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FINAL ENVIRONMENTAL IMPACT STATEMENT

on a

Proposed Nuclear Weapons Nonproliferation Policy Concerning Foreign Research Reactor Spent Nuclear Fuel

Appendix C
Marine Transport and Associated Environmental Impacts

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Appendix C
Marine Transport and Associated Environmental Impacts

C.1 Introduction

Shipment of any material via ocean transport entails risks to both the ship's crew and the environment. The risks result directly from transportation-related accidents and, in the case of radioactive or other hazardous materials, also include exposure to the effects of the material itself.

This appendix provides a description of the approach used to assess the risks associated with the transport of foreign research reactor spent nuclear fuel from a foreign port to a U.S. port(s) of entry. This appendix also includes a discussion of the shipping configuration of the foreign research reactor spent nuclear fuel, the possible types of vessels that could be used to make the shipments, the risk assessment methodology (addressing both incident-free and accident risks), and the results of the analyses. Analysis of activities in the port(s) is described in Appendix D.

The incident-free and accident risk assessment results are presented in terms of the per shipment risk and total risks associated with the basic implementation of Management Alternative 1 and other implementation alternatives. In addition, annual risks from incident-free transport are developed.

C.2 Scope

This appendix addresses the modes of marine transportation and the nonradiological and radiological risks associated with marine transportation.

Transportation Modes: Marine transport of foreign research reactor spent nuclear fuel could occur via a combination of four types of vessels: container ships, roll-on/roll-off vessels, general cargo (breakbulk) vessels, or purpose-built vessels. In the incident-free analysis, it was assumed that all shipments would be made on breakbulk vessels. Breakbulk cargo vessel speeds are typical of the four types of cargo vessels considered, which means that the breakbulk vessel time enroute, (i.e., from port of origin to port of entry) is representative of the four vessel types. The ship speed selected for the analysis, 15 knots or 17.3 mph, is at the lower end of the range of speeds for commercial cargo vessels. This, in turn, maximizes the radiation dose received by the ship's crew, which bounds the incident-free risk. No vessel type assumption is necessary for the analysis of the impacts associated with the accident conditions, since these impacts are essentially independent of the type of ship.

Nonradiological Impacts: These risks were assessed as resulting in a negligible impact on the health of the public and workers. The limited number of shipments (less than a thousand individual spent nuclear fuel containers) would not result in a significant change in the number of ocean crossings by transport vessels. Regardless of the ship selection – general cargo, container, roll-on/roll-off, or purpose-built vessel – a negligible increase in the exposure of the public to exhaust emissions or transportation-related accidents would occur.

More than 56,000 port calls of ships engaged in foreign trade are made at U.S. ports each year (DOC, 1994). The basic implementation of Management Alternative 1 would result in the addition of less than 50 round trip voyages by vessel per year; the actual number of voyages that might occur would be dependent on the manner in which the policy, if adopted, was implemented. On average, less than

60 foreign research reactor spent nuclear fuel casks would be required to be shipped each year to fulfill the basic implementation shipping needs. These shipments could be made on regularly scheduled commercial cargo vessels. Alternatively, these shipments could be made in a chartered vessel, where the transportation casks would be the only cargo onboard the vessel.

If commercial cargo vessels were used, the shipment of foreign research reactor spent nuclear fuel transportation casks would not result in additional voyages specifically for the transport of the foreign research reactor spent nuclear fuel. The approximately 60 transportation casks per year would be part of the general cargo carried by the ships. As discussed in Section C.3.1.2, container vessels typically have a capacity in the range of 800 to 1,000 containers, while some carry many more. General cargo vessels tend to be somewhat smaller, but still have capacities equivalent to several hundred containers. Each foreign research reactor spent nuclear fuel transportation cask is assumed to be shipped within a container. Therefore, for the tens of thousands of vessels received at U.S. ports each year, each carrying hundreds of containers, or their equivalent, the basic implementation alternative would add approximately 60 containers per year. This is equivalent to much less than the capacity of one cargo vessel.

If chartered vessels were to be used for the shipment of the foreign research reactor spent nuclear fuel, the number of shipments required per year would depend on the number of transportation casks loaded into each vessel. Many factors would affect this number, such as the size of the ship, the availability of the ship, originating point for the shipments, and the readiness of foreign research reactor operators to ship the

All radiologically-related impacts on humans are calculated in terms of committed dose and associated health effects in the exposed populations. The radiation dose calculated is the total effective dose equivalent (EDE), which is the sum of the EDE from the external radiation exposure and the 50-year committed EDE from internal radiation exposure. The EDE is the sum of the tissue and organ-weighted dose equivalents for all irradiated tissues and organs. The committed EDE considers the initial exposure and the effects of radioactive decay and elimination of the radionuclide through ordinary metabolic processes over the 50-year period. Radiation doses are presented in units of person-rem for collective population and rem or mrem (equal to 0.001 rem) for individuals. The impacts are further expressed as

Lifting, stowage, and transfer of containers is described in Appendix D.

Casks are mounted within the container using specially designed supports in the container floor. These supports mate with the tiedown structure of the cask to secure it to the container.

Figure C-1 shows a spent nuclear fuel cask being loaded into an International Standards Organization container. Containers may be either completely enclosed using a removable top, as shown in Figure C-1, or have open sides and top. Usually, an enclosed container is used with a cask that is certified for transport with a "personnel barrier." As its name implies, the personnel barrier is a structure that surrounds the cask in transport, to preclude inadvertent personnel contact with the cask surface. The barrier is a required feature if the cask surface can exceed about 52°C (125°F) in non-exclusive-use transport. The cask may become warm in transport due to the decay heat of the spent nuclear fuel within the cask. Usually, the barrier is constructed of expanded metal screen or other lightweight material. Casks that do not require a barrier may be mounted in open containers. In either case, the floor of the container is specially designed to support the weight of the cask, and to incorporate the tiedown fixtures of the cask. The tiedowns may be unique, as those shown in Figure C-1, or they may be bolts that secure the skid, pallet, or cradle to the floor of the container.

Since the introduction of International Standards Organization containers, shipment of spent nuclear fuel in casks mounted in containers has become the preferred configuration. Use of containers provides an improvement in the ease of securing the cask to the vessel. It also permits the use of standard container handling and transport equipment that is used at many ports.

Roll-On/Roll-Off Cask Configuration: Casks can be transported by vessel on a wheeled trailer that allows the cask to be rolled onto the vessel, and at the destination, rolled off. The cask (on its own unique, dedicated trailer) is moved on and off the vessel using a standard truck tractor or wheeled tug across a ramp extending between the vessel and the dock.

A few shipments have been made to the United States from Europe using casks mounted on their own dedicated trailers. However, current Federal regulations (49 CFR 176.76(b)) restrict trailered hazardous cargo (such as spent nuclear fuel) to transport on a trailership (roll-on/roll-off), trainship, ferry vessel, or car float. This regulation would preclude shipment of trailered casks containing spent nuclear fuel on general cargo, or other vessels. It has been assumed that the foreign research reactor spent nuclear fuel will be shipped as containerized cargo, not mounted on trailers. Use of containers will not limit the type of vessel that can be selected for transport.

Free-Standing Cask Configurations: Casks could be transported as a free-standing package. In this configuration, the cask would be mounted on a skid, pallet, or cradle to facilitate both lifting and tiedown. A pallet is usually required because casks have unique tiedowns and lift points that may not be readily accommodated by more common rigging and stowage bindings. The pallet is usually designed to provide a means of attaching the cask to the transport trailer or railcar. The cask is usually either attached to the pallet by bolting at the cask tiedown fixtures, or by the use of specially designed turn buckle cables.

Free-standing casks have previously been transported on general cargo vessels that carry cargo as "breakbulk." Breakbulk cargo is any cargo that is handled individually and may be containerized or otherwise unitized.

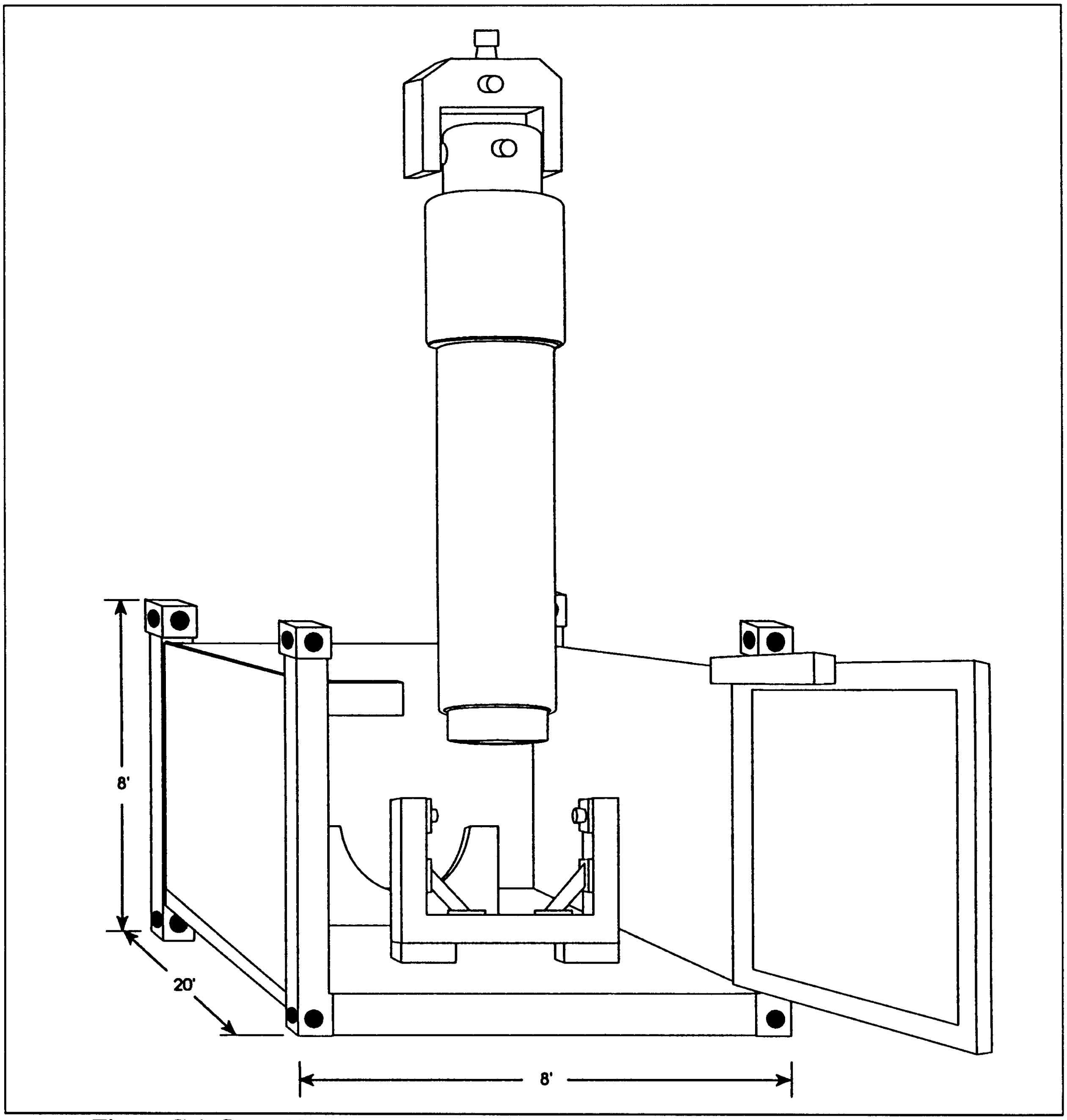

Figure C-1 Spent Nuclear Fuel Cask Being Loaded into an International Standards Organization Container

Recently, several purpose-built ships have been placed in service that transport casks in a free-standing (non-containerized) configuration. Purpose-built vessels are described in Section C.3.1.2. These dedicated vessels incorporate holds containing structural tiedowns designed to mate with the cask, and which provide additional shielding from radiation. The purpose-built vessels are operated by crews both trained in radiological safety and with a radiological control program in place.

