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A Generic Assessment of Barge Transportation of Spent Nuclear Fuel

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A GENERIC ASSESSMENT OF BARGE TRANSPORTATION OF SPENT NUCLEAR FUEL

Prepared for the
Atomic Industrial Forum, Inc.

by

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PREFACE

The National Environmental Studies Project sponsored this investigation for the purpose of providing the nuclear power industry with information, data and methodologies needed to evaluate the transportation of spent reactor fuel by barge or barge-rail intermodal methods. Although the results of the study are generic in nature they are readily adaptable for site-specific analyses. Prior to this investigation, there was very little published by either the industry or government on transporting spent reactor fuel by intermodal/water means, even though relatively large body of literature addressed overland transport. It should be noted that while this study rather specifically treats the shipment of spent fuel from reactors to reprocessing plants (the investigation was started before the current Federal administration decided to indefinitely defer reprocessing), the results given in this report are equally applicable for the intermodal/water transport of spent fuel to interim or permanent storage facilities.

One of the primary reasons this study was funded was because there are over 100 reactors on navigable waterways and many of those are not serviced by rail. Stations may not have rail service because of the high cost of rail spurs from the site to existing rail lines or because of unsuitable soil conditions or rough terrain. This lack of rail service is an important consideration because Allied General Nuclear Services' reprocessing facility in Barnwell, SC was designed to receive essentially all shipments in large rail-casks, as opposed to truck; similarly, Exxon Nuclear's proposed plant at Oak Ridge, TN would rely on large rail-cask shipments. Moreover, large rail-size casks are not suitable for highway transit due to weight restrictions, and many utilities, which have assessed problems related to large vs. small casks, would agree that shipping in large casks is desirable.

This study addressed a wide range of topics, which include the operational methods, equipment requirements and availability, manpower requirements, regulations, radiological impacts and economics associated with several different barge routes and barge-rail intermodal mixes. However, the primary thrust was to estimate the probabilities of barge accidents under different conditions and severities and to evaluate the radiological consequences of such accidents. The contractor also estimated radiation doses to the public and personnel under normal operating conditions. These radiological analyses are the most original contributions presented in this report and they provide a compilation of some of the more obscure and difficult information and data (i.e., barge accident data and radionuclide source term estimates) that are necessary to perform an adequate radiological assessment of transporting spent reactor fuel by barge.

It is NESP's hope that the Departments of Energy and Transportation, the Nuclear Regulatory Commission, and utilities will find this generic investigation an important contribution to future site-specific evaluations of transporting spent fuel by intermodal/water means.

Philip Garrett
National Environmental Studies Project

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SUMMARY

Intermodal transportation of spent nuclear fuel between utility sites and receiving facilities is being considered by the utilities as a means of meeting spent fuel shipping requirements in the coming decades. This report is the culmination of a study sponsored by the Atomic Industrial Forum to determine the following:

- the extent to which intermodal transport is useful for access to utility sites
- the equipment and manpower requirements for spent fuel shipping campaigns
- the regulatory constraints on the configuration of equipment and procedures used for intermodal transport
- the impact, if any, of intermodal transport on radiation risk to the public from normal operations and accidents
- the cost of intermodal transport compared with other modes of transport

The following conclusions are drawn from this study:

- There are intermodal transport access routes for a majority of the utility sites with plants on line or expected to be on line by 1985. Approximately 90% of the sites with presently operating reactors, and 80% of the sites with reactors expected to be on line by 1985, have definable intermodal routes in which more than 90% of the mileage is waterborne.

- The equipment necessary to handle intermodal shipments of spent fuel is available today. More efficient transfer equipment designs can be developed if the volume of spent fuel shipped intermodally becomes significant. Extensive utilization of intermodal transport of spent fuel in the U.S. (40% of all spent fuel shipments) would require 25 to 30 tug-barge units, which would not overtax the presently available equipment.

- NRC and DOT regulations do not impose severe constraints on the equipment and procedures which can be used in intermodal transport. In particular, doses accumulated by the rigging and barge crews during intermodal transfer of full casks are within the guidelines for non-radiation worker classifications.

- The maximum individual dose received by an individual member of the public from normal intermodal transport operations is 1.9×10^{-3} mrem/R-yr, which is a factor of 4×10^{-6} smaller than the allowable dose from nuclear activities cited in 10CFR20.105.

