories, Albuquerque, New Mexico, July 1984.

S. D. Wix et al., *Modeling Fires in Adjacent Ship Compartments with Computational Fluid Dynamics*, Proceed. 12th Intl. Conf. on the Packaging and Transportation of Radioactive Materials (PATRAM '98), May 10-15, 1998, Paris, France.

M98004464

Report Number (14) SAND--97-0865C
CONF-980507--

Publ. Date (11) 199803
Sponsor Code (18) DOE/EM, XF
UC Category (19) UC-2000, DOE/ER

DOE