C.3.1.2 Vessel Types, Cask Handling Requirements, and Methods of Service

This section describes the four principal types of vessels that could be used for the transport of casks. The vessel types include container, roll-on/roll-off, general cargo (also called breakbulk), and purpose-built vessels.

Each of these types of vessel have somewhat different handling requirements for the cargo they carry. Cask handling and equipment requirements are also described.

Individual shipments could be made by scheduled commercial vessel, or by charter vessel. Vessels on scheduled routes generally call on the more important ports. Scheduled vessels also typically call at intermediate ports between a given origin and destination.

Because of the general public aversion to nuclear materials, there has been a marked decrease in the number of steamship lines that will accept spent nuclear fuel cargoes in scheduled service. Also, many foreign ports and some U.S. ports do not currently permit docking or handling of spent nuclear fuel shipments, either en route or as a destination. This has led to an increased reliance on spent nuclear fuel ocean transport by chartered vessel. Vessels for charter are available from any number of steamship lines. Generally, smaller general cargo (breakbulk) vessels are used for charter shipments.

Container Vessels: Container vessels are typically large ships that are specifically intended for the transport of International Standards Organization containers (Figure C-2). Modern container ships can transport up to about 5,000 containers, although a more typical capacity is in the range of 800 to 1,000. A principal advantage of container vessels, because of standardization of containers, is that the vessel can be rapidly loaded or off loaded at those ports equipped with container gantry cranes. Containers can be removed from (or placed on) the vessel at an average rate of about 45 containers per hour. At well equipped container vessel ports, two cranes are used to move containers. Smaller container vessels may be equipped with an onboard crane allowing calls at ports that are less well equipped.

Because of cost, the only container ships generally used to transport spent nuclear fuel are in scheduled service. Smaller general cargo vessels are more suitable to chartered service, and these vessels accommodate containers.

Roll-On/Roll-Off Vessels: Roll-on/roll-off vessels are vehicle carriers (Figure C-3) used for the ocean transport of cars and trucks. The vessels are loaded and unloaded using a ramp between the vessel and dock. Ordinarily, the vessel carries its own ramp, which is deployed by an on-board crane, hydraulic cylinders, or chain drives. The ramp may extend from the stern of the vessel or from a hatch in the side hull of the vessel. At docks intended for roll-on/roll-off service, additional ramps may be deployed from the dock to expedite loading or unloading. For ocean transport, the trailers are lashed to the deck(s) of the vessel using ratchet or turnbuckle type bindings to fixed securement points in the deck. It is likely that a roll-on/roll-off capable vessel could be leased, should a roll-on/roll-off capability be required.

General Cargo (Breakbulk) Vessels: General cargo vessels (Figure C-4) are small-to-medium sized ships (compared to container vessels) that typically call on less well developed or equipped ports. They have on-board jib or boom type cranes that can be used to load or unload the ship. As the name implies, these vessels are intended to accommodate a wide variety of cargoes. Since the advent of the widespread use of containers, most of these ships are equipped with International Standards Organization lock fixtures to secure containers to the ship deck(s) and to each other. If necessary, containers can be lifted on and off these ships by using four-legged slings between the corners of the container and the hook of the crane. Because of the versatility of these vessels, casks configured for containerized or free-standing transport can be accommodated.