- Risks to the public from intermodal or rail transport of spent fuel are comparable and small. If intermodal transport is used to remove spent fuel from a reactor, the risk to the public from radiation releases as a result of a spent fuel accident is estimated at approximately 1.2×10^{-6} man-rem per reactor-year. The risk associated with transport by rail only is 3.7×10^{-7} man-rem per reactor-year.

- Intermodal transport of spent nuclear fuel is more costly than either rail transport or transport by legal weight truck. The relatively high cost of intermodal transport is largely a result of high cask rental charges which accrue during long transit and transfer periods at the utility and receiving facility. The cost of intermodal transport should become more attractive as crews become increasingly familiar with the transfer operation and better transfer equipment designs come on line.

- Intermodal transport represents a viable alternative to rail and truck transport, especially for sites near navigable waterways which do not have rail service.

The report is divided into seven sections, each of which is summarized at its beginning for clarity. The contents of these sections are briefly described below.

- Section 1.0
  The scope of intermodal transport is assessed. Intermodal routes to utility sites, including those expected to be active by 1985, are mapped. Generalized routes which have features of a number of individual routes are formulated for use in the probabilistic risk assessment. Equipment requirements for extensive utilization of intermodal spent fuel transport are determined.

- Section 2.0

  A number of available and proposed intermodal transport systems are reviewed. Equipment designs are discussed, operational procedures detailed and labor requirements estimated.

- Section 3.0

  NRC and DOT regulations regarding intermodal transport of fuel are reviewed.

- Section 4.0

  Radiation doses to the barge and transfer crews from normal intermodal transport operations are evaluated. In addition, dose commitments to the public from waterborne transit of spent fuel are estimated and compared with NRC guidelines.

- Section 5.0

  An assessment is made of the probability of occurrence of intermodal transport accidents with potential radioactive releases. Fault trees are used to evaluate the probability of postulated releases.

- Section 6.0

  The consequences of potential radioactive releases resulting from postulated intermodal transport accidents are estimated in terms of dose to the public. In addition, probabilistic risk to the public due to intermodal transport is compared with the risk from other modes of spent fuel transport.

- Section 7.0

  The cost of spent fuel transport by intermodal transport, rail, and legal weight truck are compared.

1.0 SCOPE OF INTERMODAL TRANSPORT

1.1 Purpose and Summary

This section has two purposes. The first is to assess the utility of intermodal transportation of spent nuclear fuel between reactor sites and receiving facilities and to determine the number of sites for which intermodal routes are feasible. Intermodal transport, as used in this study, applies to the transport of spent nuclear fuel between the utility site and the receiving facility using a combination of barge and overland (rail or truck) conveyance.

The second is to define a feasible intermodal transport route between each reactor site and its closest receiving facility. Each intermodal route is defined by its important characteristics, including the waterborne distance, the overland distance,* and the makeup of the waterborne route. A set of eight generic routes is defined, each of which represents the important characteristics of a number of routes. These generic routes are utilized in later sections of the study to estimate public risk from intermodal transport and to evaluate the comparative economics of intermodal transport as opposed to strictly overland transport. Results of the scoping assessment are as follows:

a) Eighty-nine of the 111 reactor sites now operational or projected to be operational by 1985 can be serviced by intermodal transport for the removal of spent fuel.

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* Between the reactor site and its intermodal transfer point and between the receiving facility and its intermodal transfer point.

b) Fifty-five of the 62 reactor units operating in 1977 (nearly 90%) are serviceable by intermodal transport. By 1985, 153 of the 191 units* expected to be in operation (80%) will be serviceable by intermodal transport.

c) A set of eight generic routes, ranging in length from 100 to 1650 waterborne miles, describes the characteristics of all intermodal transport routes feasible by 1985.

d) The average waterborne portion for intermodal transport routes is 1300 miles one way. The average cycle could require approximately 34 days.

e) Extensive utilization of intermodal transport of spent fuel, i.e., servicing 40% of the reactors operating in 1985, would require the full time services of 25 tug-barge units. Up to 30 tug-barge units could be required if waterway conditions become markedly more crowded, substantially increasing lock waiting times.

1.2 Available Waterborne Routes

The three major kinds of waterways used for transporting goods in the United States are the rivers, the intracoastal waterways and the Great Lakes. These are shown in Figures 1.1, 1.2 and 1.3, respectively. Total

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* Information correct as of 1977 (see Appendix A).