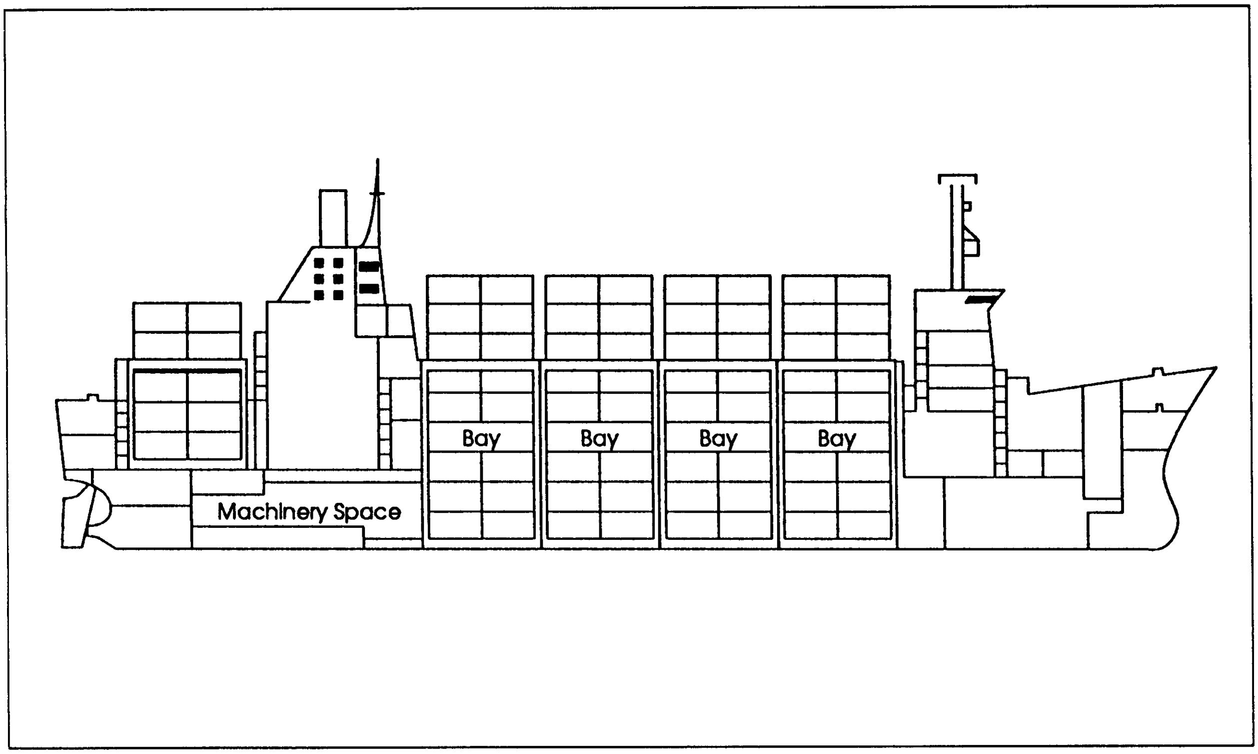

Figure C-2 Container Vessel

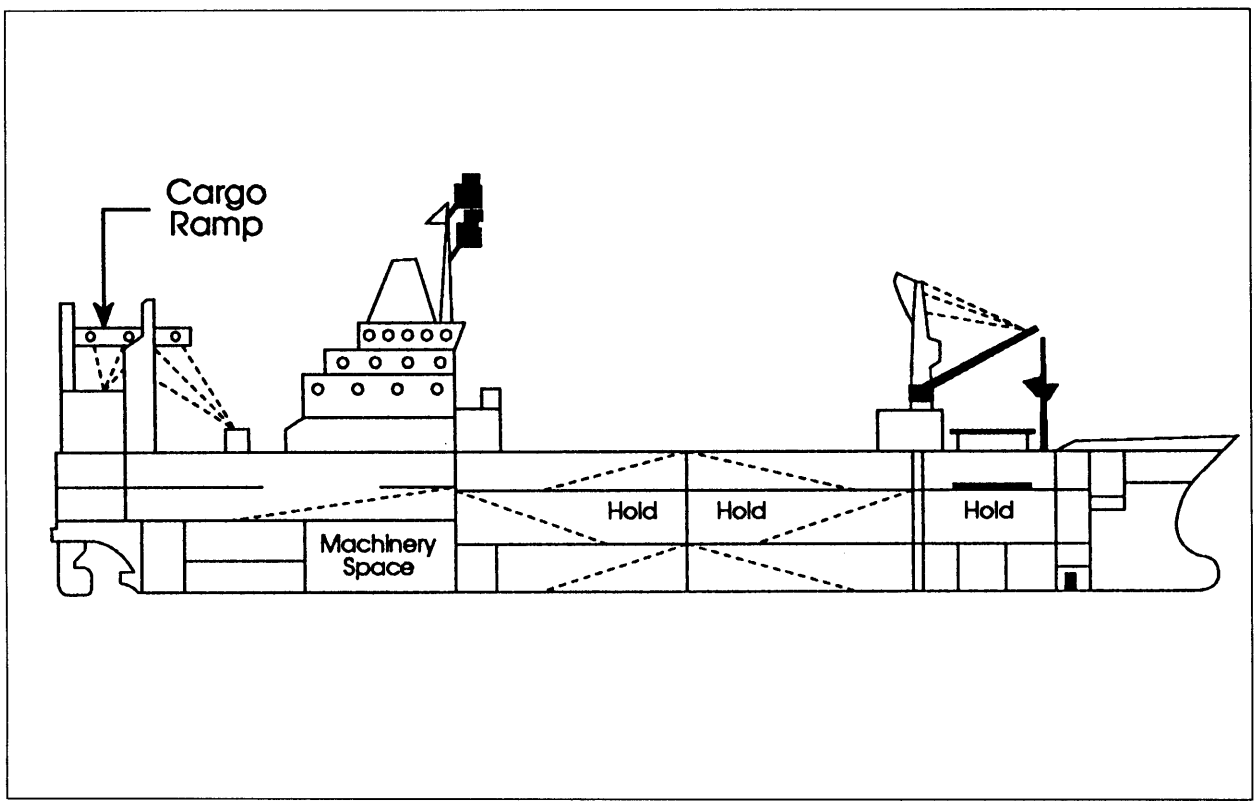

Figure C-3 Roll-on/Roll-off Vessel

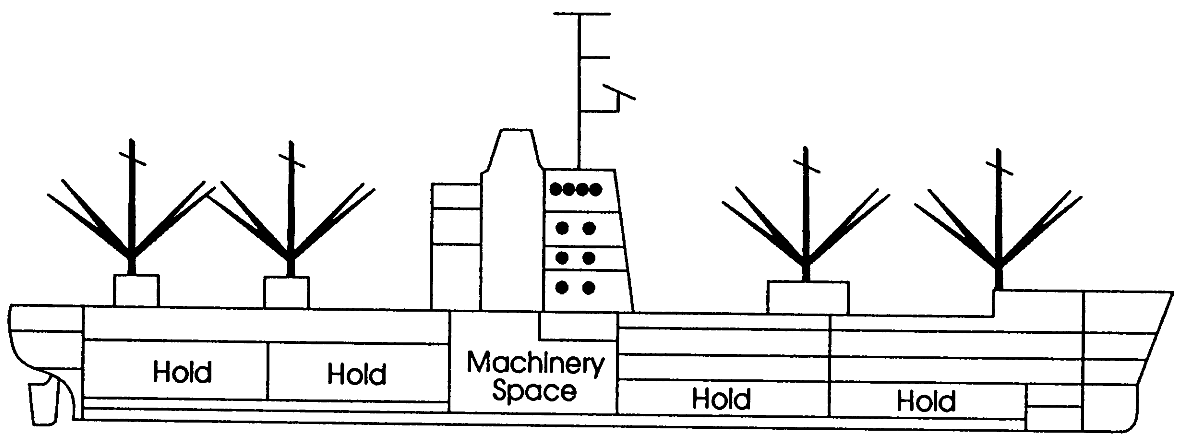

Figure C-4 General Cargo Vessel

Free-standing casks would be palletized for transport on a general cargo vessel. For stowage, the pallet would be lashed to the vessel hold or deck using conventional chains or binders. Pallets do not have standard tiedown fixtures, so there is wide variability in the specific tiedown requirements for each pallet design. Also, there is variability in provisions for lifting the pallet. The standard tiedown configuration of containers eliminates much of this variability. Consequently, containerized cask handling has resulted in an increase in the use of this configuration for the shipment of casks, and there has been a significant reduction in the number of casks shipped in the free-standing configuration.

General cargo ships have been routinely available for chartered shipment of containerized casks containing spent nuclear fuel from any number of U.S. or foreign ship lines. Because there are a comparatively small number of casks that are available for use, chartered small general cargo vessels are an option to scheduled service.

Purpose-Built Vessels: Purpose-built vessels, as used here, are those vessels specifically designed to transport spent nuclear fuel casks (Figure C-5). These vessels are not used for the transport of any other cargo and they operate as dedicated vessels. Casks are loaded directly into the holds of the vessel because the cargo compartments contain the hardware needed to mate with the tiedown fixtures of the cask. If the vessel has no crane, dockside cranes are used for loading and unloading. The cargo compartments are typically intended to handle a specific cask, and other casks cannot be used without modification to the tiedown mechanisms. For the relatively efficient transport of spent nuclear fuel, the casks normally used are very large. They are intended for the transport of power reactor spent nuclear fuel, and have a loaded weight on the order of 90 to 115 metric tons (99 to 126.5 tons). Commercial docks are not normally used, but most could be without significant problems.

The vessels have double bottoms and hulls, watertight compartments, and collision damage resisting structures within the hull. The vessel crew is trained in the handling of the cargo and in emergency response. These vessels also incorporate security features and satellite tracking systems.

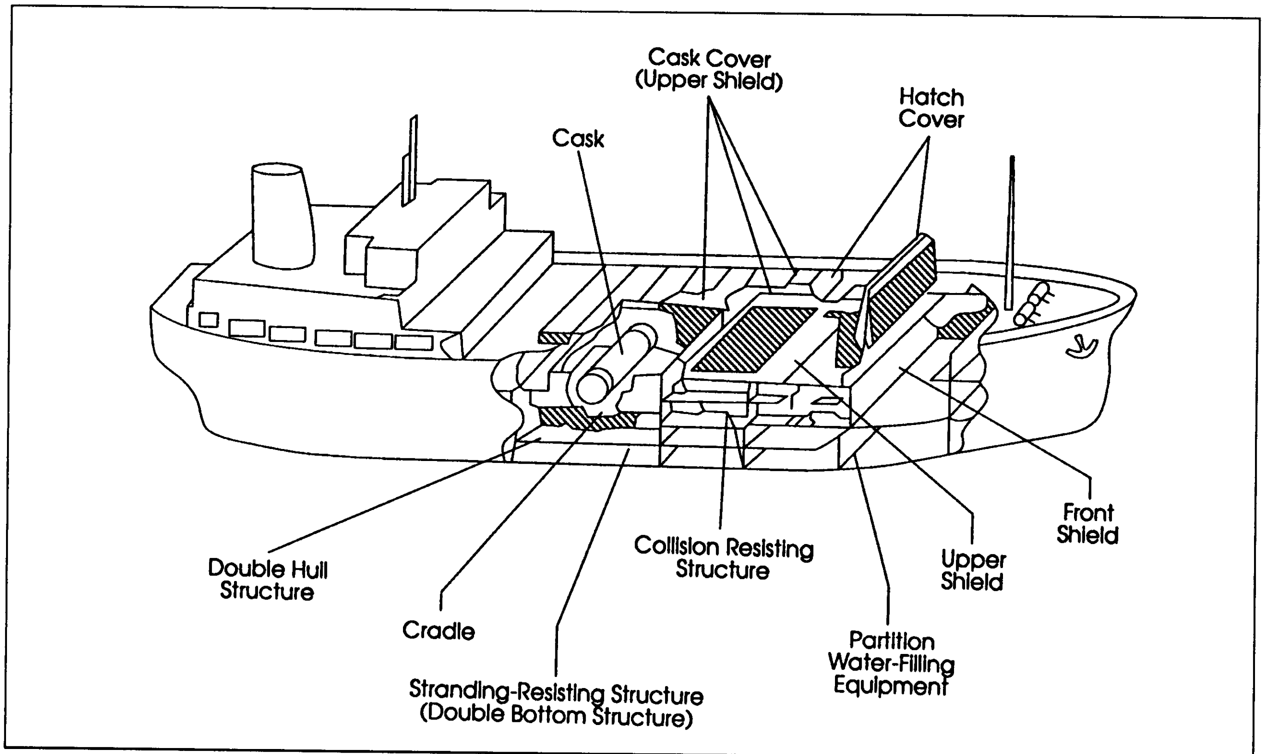

Figure C-5 Purpose-Built Ship

At present, purpose-built vessels are operated by Nuclear Transport Services of Japan, by the Swedish Nuclear Fuel and Waste Management Company, and by British Nuclear Fuels, Limited. They are used to move spent nuclear fuel from operating nuclear power plants to spent nuclear fuel reprocessing facilities operated by Cogema and British Nuclear Fuels, Limited; or, in the case of Sweden, to the repository in Forsmark. There are no U.S.-owned purpose-built vessels for spent nuclear fuel transport.

C.3.2 Identification of Routes

The foreign research reactor spent nuclear fuel that might be transported by sea under the proposed action could originate from 40 different countries. For calculation of shipping distances to the United States, shipping routes were selected to represent the transport of the fuel from a convenient port in the country of origin (for land-locked nations a port near the country of origin was selected) to both an East Coast and a West Coast U.S. port. Norfolk, VA, and Los Angeles, CA, were selected as the two port cities for use in determining a representative distance from the country of origin to the East and West Coasts of the United States. These distances were then combined to generate an average shipping distance between the country of origin and the United States. By using a city on both coasts of the United States to determine an average distance between ports, the analysis considers the possibility that shipments of foreign research reactor spent nuclear fuel would not necessarily be made to the closest U.S. port and, in fact, may be shipped to the "opposite" coast.

Table C-1 is a compilation of the distances for shipments from each of the countries that may participate in this program (except Canada) to the ports on both U.S. coasts. All route distances were obtained by using normal shipping lanes (DMA, 1991). For some of the shipments that might be received at the "opposite" U.S. coast port, the use of the Panama Canal was assumed. Other than the shipping requirements

Table C-1 Voyage Data

Country of Origin	Distance East (nautical miles)	Distance West (nautical miles)	Average Distance (nautical miles)	Voyage Duration (days)	Number of Casks	Number of Voyages
Argentina	5,824	7,265	6,545	21.2	9	5
Australia	12,728	6,511	9,620	29.7	9	5
Austria	5,026	8,955	6,991	22.9	8	4
Bangladesh	10,017	9,384	9,701	31.0	3	2
Belgium	3,582	7,782	5,682	19.3	59	30
Brazil	4,723	8,109	6,416	20.8	8	4
Chile	4,438	4,808	4,623	16.3	2	1
Colombia	2,174	3,265	2,720	11.1	1	1
Denmark	3,990	8,190	6,090	20.4	22	11
France	3,181	7,287	5,234	18.0	149	75
Finland	4,453	8,653	6,553	21.7	6	3
Germany	3,919	8,119	6,019	20.2	61	31
Greece	4,685	8,614	6,650	22.0	8	4
Indonesia	10,566	8,392	9,479	30.3	14	7
Iran	12,013	11,783	11,898	36.6	1	1
Israel	5,366	9,295	7,331	23.9	6	3
Italy	4,336	8,265	6,301	21.0	18	9
Jamaica	1,279	3,507	2,393	10.2	1	1
Japan	9,504	4,839	7,172	23.4	110	55
Korea (South)	10,480	5,229	7,855	25.3	18	9
Malaysia	10,417	7,867	9,142	28.9	3	2
Mexico	1,772	1,501	1,637	7.6	6	3
The Netherlands	3,582	7,782	5,682	19.3	49	25
Pakistan	11,460	10,749	11,105	34.4	3	2
Peru	3,172	3,655	3,414	13.0	1	1
Philippines	11,169	6,530	8,850	28.1	6	3
Portugal	3,129	7,550	5,340	18.3	3	2
Romania	5,353	9,282	7,318	23.8	48	24
Slovenia	4,172	8,372	6,272	20.9	13	7
South Africa	6,790	9,385	8,088	26.0	2	1
Spain	3,303	7,564	5,434	18.6	1	1
Sweden	4,331	8,531	6,431	21.4	37	19
Switzerland	5,026	8,955	6,991	22.9	5	3
Taiwan	11,732	7,093	9,413	29.7	9	5
Thailand	13,169	7,775	10,472	33.1	5	3
Turkey	5,002	8,931	6,967	22.9	4	2
United Kingdom	3,101	7,301	5,201	18.5	4	2
Uruguay	5,710	7,171	6,441	20.9	1	1
Venezuela	1,687	3,757	2,722	11.1	4	2
Zaire	5,864	8,583	7,224	23.6	4	2
Totals					**721**	**371**
Average				**21.3**		

Distance East - Distance in nautical miles from country of origin to Norfolk, Virginia
Distance West - Distance in nautical miles from country of origin to Los Angeles, California
Average Distance - Distance in nautical miles from country of origin to both U.S. ports
Voyage Duration - Average distance divided by 15 knots per hour plus additional days for busy way points (i.e., Panama Canal) and three days for additional stops
Number of Casks - Total casks from country of origin
Number of Voyages - Number of trips required assuming two casks per voyage

applicable to the entire journey, there are no known restrictions for spent nuclear fuel passing through either the Suez or Panama Canals. Figure C-6 provides a representation of the shipping routes selected for these shipments, although other normal shipping routes may be used.

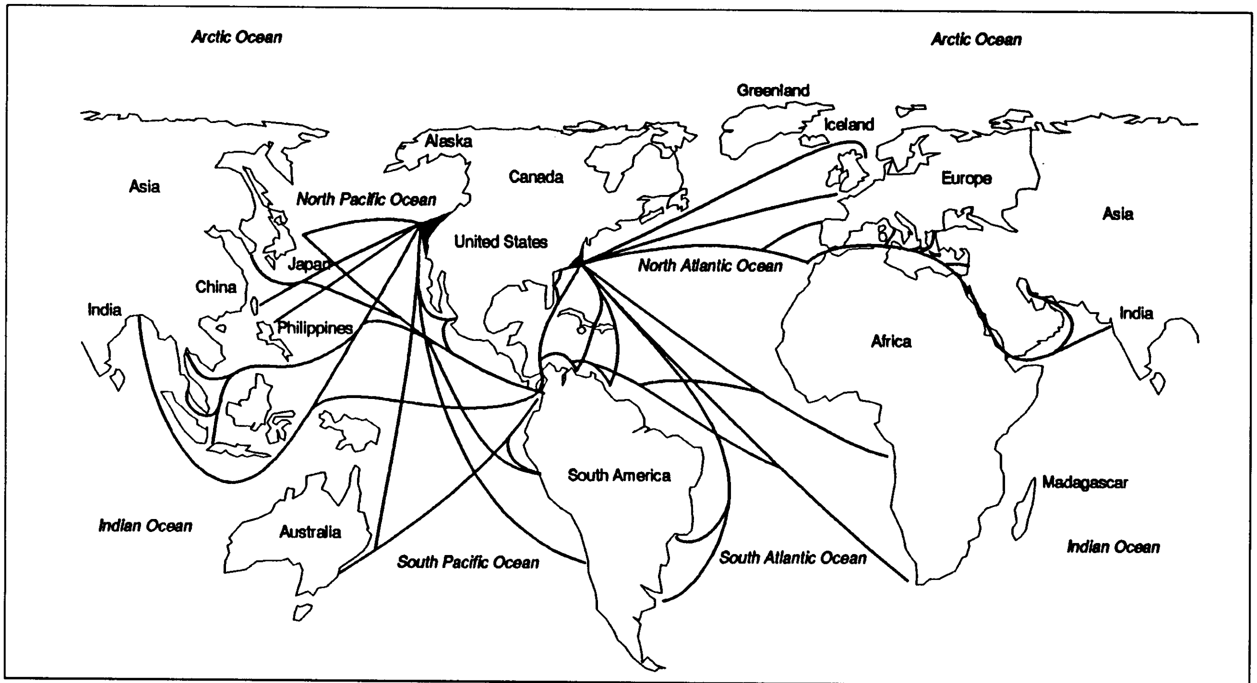

Figure C-6 Representative Shipping Routes for Foreign Research Reactor Spent Nuclear Fuel

C.4 Incident-Free Impacts: Methods and Results

C.4.1 Incident-Free Risk Assessment Methodology

External radiation from an intact transportation cask must be below specified limits that control the exposure of the handling personnel and general public. The U.S. limits are set forth in 49 CFR 173. The limit of interest established therein is 10 mrem per hour at any point 2 m (6.6 ft) from the vertical planes [illegible] reactor spent nuclear fuel shipments. Appendix F, Section F.5, provides a discussion of the development of the exposure dose rate versus distance relationship for a transportation cask having a dose rate at the selected exclusive-use regulatory limit.

The application of the 10 mrem per hour at 2 m (6.6 ft) exclusive-use regulatory dose limit and the "historical" dose rates provide two significant estimates for the assumed external dose rates. The exposure derived from the use of the selected regulatory limit for the dose rate is an estimate of the [illegible]

is closer to an expected value for the incident-free impacts. Therefore, the results of these two analyses provide an estimate of the range of incident-free impacts from the shipment of the foreign research reactor spent nuclear fuel.

The primary impact of incident-free marine transport of spent nuclear fuel is on the crews of the ships used the first two spent nuclear fuel casks. The radiological exposure to the crew for a shipment of many casks would be equivalent to the radiological exposure due to multiple shipments of fewer casks. For example, if four casks are shipped on a single vessel, the crew dose for that single shipment would be equal to the crew dose from two shipments of two casks each.

The second set of assumptions addresses the use of a chartered cargo vessel for the shipment of the foreign research reactor spent nuclear fuel. Use of a chartered vessel (either a chartered commercial freighter or a purpose-built vessel) could result in the shipment of more than two casks per voyage. Economic considerations would suggest that a larger number of casks be shipped per voyage. For this analysis it has been assumed that eight transportation casks would be shipped on a chartered vessel. Consistent with the assumption made for the regularly scheduled commercial vessel, it has been assumed that the transportation casks would be loaded two to a hold. Again, this results in doses to the crew from the first cask loaded during activities associated with the loading of the second cask in the hold.

During loading operations, both on the regularly scheduled commercial and chartered vessels, it is assumed that five members of the ship's crew (Chief Mate, Mate on Watch, Bosun, and two Seamen) will be present during loading and securing of the spent nuclear fuel casks. While longshoremen will most likely be used for the cargo handling activity, ship's crew will be present, and therefore the crew dose resulting from this activity has been included in the analysis. Table C-2 shows the crew member distances from the spent nuclear fuel shipping cask and the duration of the crew members' exposure for each crew member during the time leading up to the stowage of the cask prior to setting sail for the ocean voyage. The distances and times are based on vessel loading activities for a two-cask-per-hold shipment. The total dose (based on the selected exclusive-use regulatory limit external dose rate of 10 mrem per hour at 2 m or 6.6 ft from the surface of the container) for each individual is calculated for each shipment. Since two casks are assumed to be shipped in each hold, when quantities allow, the condition exists for loading and securing of a cask to take place in the vicinity of another cask. The additional dose received by working around a cask already in the hold are accounted for in Table C-2. This was accomplished by increasing the exposure rate by a factor of 1.5 for the activities associated with securing the second cask. As listed, the estimated exposure represents the crew exposure for the regularly scheduled commercial vessel, which has been assumed to be limited to a total of two transportation casks. The exposure for each listed crew member in a chartered vessel would be four times these values, since the eight casks are assumed to be loaded into four holds.

Table C-2 Ship Crew Exposure During Loading of a Hold Containing Two Foreign Research Reactor Spent Nuclear Fuel Casks (Based on Regulatory Dose Limits)

	Tasks						Total Dose
	Rail to Hold			Secure Cask			
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	

While at sea, the crew dose is limited to those individuals who enter the ship's hold during transit. At all other times, the crew is shielded from the spent nuclear fuel cask by the decking and other structures of the vessel. The number of entries and inspections is a function of the voyage distance from the port of loading to the port of offloading (the U.S. port of entry for the foreign research reactor spent nuclear fuel). Since the port of offloading is unknown at this time, voyage distances were determined for each country of origin to a West and East Coast port of the United States. The average of these two distances was then calculated. Table C-1 shows the countries of origin, the number of casks, the distances to the East and West Coast ports, the average voyage distance, the days of travel, and the estimated number of casks and shipments for the basic implementation of Management Alternative 1. Because the actual shipping schedule is unknown, the average annual number of shipments was estimated. The length of a voyage was determined by assuming that the vessel would have an average speed of 15 knots for the entire duration of the voyage. In addition, intermediate port stops would be made, and additional travel time was added to account for portions of the voyage during which the vessel would not be expected to have a speed of 15 knots, (i.e., passage through busy locations, such as the Panama Canal).

Once a day while at sea or in port, the Chief Mate, the Bosun, and an Engineer are assumed to enter each cargo hold to inspect the bilges and verify the lashings for the containers. Table C-3 describes the times required for these activities, the distances from the casks during the activity, and doses received from the casks during the activity (based on the selected exclusive-use limit of external dose rate of 10 mrem per hour at 2 m or 6.6 ft from the surface of the container) for each of these individuals. The total dose due to [illegible] duration and the number of holds that contain foreign mechanical problems or extreme weather and was forced to make an unscheduled port call, the incident-free radiation exposure to the ship's inspection crew would slightly increase as a result of the additional duration of the voyage. People in the refuge port would not receive any exposure because the foreign research reactor spent nuclear fuel would remain on the ship and would not be handled.

Once at the port of entry, all casks of the spent nuclear fuel would be off loaded. Table C-4 describes the estimated dose (based on the selected exclusive-use limit of an external dose rate of 10 mrem per hour at 2 m or 6.6 ft from the surface of the container) received by crew members involved in the offloading activities associated with the offloading of a single hold, that is, two casks. These doses are the same as those received during the loading phase of the transport activity. Once the spent nuclear fuel cask is over the rail of the ship, the ship's crew would not be in close proximity to it. As a result, no ship crew personnel are assumed to be involved with any of the activities associated with disengaging the spent nuclear fuel container from the handling gear or in securing the container to any transport vehicle used to move the container off the pier.

Table C-4 Ship Crew Exposure During Offloading of a Hold Containing Two Foreign Research Reactor Spent Nuclear Fuel Casks (Based on Regulatory Dose Limits)

Crew Member	Tasks						Total Dose per Loading[c] (person-rem)
	Rail to Hold			Secure Cask			
	Distance[a] (m)	Exposure Rate[b] (mrem/hr)	Time (min)	Distance[a] (m)	Exposure Rate[b] (mrem/hr)	Time (min)	
Chief Mate	20	1	5	5.5	3.5	60	0.009
Mate on Watch	20	1	5	8	2.1	60	0.005
Bosun	20	1	5	5.5	3.5	60	0.009
Seaman (2)	20	1	5	5.5	3.5	60	0.018

[a] *Distance is the average distance of the crew member from the spent nuclear fuel cask during the entire duration of that activity.*

[b]

Table C-5 Total Regularly Scheduled Commercial Ship's Crew Exposure for Marine Transport of Foreign Research Reactor Spent Nuclear Fuel Casks (Based on Regulatory Dose Limits and Assuming Intermediate Port Stops)

Crew Member	*Maximum Individual Exposure per Trip (mrem)*	*Maximum Individual Exposure per Year[a] (mrem)*	*Program Dose Total (All Ships' Crews) (person-rem)*
Chief Mate	66	599	24.8
Mate on Watch	11	98	4.0
Bosun	66	599	24.8
Seaman (2)	18	158	13.1
Engineer	49	441	18.2
Total			**84.9**

[a] *Exposure per year based on nine voyages per year, two casks per voyage.*

Table C-6 Total Chartered Ship's Crew Exposure for Marine Transport of Foreign Research Reactor Spent Nuclear Fuel Casks (Based on Regulatory Dose Limits and Assuming No Intermediate Port Stops)

Crew Member	*Maximum Individual Exposure per Trip (mrem)*	*Maximum Individual Exposure per Year[a] (mrem)*	*Program Dose Total (All Ships' Crews) (person-rem)*

inspection of the cargo holds. The three day reduction in the voyage duration (gained when a chartered vessel is used) reduces the dose received from the daily inspections and results in the ten percent difference between the use of regularly scheduled commercial and chartered vessels.

Tables C-7 through C-11 present the results of the above analysis with one change. The exposure and crew doses are calculated based on the "historical" external dose rate data developed from measurements taken during earlier shipments of research reactor spent nuclear fuel (a dose rate of 2.25 mrem per hour at 1 m or 3.3 ft from the surface of the shipping cask, which is equivalent to 1 mrem per hour at 2 m or 6.6 ft from the cask surface). See Appendix F, Section F.5 for the data used to derive this historical dose rate. Although this "historical" data are based on distance from the surface of the cask, it has conservatively been assumed in this analysis that this dose rate represents the dose at distances from the surface of the container in which the cask is shipped. This set of calculations was performed in order to provide additional perspective about the risks associated with the foreign research reactor spent nuclear fuel program. Use of the exclusive-use regulatory limit for the external dose rate ensures that the estimates discussed previously are upper bounds on the potential risks to the ship's crew from incident-free transport of the spent nuclear fuel. Use of the historical data provides an estimate that is closer to the expected risks associated with the shipment of all of the foreign research reactor spent nuclear fuel. Although the exact external dose rates cannot be determined in advance for all shipments, most should be similar to those for shipments made in the past. Therefore, the "historical" external dose rates should be a more accurate prediction of the risks resulting from the shipment of all 721 casks.

In this analysis, all other assumptions regarding voyage length, crew activity (time and distance from the spent nuclear fuel cask), number of shipments, and the assumptions made to estimate annual doses remained the same as in the analysis performed using the external dose rates derived from the exclusive-use regulatory limit of 10 mrem per hour at 2 m (6.6 ft) from the surface of the shipping container.

Using the historic dose rates, the maximum dose to an individual per regularly scheduled commercial vessel shipment would be 6.6 mrem, and the annual maximum individual dose would be 60 mrem (this dose is calculated assuming that the same crew member is involved in nine separate voyages transporting two spent nuclear fuel casks each during a single year). These doses are an order of magnitude lower than the corresponding doses calculated using the exclusive-use regulatory external dose rates. The calculated maximum individual dose is well below the maximum allowable annual dose to a member of the public of 100 mrem.

Use of a chartered vessel for the shipments, versus the use of a regularly scheduled commercial vessel, would result in a ten percent reduction in the total ships' crews doses. The use of a chartered vessel would result in annual exposure at slightly less than twice the public dose limits for exposure to radiation established by both DOE and NRC (100 mrem per year).

The dose total for the marine transport portion of the entire program can be expressed as the number of LCFs that are calculated to result from exposures of that size. For a regularly scheduled commercial vessel a total exposure of approximately 8.5 person-rem translates to 0.0034 LCFs. The total calculated exposure associated with the shipment of the foreign research reactor spent nuclear fuel on a chartered vessel, approximately 7.6 person-rem, translates into 0.0030 LCFs.

Table C-7 Ship Crew Exposure During Loading of a Hold Containing Two Foreign Research Reactor Spent Nuclear Fuel Casks (Based on Historical Cask Dose Rates)

	Tasks						
	Rail to Hold			Secure Cask			Total Dose per
		Exposure			Exposure		

Table C-10 Total Regularly Scheduled Commercial Ships Crew Exposure for Marine Transport of Foreign Research Reactor Spent Nuclear Fuel Casks Assuming Intermediate Port Stops (Based on Historical Cask Dose Rates)

Alternative 2). The implementation subalternative of accepting spent nuclear fuel only from developing countries would result in a reduction in the amount of spent nuclear fuel transported by ship. Table C-12 lists the countries that are considered developing countries and the number of shipments that would be required to transport their spent nuclear fuel to the United States.

Table C-12 Voyage Data for Acceptance of Foreign Research Reactor Spent Nuclear Fuel from Developing Nations Only

Port	*Voyage Duration (days)*	*Number of Casks*	*Number of Trips*
Argentina	21.2	9	5
Bangladesh	31.0	3	2
Brazil	20.8	8	4
Chile	16.3	2	1
Colombia	11.1	1	1
Greece	22.0	8	4
Indonesia	30.3	14	7
Iran	36.6	1	1
Jamaica	10.2	1	1
Korea (South)	25.3	18	9
Malaysia	28.9	3	2
Mexico	7.6	6	3
Pakistan	34.4	3	2
Peru	13.0	1	1
Philippines	28.1	6	3
Portugal	18.3	3	2
Romania	23.8	48	24
Slovenia	20.9	13	7
South Africa	26.0	2	1
Thailand	33.1	5	3
Turkey	22.9	4	2
Uruguay	20.9	1	1
Venezuela	11.1	4	2
Zaire	23.6	4	2
Totals		**168**	**90**
Average	**23**		

Under the implementation subalternative of using a policy duration of five years for the acceptance of foreign research reactor spent nuclear fuel, the number of transportation casks of foreign research reactor spent nuclear fuel requiring ocean transport would be reduced to 586. Appendix B presents the derivation of the total number of shipments (ocean transport plus land transport from Canada) estimated in this alternative.

Subalternative 1b (overseas reprocessing) under Management Alternative 2 also has the capability to impact the results of the incident-free marine risk analysis since it involves shipment of the vitrified waste to a storage facility in the United States. Under this subalternative to Management Alternative 2, eight transportation cask shipments of vitrified waste would be made to the United States.

In addition, a Hybrid Alternative was analyzed. In the Hybrid Alternative, those countries (for this option, assumed to be Belgium, France, Germany, Italy, Spain, Switzerland, and the United Kingdom) that have the capability to store high-level waste would be encouraged to reprocess the aluminum-based research reactor spent nuclear fuel and to accept for management the resulting high-level waste. The United States would accept for management the research reactor spent nuclear fuel from those countries deemed not to have the high-level waste storage capability, and all TRIGA fuel. This Hybrid Alternative includes all countries identified in Table C-1 except for those seven nations just listed. Under this Hybrid Alternative, 452 shipments of spent nuclear fuel are assumed to be sent to the United States, excluding shipments of Canadian origin.

The incident-free marine risks associated with the two implementation subalternatives of Management Alternative 1 and the subalternative of Management Alternative 2 are discussed in the following sections.

Management Alternative 1, Implementation Subalternative 1a — Acceptance of Foreign Research Reactor Spent Nuclear Fuel Only from Developing Countries: This implementation subalternative of Management Alternative 1 would result in the shipment of 168 casks of foreign research reactor spent nuclear fuel. The assumptions used in the analysis of the incident-free marine impact of the basic implementation of Management Alternative 1 have been used in the analysis of this implementation subalternative. This implementation subalternative has been analyzed using the "exclusive-use" shipment regulatory transportation cask external dose rates. To compare this implementation subalternative to the basic implementation, it is only necessary to perform the analysis using one estimate of the external dose rate of the transportation cask. The relationship between the calculated impact of the two implementation subalternatives using the regulatory external dose rate would be the same as that calculated using the "historical" data. Therefore, the use of the one dose rate provides a sufficient point of comparison between the two alternatives.

The assumptions that have not changed between the analysis for the basic implementation and this implementation subalternative include the following:

- The same types of vessels should be available for use, so, the option for using chartered or regularly scheduled commercial vessels was examined, and
- The activities associated with the loading of the foreign research reactor spent nuclear fuel, the daily inspections of the cargo during the voyage, and the offloading of the foreign research reactor spent nuclear fuel do not change simply because there is a reduction in the number of shipments to be made.

The average duration of the voyages from these developing countries to the United States is slightly longer than the average for the voyages associated with the basic implementation. As shown in Table C-12, the average duration is 23 days (for a regularly scheduled commercial vessel) versus the 21 days in the basic

The 168 cask-shipments, requiring 90 ocean voyages using regularly scheduled commercial cargo vessels (up to 23 voyages using chartered vessels), represent approximately 24 percent of the total number of shipments in the basic implementation. The total population (ship's crew) exposure resulting from this implementation subalternative would be approximately 27 percent of the exposure calculated for the basic implementation. The difference in these two percentages is a direct result of the longer average duration of ocean crossings. The total population exposure for the implementation subalternative, assuming that regularly scheduled commercial vessels are used, would be approximately 22.0 person-rem, and would be approximately 20.3 person-rem if chartered vessels are used. These population exposures translate into a risk to the ship's crew of 0.0091 LCF and 0.0081 LCF, respectively. As discussed in Section 4.1, the relationship between a dose and LCFs for workers (ship's crew) is that a 1 rem dose equates to 0.0004 LCFs.

Management Alternative 1, Implementation Subalternative 2a — Acceptance of Foreign Research Reactor Spent Nuclear Fuel for Five-Year Policy Duration: As stated above, this implementation subalternative results in the shipment of 586 casks of foreign research reactor spent nuclear fuel. The assumptions used in the analysis of the incident-free marine impact of the basic implementation have been used in the analysis of this implementation subalternative. This implementation subalternative has been analyzed using the "exclusive-use" shipment regulatory transportation cask external dose rates. To compare this implementation subalternative to the basic implementation it is only necessary to perform the analysis using one external dose rate. The relationship between the calculated impact of the implementation subalternative and the basic implementation using the regulatory external dose rate would be the same as that calculated using the "historical" data. Therefore, the use of the one dose rate provides a sufficient point of comparison.

The assumptions that have not changed between the analysis for the basic implementation and this implementation subalternative include the following:

- The same types of vessels should be available for use, and the option for using chartered or regularly scheduled commercial vessels was examined;

- The average voyage duration that was used in the analysis of the incident-free marine risk for the basic implementation was used for this implementation subalternative. The 586 shipments represent approximately 81 percent of the shipments made under the basic implementation and the distribution of shipments from the different countries of origin is similar to that modeled for the basic implementation; and

- The activities associated with the loading of the foreign research reactor spent nuclear fuel transportation casks, the daily inspections of the cargo during the voyage, and the offloading of the foreign research reactor spent nuclear fuel transportation casks do not change simply because there is a reduction in the number of shipments to be made.

Because there are no differences between the per-shipment activities in this implementation subalternative and the basic implementation, the per-voyage crew exposures will not differ from those presented in Tables C-5 and C-6 for the basic implementation. In addition, the maximum annual exposures to individual crew members will not change. The analysis has assumed a maximum number of voyages that

The total population (ship's crew) exposure resulting from this implementation subalternative would be approximately 81 percent of exposure calculated for the basic implementation. The total population exposure for the implementation subalternative, assuming that regularly scheduled commercial vessels are used, would be approximately 69 person-rem, and would be approximately 61 person-rem if chartered vessels were to be used. These population exposures translate into a risk to the ships' crew of 0.028 LCF and 0.025 LCF, respectively. As discussed in Section 4.1, the relationship between a dose and LCFs for workers (ship's crew) is that a 1 rem dose equates to 0.0004 LCF.

Management Alternative 2, Subalternative 1b – Overseas Processing with Shipment of Waste to a U.S. Storage Facility: In this subalternative, the foreign research reactor spent nuclear fuel would be reprocessed overseas (most probably in Great Britain or France) and the waste products would be contained within a small number of vitrified waste logs. This high-level waste might be brought to the United States for storage at one of the management site facilities evaluated under the basic implementation of Management Alternative 1. Under these conditions, up to eight transportation casks containing 16 European-size canisters of vitrified waste would be shipped from Europe to the United States (see Section 4.4.2.2 for more information on the vitrification of the waste material). This analysis addresses the incident-free marine risks associated with transporting these eight casks of vitrified waste from Europe to the United States.

As with the shipment of unprocessed spent nuclear fuel, the primary impact of incident-free marine shipping of the vitrified waste is upon the crews of the ships used to carry the casks. Most of the assumptions used in the analysis of the crew exposure to the spent nuclear fuel (see Section C.4.1 of this appendix) have been used to analyze the impact of the shipment of vitrified waste. The crew exposure due to loading and offloading activities have been considered, but the primary contribution to the crew dose comes from the daily cargo inspection activities. The inspection activities on the ship carrying the vitrified waste have been modeled in the same manner as the inspections aboard the vessels carrying the spent nuclear fuel. Three crew members have been modeled as performing the inspections, and the same three crew members are assumed to perform this task for the entire voyage. For the purposes of this analysis, it has been assumed that the vitrified waste will be transported on a chartered vessel, there will be no intermediate port calls, and the shipment will originate in Europe. Because there are no intermediate port calls and the shipments originate in Europe, the voyage duration is estimated to be 15 days. This estimate is based on the average of the voyage durations for one trip from the United Kingdom to the East Coast of the United States, one to the West Coast of the United States, and the average of a trip from France to both U.S. coasts. The assumption that there are no intermediate port calls reduces the average duration of each of these trips by three days from the estimates presented in Table C-1.

Little information is available on the casks that might be used to transport the vitrified waste. Therefore, the assumption has been made that the exposure to the crew will be limited to the exclusive-use regulatory limit (10 CFR 71) of 10 mrem per hour at 2 m (6.6 ft) from the surface of the container. No attempt was made to extrapolate limited historical data to determine crew incident-free impacts from any other exposure rate other than the limit set forth in NRC and DOE regulations.

It has been assumed that two casks are being transported as part of a single shipment. This assumption results in additional exposure to the crew members due to exposure to two radiation fields during all activities which bring crew members into the vicinity of the transportation casks. Should all of the casks be shipped at once, this assumption is equivalent to assuming that this single shipment is made with two casks per hold on the vessel. The crew risk would be the same for this single (eight cask) shipment as for the four shipments with two casks per vessel.

Based on the assumptions outlined above, the incident-free impact of the shipment of vitrified waste on the ship's crew would be slightly less per shipment than that calculated for the shipment of foreign research reactor spent nuclear fuel. The trip duration of only 15 days, versus the average duration of 18 days, for a chartered vessel in the basic implementation of Management Alternative 1 results in a reduction of the dose to each inspector, the Chief Mate, the Bosun, and the Engineer, of approximately 6.9 mrem per journey (three fewer inspections, each of which would have resulted in a dose of 2.3 mrem). The population dose to the ship's crew, per voyage, can be derived from the data contained in Table C-6. Incorporating the reduction in the inspection dose into the data from this table, the individual doses would be: 210 mrem to the Chief Mate and the Bosun, 43 mrem to the Mate on Watch, 70 mrem to each of two Seamen, and 140 mrem to the ships Engineer. Per voyage, the total population dose to the ship's crew would be 0.74 person-rem.

With only eight casks to be shipped, the subalternative action could be achieved with a single shipment (the crew dose would be the same as that calculated if four shipments of two casks each were made). The population exposure results in a risk to the crew of 0.00030 LCF. Due to the reduced number of shipments, compared to the 721 shipments of spent nuclear fuel in the basic implementation of Management Alternative 1, the marine incident-free risk to the crew is approximately two orders of magnitude lower than that calculated for the basic implementation.

Management Alternative 3 – Combination of Components of Management Alternative 1 and 2 (Hybrid Alternative): Under the Hybrid Alternative, the United States would accept foreign research reactor spent nuclear fuel from countries without high-level waste storage capability. This Hybrid Alternative could result in the shipment of 452 casks of foreign research reactor spent nuclear fuel. The assumptions used in the analysis of the incident-free marine impact for the basic implementation of Management Alternative 1 have been used in the analysis of this Hybrid Alternative. This alternative has been analyzed using the selected "exclusive-use" regulatory dose limit for the shipment of spent nuclear fuel casks.

Included in the assumptions that have not changed between the analysis for the basic implementation and this alternative are the following:

- The same types of vessels should be available for use under this Hybrid Alternative, the option for using chartered or regularly scheduled commercial vessels was examined, and
- The activities associated with the loading of the foreign research reactor spent nuclear fuel, the daily inspection of the cargo during the voyage, and the offloading of the foreign research reactor spent nuclear fuel do not change simply because there is a reduction in the number of shipments to be made.

The average duration of the voyages from the countries without high-level waste storage capability to the United States is slightly longer than the average for the voyages associated with the basic implementation. Using the data in Table C-12, and eliminating the aluminum-based spent fuel shipments from Belgium, France, Germany, Italy, Spain, Switzerland, and the United Kingdom, the average voyage duration is almost 23 days (for a regularly scheduled commercial vessel) versus the 21 days for the basic implementation. For a chartered vessel, the voyage duration is three days less (i.e., almost 20 days). The longer average voyage duration results in an increase in the total of the daily inspection-related crew doses of approximately 4.6 mrem per crew member involved in the inspection. The inspection dose for a 23-day voyage would be 52.9 mrem (2.3 mrem times 23 days) per inspector.

The population dose to the ship's crew, per voyage, can be derived from the data contained in Tables C-5 and C-6. Incorporating the increase in the inspection dose into the data from Table C-5, the individual doses on a regularly scheduled commercial vessel would be 71 mrem to the Chief Mate and the Bosun, 11 mrem to the Mate on Watch, 18 mrem to each of two Seamen, and 54 mrem to the ship's Engineer. The population (ship's crew) dose per shipment would be 243 mrem. If a chartered vessel is used (carrying eight transportation casks instead of two for the regularly scheduled commercial vessel), the corresponding doses are 257 mrem to the Chief Mate and the Bosun, 43 mrem to the Mate on Watch, 70 mrem to each of two Seamen, and 187 mrem to the ship's Engineer. The population (ship's crew) dose per shipment would be 884 mrem.

The 452 cask shipments, requiring 236 ocean voyages using commercial regularly scheduled commercial cargo vessels, represent approximately 63 percent of the total number of shipments for the basic implementation. The total population (ships' crew) exposure resulting from this Hybrid Alternative would be approximately 69 percent of the exposure calculated for the basic implementation. The differences in these two percentages is a direct result of the longer average duration of ocean crossings. The total population exposure for the Hybrid Alternative, assuming that regularly scheduled commercial vessels are used, would be approximately 57.2 rem and would be approximately 52.2 rem if chartered vessels were used. These population exposures translate into a risk to the ships' crew, in terms of LCFs, of 0.024 LCF and 0.021 LCF, respectively. As discussed in Section 4.1, the relationship between a dose and LCFs is that a 1 rem dose equates to 0.0004 LCFs.

C.5 Accident Impacts: Methods and Results

C.5.1 Introduction

If the cask sinks anywhere in U.S. coastal waters, it will be recovered, regardless of depth. U.S. coastal waters in this case refers to waters within the 12-mile territorial limit. Recovery would be accomplished, even in the deepest parts of U.S. coastal waters, such as in Puget Sound, which reaches 305 meters or inventory of radioactive material in the foreign research reactor spent nuclear fuel is considerably different than the vitrified high-level waste inventory. With modifications to compensate for these differences, the Nuclear Energy Agency results were used to predict the peak individual dose and biota dose for Scenario A and Scenario B.

C.5.2 Assumptions

1. The spent nuclear fuel and cask modeled are the BR-2 fuel and the Pegase cask. Based on the information provided in Appendix B, the loaded Pegase cask contains 0.0155 metric tons of heavy metal (MTHM) (15.5 kg) of fuel (assuming the cask is loaded with BR-2 type fuel). This fuel type was selected because BR-2 fuel has the highest isotope content per unit mass of heavy metal of the three fuel types considered in this analysis. Use of the highest inventory of radionuclides establishes a conservative upper bound on the estimated dose rates from the leaching of radionuclides into the sea. This is because the dose rates are a function of the corrosion rate of spent nuclear fuel, expressed in terms of mass per unit of time, and the specific activity of the spent nuclear fuel, expressed in terms of radioactivity per unit of mass.

2. The fuel rods contain aluminum-clad metallic spent nuclear fuel elements.

3. The deep ocean model is for the South Nares Abyssal Plain.

4. Corrosion of spent nuclear fuel inside a damaged cask begins immediately; corrosion of spent nuclear fuel inside an undamaged cask begins at the time the cask fails and allows seawater to come in contact with the spent nuclear fuel.

5. Once free of the fuel matrix through corrosion, the fission products exit the failed cask without delay.

6. The corrosion rate for spent nuclear fuel elements is constant. Radionuclides are leached from the spent nuclear fuel elements at a rate proportional to the corrosion rate depending on their relative concentrations.

Data from the Nuclear Energy Agency vitrified high-level waste model and on spent nuclear fuel corrosion rates are summarized in Table C-13.

Table C-13 Data For Estimating Spent Nuclear Fuel Dose Rates From the Nuclear Energy Agency Assessments for Vitrified High-Level Waste

Parameter Description	Value[a]	Source
Corrosion Rate for Glass (α_o)	0.000036 kg/m^2 day	NEA 1988
Corrosion Rate for Aluminum-Clad Fuel (α_1)	0.0086 kg/m^2 day	Rechard 1994
Sensitivity Coefficient for Corrosion Rate (a)	0.99	NEA 1988
Undamaged Cask Peak Individual Dose	9 rem/yr	NEA 1988
Damaged Cask Peak Individual Dose	650 rem/yr	NEA 1988
Undamaged Cask Peak Biota Dose (Fish)	3.6 rad/yr	NEA 1988
Undamaged Cask Peak Biota Dose (Crustaceans)	3.8 rad/yr	NEA 1988
Undamaged Cask Peak Biota Dose (Mollusks)	10.0 rad/yr	NEA 1988
Damaged Cask Peak Biota Dose (Fish)	29.0 rad/yr	NEA 1988
Damaged Cask Peak Biota Dose (Crustaceans)	31 rad/yr	NEA 1988

C.5.3 Calculational Method For Dose Rate Estimates

The calculations presented here are designed to account for two differences between the Nuclear Energy Agency radiological assessment and the radiological assessment required for this EIS. First, in the radiological assessment performed for the Nuclear Energy Agency, a vitrified glass waste form was assumed. For this EIS, aluminum-clad metal matrix fuel elements are assumed. Thus, the corrosion rate of the matrix containing the radionuclides will be different in the two cases. Second, the radiological assessment for the Nuclear Energy Agency was performed assuming reprocessed fuel equivalent to 100,000 MTHM containing a total of 10 billion curies, for a specific activity of 100,000 Ci per MTHM. For this EIS, it is assumed that one Pegase cask contains 0.0155 MTHM (15.5 kg) of spent nuclear fuel and 930,000 Ci, for a specific activity of 60 million Ci per MTHM. Table C-14 contains a detailed list of the inventory of radionuclides for both the Nuclear Energy Agency vitrified high-level waste and the foreign research reactor spent nuclear fuel. The specific activity for the vitrified high-level waste is significantly lower than that of the foreign research reactor spent nuclear fuel because the Nuclear Energy Agency study uses data assuming a 100-year decay time for the waste, while the foreign research reactor spent nuclear fuel is assumed to only have been out of the reactor less than a year. The Nuclear Energy Agency study used 100-year decay time because in their study the spent nuclear fuel was not vitrified until it was 50 years out of the reactor, and it was assumed to take 50 years for their cask to fail once it was in the ocean.

The dose estimates from the Nuclear Energy Agency analysis are scaled for this EIS to reflect (1) the fact that spent nuclear fuel corrodes faster than vitrified glass, (2) there is significantly less mass of heavy metal in a spent nuclear fuel cask than was used in the Nuclear Energy Agency dose risk models, and (3) the specific activity of the foreign research reactor spent nuclear fuel is higher than the specific activity of the Nuclear Energy Agency vitrified high-level waste.

To account for differences in the waste matrix corrosion rate, the sensitivity of the calculated dose to the corrosion rate was used. In its radiological assessment, the Nuclear Energy Agency published sensitivity studies. For the accident analyses, an adjoin method was used to determine the sensitivity of the peak individual dose and the collective dose to key parameters in their performance assessment model, including the waste matrix corrosion rate.

The adjoin method employs a mathematical algorithm for calculating directly in one run the sensitivity of

Table C-14 Comparison of Radionuclide Inventories for Nuclear Energy Agency High-Level Waste Sub-Seabed Disposal Studies and BR-2 Foreign Research Reactor Spent Nuclear Fuel

Radionuclide	*Nuclear Energy Agency Vitrified High-Level Waste Inventory[a] (Ci)*	*Foreign Research Reactor Spent Nuclear Fuel Inventory[b] (Ci)*	*Radionuclide*	*Nuclear Energy Agency Vitrified High-Level Waste Inventory[a] (Ci)*	*Foreign Research Reactor Spent Nuclear Fuel Inventory[b] (Ci)*
Hydrogen-3	0.0	86.4	Cerium-141	0.0	5,700
Selenium-79	33,000	0.0	Cerium-144	0.0	310,000
Krypton-85	0.0	2,500	Promethium-147	11,000	48,000
Strontium-89	0.0	41,000	Promethium-148m	0.0	75.6
Strontium-90	2,000,000,000	21,000	Samarium-151	27,000,000	0.0
Yttrium-90	2,000,000,000	0.0	Europium-154	8,600,000	620
Yttrium-91	0.0	73,000	Europium-155	480,000	130
Niobium-95	0.0	220,000	Uranium-233	178	0.0
Zirconium-93	180,000	0.0	Uranium-234	300	0.0091
Zirconium-95	0.0	110,000	Uranium-235	0.0	0.014
Technicium-99	1,400,000	0.0	Uranium-236	47	0.0
Ruthenium-103	0.0	8,900	Uranium-238	0.0	0.00034
Ruthenium-106	0.0	22,000	Neptunium-237	32,000	0.0
Palladium-107	10,000	0.0	Plutonium-238	0.0	64.2
Tin-123	0.0	430	Plutonium-239	120,000	1.8
Tin-126	58,000	0.0	Plutonium-240	620,000	1.2
Antimony-125	990	890	Plutonium-241	3,500,000	280
Antimony-126m	58,000	0.0	Plutonium-242	600	0.0
Tellurium-125m	0.0	210	Americium-241	6,900,000	0.4
Tellurium-127m	0.0	890	Americium-242m	0.0	0.0011
Tellurium-129m	0.0	200	Americium-243	2,000,000	0.0043
Iodine-129	3.0	0.0	Curium-242	0.0	1.8
Cesium-134	108	16,000	Curium-244	0.0	1.3
Cesium-135	150,000	0.0	Curium-245	21,000	0.0
Cesium-137	3,000,000,000	21,000	Curium-246	5,500	0.0
Barium-137m	2,900,000,000	0.0			
			Total	**10,000,000,000**	**930,000**

[a] *Nuclear Energy Agency vitrified high-level waste radionuclide inventories are based on 100,000 MTHM that represent spent nuclear fuel radionuclide inventories for 100 years out of reactor. The Nuclear Energy Agency analysis based its dose rate estimate calculations on vitrified high-level waste that was produced from commercial light water reactor spent nuclear fuel at 50 years out of reactor, then the Nuclear Energy Agency analysis models the release of the vitrified high-level waste inventory into the ocean only after an additional 50 years of submersion.*

[b] *Foreign research reactor spent nuclear fuel radionuclide inventories are based on a Pegase cask filled with 36 elements of BR-2 spent nuclear fuel, 300 days out of reactor.*

$$\ln (D_1/D_0) = a \ \ln (\alpha_1/\alpha_0) \tag{3}$$

Using the data provided in Table C-13,

$$\ln (D_1/D_0) = 0.99 \ln (8.6 \, x \, 10^{-3}/3.6 \, x \, 10^{-5}) \tag{4}$$

or

$$D_1 = 227 \, D_0 \tag{5}$$

Where D_1 is the dose by foreign research reactor spent nuclear fuel, adjusted only for the difference in leach rate, and D_0 is the Nuclear Energy Agency dose.

Since the derivative in Equation (1) is evaluated at a particular value of each model parameter, it is by definition the sensitivity coefficient of the dose to small variations in each parameter around their assigned value. As a result, the calculation of dose using the sensitivity coefficient is valid only when changes in the leach rate remain "sufficiently small" compared to the leach rate. However, the Nuclear Energy Agency assessment states that many of the models in their assessment are linear, and it is possible to estimate changes in the dose even for large variations in the leach rate.

To account for differences in the waste inventory, the dose was scaled linearly according to the ratio of the specific activity of the BR-2 spent nuclear fuel to the specific activity of the vitrified high-level waste as shown in Equation (6).

$$D = D_1 \frac{\beta_{EIS}}{\beta_{NEA}} = D_1 \frac{0.0155}{1.0E{+}05} \frac{6.0E{+}07}{1.0E{+}05} = 9.3E{-}05 \ D_1 \tag{6}$$

Finally,

$$D = 0.021 \ D_0 \tag{7}$$

C.5.4 Results

Dose rates were calculated in the Nuclear Energy Agency study for two types of ocean environments, coastal waters and deep ocean floors. The results of scaling the Nuclear Energy Agency dose rate estimates for the scenario of losing a cask of foreign research reactor spent nuclear fuel in coastal waters are shown in Table C-15, with the comparable Nuclear Energy Agency results. In Table C-16, the results of losing a cask containing foreign research reactor spent nuclear fuel in deep ocean waters are shown. Table C-15 presents results for both an undamaged and a damaged cask, however Table C-16 provides the estimated dose for a damaged cask only because it is assumed that the pressure from the deep ocean will damage the cask seals.

The doses associated with the foreign research reactor spent nuclear fuel in Table C-16 are, in the case of the mollusks, very high. However, to properly interpret this result, several factors must be considered. First, the calculation that produced these results is very conservative for two reasons. The radioactive material, once corroded, was assumed to immediately be released into the open ocean water. In fact, the cask is expected to provide a significant "hold-up" time. This is because only the seal is expected to fail, which means that, due to the small area of the seal, only a very limited amount of water movement through the cask will be experienced. Over time, this small flow would carry out all of the soluble fission products, but insoluble precipitates would remain in the cask. Also, no account was taken for the possibility that the cask would likely become buried in silt, greatly slowing the fission product's entry into

Table C-15 Coastal Waters Dose Rate Estimates for 100,000 MTHM Vitrified High-Level Waste and a Pegase Cask Loaded With BR-2 Foreign Research Reactor Spent Nuclear Fuel

Dose Category	*D_0 (NEA)*	*D (BR-2)*
Undamaged Cask Peak Individual Dose	9.0 rem/yr	0.19 rem/yr
Damaged Cask Peak Individual Dose	650 rem/yr	14 rem/yr
Undamaged Cask Peak Biota Dose (Fish)	3.6 rad/yr	0.077 rad/yr
Undamaged Cask Peak Biota Dose (Crustaceans)	3.8 rad/yr	0.081 rad/yr
Undamaged Cask Peak Biota Dose (Mollusks)	10 rad/yr	0.21 rad/yr
Damaged Cask Peak Biota Dose (Fish)	29 rad/yr	0.62 rad/yr
Damaged Cask Peak Biota Dose (Crustaceans)	31 rad/yr	0.66 rad/yr
Damaged Cask Peak Biota Dose (Mollusks)	660 rad/yr	14 rad/yr

Table C-16 Deep Ocean Dose Rate Estimates for 100,000 MTHM Vitrified High-Level Waste and a Pegase Cask Loaded with BR-2 Foreign Research Reactor Spent Nuclear Fuel

Dose Category	*D_0 (NEA)*	*D (BR-2)*
Damaged Cask Peak Individual Dose	0.00053 rem/yr	0.114 rem/yr
Damaged Cask Peak Biota Dose (Fish)	30,000 rad/yr	640 rad/yr

expected to occur with the consequence estimates, an estimate of the risk associated with ocean transportation can be developed. The frequency of a cask becoming submerged is: the mathematical product of the annual frequency of foreign research reactor spent nuclear fuel shipments, the probability that a shipment is involved in an accident, the probability that a ship sinks (given that an accident occurs), and the probability that a submerged cask is not recovered. Additionally, the frequency of a damaged cask becoming submerged in coastal waters includes the probability that a cask is damaged given that an accident occurs. The data for these events were taken from two sources, the Nuclear Energy Agency study (NEA, 1988) and the Environmental Assessment of Urgent-Relief Acceptance of Foreign Research Reactor Spent Nuclear Fuel (DOE, 1994). These data are summarized in Table C-17.

Table C-17 At Sea Risk Assessment Data

Parameter	*Coastal Data*	*Deep Ocean Data*
Shipment Accident Rate	0.00032/Shipment (DOE, 1994)	0.000046/Shipment (NEA, 1988)
Probability that Cask is Damaged, Given an Accident	0.002 (DOE, 1994)[a]	1.0[c]
Probability that a Ship Sinks Given an Accident	0.001 (Wheeler, 1994)	0.001 (Wheeler, 1994)
Probability that a Submerged Cask is not Recovered	0.0001 (NEA, 1988)[b]	0.05 (NEA, 1988)
Number of Shipments	721	721
Probability - Submerged Cask, Damaged, Unrecovered	4.6×10^{-11}	0.0000017
Probability - Submerged Cask, Undamaged, Unrecovered	2.3×10^{-8}	0.0c

[a] *This value represents the conditional probability that the severity of an accident is greater than Category II, as shown in Appendix E, Environmental Assessment of Urgent Relief Acceptance of Foreign Research Reactor Spent Nuclear Fuel (DOE, 1994).*

[b] *Derivation of this probability is based in a fault tree analysis using data from the Nuclear Energy Agency analysis.*

[c] *The cask is assumed to fail at deep ocean depths.*

The risk estimate results for the basic implementation of Management Alternative 1 are shown in Table C-18. The risk for a peak dose to an individual is 6.4×10^{-7} mrem per year for a damaged cask in coastal water and 0.0000043 mrem per year for an undamaged cask. Risk associated with a submerged, unrecovered cask in the deep ocean is 0.00019 mrem per year for a damaged cask.

Table C-18 Radiological Risk Estimates for At Sea Accidents

Dose Category	*Damaged Cask*	*Undamaged Cask*
Coastal Dose Rate Risk Estimates		
Peak Individual Dose	6.4×10^{-7} mrem/yr	0.0000043 mrem/yr
Peak Biota Dose (Fish)	2.8×10^{-8} mrad/yr	0.0000018 mrad/yr
Peak Biota Dose (Crustaceans)	3.0×10^{-8} mrad/yr	0.0000019 mrad/yr
Peak Biota Dose (Mollusks)	6.4×10^{-7} mrad/yr	0.0000048 mrad/yr
Deep Ocean Risk Estimates		
Peak Individual Dose	0.00019 mrem/yr	Cask is assumed to fail at deep ocean depths
Peak Biota Dose (Fish)	1.1 mrad/yr	Cask is assumed to fail at deep ocean depths
Peak Biota Dose (Crustaceans)	1.4 mrad/yr	Cask is assumed to fail at deep ocean depths
Peak Biota Dose (Mollusks)	49 mrad/yr	Cask is assumed to fail at deep ocean depths

C.5.6 Marine Accident Impacts of Policy Alternatives

In Section C.4.2, two implementation subalternatives to Management Alternative 1 and one implementation subalternative to Management Alternative 2 of the proposed action that could impact the risk calculations were identified: accepting spent nuclear fuel from developing countries only, a 5-year acceptance program, and overseas reprocessing of the foreign research reactor spent nuclear fuel. Implementation of any of these has the potential to impact the marine accident risks calculated for the basic implementation of Management Alternative 1 calculated above.

For the implementation subalternatives involving the shipment of different quantities of foreign research reactor spent nuclear fuel, the consequences of an accident are the same for the implementation subalternatives as they are for the basic implementation. In these subalternatives, the same type of spent nuclear fuel is being shipped in the same types of transportation casks and is subject to the same accidents as for the basic implementation. These are the variables between subalternatives that could have affected the consequences of a marine accident. Since none changed, the consequences do not change. Two of the implementation subalternatives fall into this category: the developing countries implementation of an accident causing the loss of a cask in the deep ocean. The consequences of this accident do not change; the peak individual dose remains at 0.114 rem per year. The loss of a damaged cask in coastal waters results in the lowest risk to man, 1.5×10^{-7} mrem per year. The risks to marine biota are reduced by the same ratio and will range from a high of 11 mrad per year to a mollusk from the loss of a cask in the deep ocean, to a low of 6×10^{-9} mrad per year to fish from the loss of a damaged cask in coastal waters.

Management Alternative 1, Implementation Subalternative 2a — Acceptance of Foreign Research Reactor Spent Nuclear Fuel for 5-Year Policy Duration: This implementation subalternative results in the shipment of 586 transportation casks of foreign research reactor spent nuclear fuel. This is 81 percent of the shipments required for the basic implementation. Using this relationship, the risks presented in Table C-18 can be scaled to produce the following results. The MEI will be exposed to a risk (in terms of a peak individual dose rate) of 0.00015 mrem per year as a result of the accident causing the loss of a cask in the deep ocean. The loss of a damaged cask in coastal waters results in the lowest risk to man, 5×10^{-7} mrem per year. The risks to marine biota are reduced by the same ratio and will range from a high of 40 mrad per year to a mollusk (deep sea accident) to a low of 2×10^{-8} mrad per year to fish (coastal water, damaged cask accident).

Management Alternative 2, Subalternative 1b — Overseas Processing with Shipment of Waste to a U.S. Storage Facility: In this subalternative, all of the foreign research reactor spent nuclear fuel (including that generated in Canada) is sent to either Great Britain or France for processing and the vitrified high-level waste generated in the process would be shipped to the United States. Based on the processing of approximately 23 metric tons (25.3 tons) of spent nuclear fuel, enough vitrified high-level waste would be generated to require up to eight transportation casks of vitrified high-level waste being shipped to the United States. Only the impact of the marine shipments from the processing facility to the United States was calculated.

The consequences of an accident at sea that results in the loss of a transportation cask filled with vitrified high-level waste can be derived from the information used to develop the marine accident consequences for a foreign research reactor spent nuclear fuel cask. The consequences listed in Tables C-15 and C-16 for D_0 represent the consequences associated with the loss of 100,000 MTHM equivalent of vitrified high-level waste. Based on eight shipments for the approximately 23 metric tons (25.3 tons) of spent nuclear fuel, each shipment in this subalternative will contain approximately 2.9 metric tons (3.2 tons) equivalent of vitrified high-level waste. Table C-19 presents the consequences from Tables C-15 and C-16 scaled to represent the consequences for an accident resulting in the loss of a transportation cask containing 2.9 metric tons (3.2 tons) equivalent.

Table C-19 Consequences Resulting from the Loss of a Transportation Cask Containing Vitrified High-Level Waste[a]

	Coastal Waters		*Deep Ocean*
	Undamaged Cask	*Damaged Cask*	*Damaged Cask*
Peak Individual Dose (Man) rem/yr	0.0003	0.019	1.5×10^{-8}
Peak Biota Dose (Fish) rad/yr	0.0001	0.0008	0.9
Peak Biota Dose (Crustaceans) rad/yr	0.0001	0.0009	1.2
Peak Biota Dose (Mollusks) rad/yr	0.0003	0.019	41

[a] *These estimates are based on the best estimate values presented in the Nuclear Energy Agency report (NEA, 1988)*

From the accident frequency data in Table C-17, a per-shipment accident frequency can be developed for all three accidents of interest: 1) the loss of an undamaged cask in coastal waters, 2) the loss of a damaged cask in coastal waters, and 3) the loss of a damaged cask in the deep ocean. These frequencies are the product of the shipment accident rate, the probability of the vessel sinking after an accident, the probability that a submerged cask is not recovered, and where applicable (for the damaged cask in coastal waters only), the probability that the cask is damaged in the accident. The resulting per shipment accident probabilities are 3.2×10^{-11} for the loss of an unrecovered, undamaged cask in coastal waters, 6.4×10^{-14} for the loss of an unrecovered damaged cask in coastal waters, and 2.3×10^{-9} for the unrecovered loss of a damaged cask in the deep ocean.

With the assumption that there are only up to eight shipments of vitrified high-level waste, the risks associated with the marine transport of this material are almost non-existent. The risks in terms of rem per year peak public dose and rad per year peak dose to marine biota, of an unrecovered cask in coastal waters are essentially zero, less than 1.0×10^{-10}. The risks calculated for the deep ocean accidents are: much less than 1×10^{-10} rem per year peak dose to man, 2×10^{-8} rad per year peak dose to fish and crustaceans, and 7×10^{-7} rad per year peak dose to mollusks.

Management Alternative 3 — Combination of Components of Management Alternatives 1 and 3 (Hybrid Alternative): Under the Hybrid Alternative, the United States would accept foreign research reactor spent nuclear fuel from countries unable to store high-level waste. This Hybrid Alternative could result in the shipment of 452 transportation casks of foreign research reactor spent nuclear fuel to the United States. This is approximately 63 percent of the shipments required in the basic alternative. Using this relationship, the risks presented in Table C-18 can be scaled to produce the following results. The MEI will be exposed to a risk (in terms of a peak individual dose rate) of 0.00012 mrem per year as a result of an accident causing the loss of a cask in the deep ocean. The consequences of this accident do not change from the basic implementation; the peak individual dose remains at 0.114 mrem per year. The loss of a damaged cask in coastal waters results in the lowest risks to man, 4×10^{-7} mrem per year. The risks to marine biota are reduced by the same ratio and will range from a high of 31 mrad per year to a mollusk (deep sea accident) to a low of 1.8×10^{-8} mrad per year to fish (coastal water, damaged cask accident).

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