Key to Figures 1.1 and 1.2 and Table 1.2

River Systems

1. Upper Mississippi
2. Lower Mississippi
3. Illinois River
4. Missouri River
5. Ohio River
6. Allegheny River
7. Monongahela River
8. Kanawha River
9. Green River
10. Cumberland River
11. Tennessee River
12. Arkansas River
13. Barkley Canal
14. New York State Barge Canal
15. Hudson River
16. Black Warrior River
17. Chattahoochee River
18. Coloosahatchee River System (Okochobee Waterway)

Intracoastal Routes

1. Gulf Intracoastal Waterway (West) (GIW)
2. Gulf Intracoastal Waterway (East) (GIW)
3. Port Allen-Morgan City cut-off
4. Atlantic Intracoastal Waterway (AIW)
5. Chesapeake Bay
6. Delaware River & Bay
7. Chesapeake & Delaware Canal
8. Atlantic Intracoastal Waterway* (Ocean Coastal) (AIW)
9. Atlantic Ocean Segment†
10. Gulf of Mexico Segment†

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* A semi-protected route still classifiable as intracoastal.

† An unprotected open ocean route usable by properly outfitted ocean-going equipment.

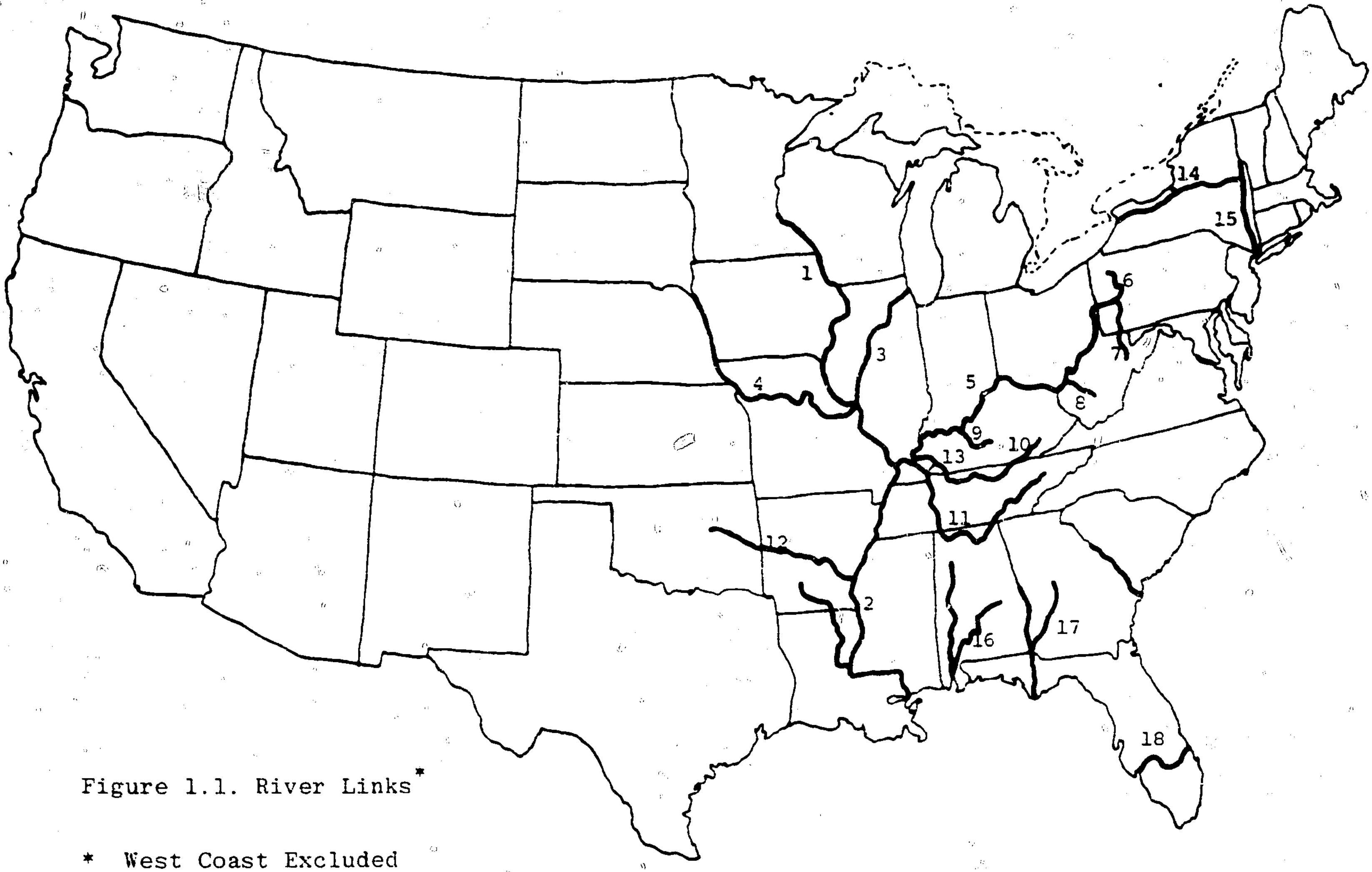

Figure 1.1. River Links*

* West Coast Excluded

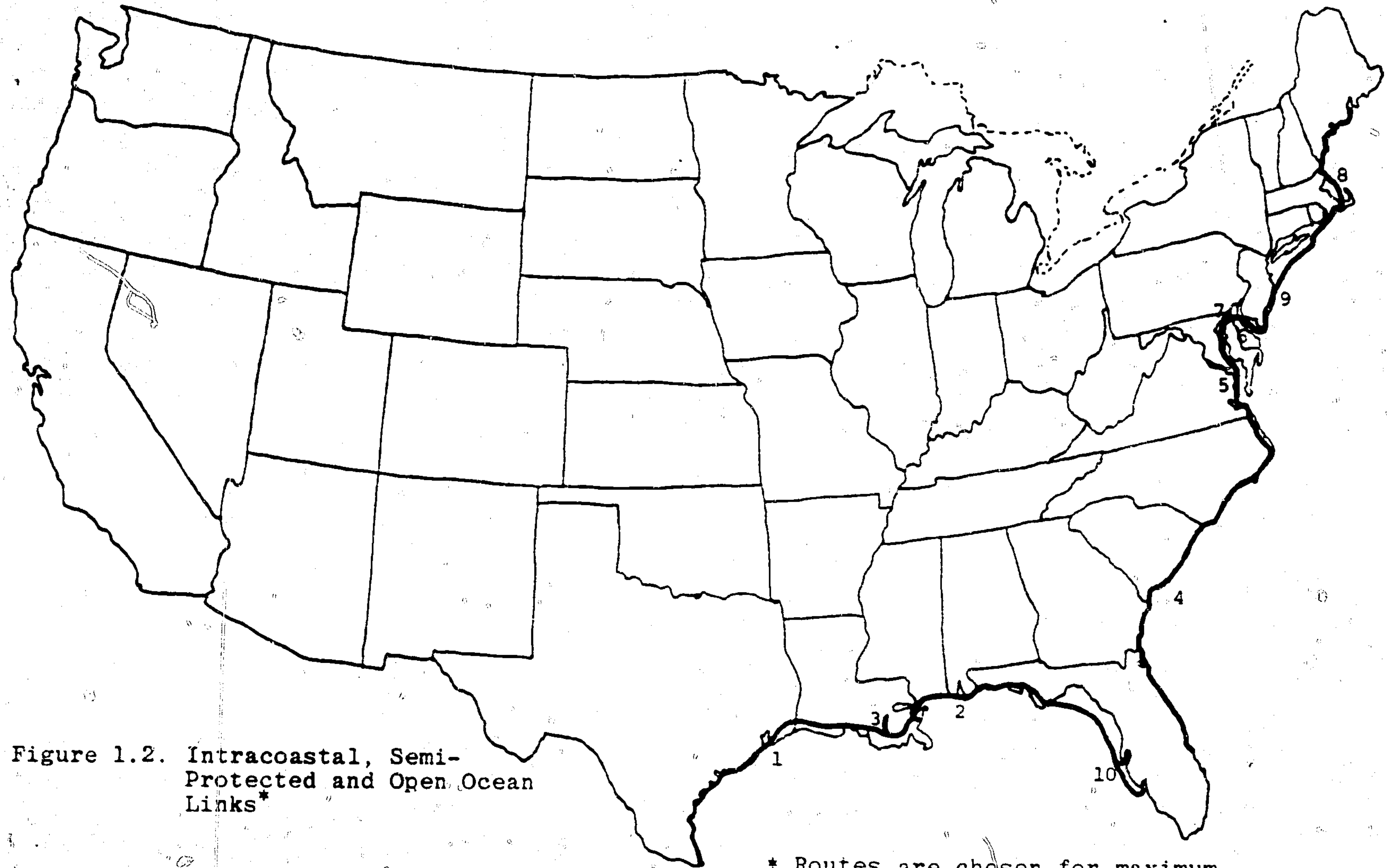

Figure 1.2. Intracoastal, Semi-Protected and Open Ocean Links*

* Routes are chosen for maximum protection enroute and do not preclude open ocean routes.

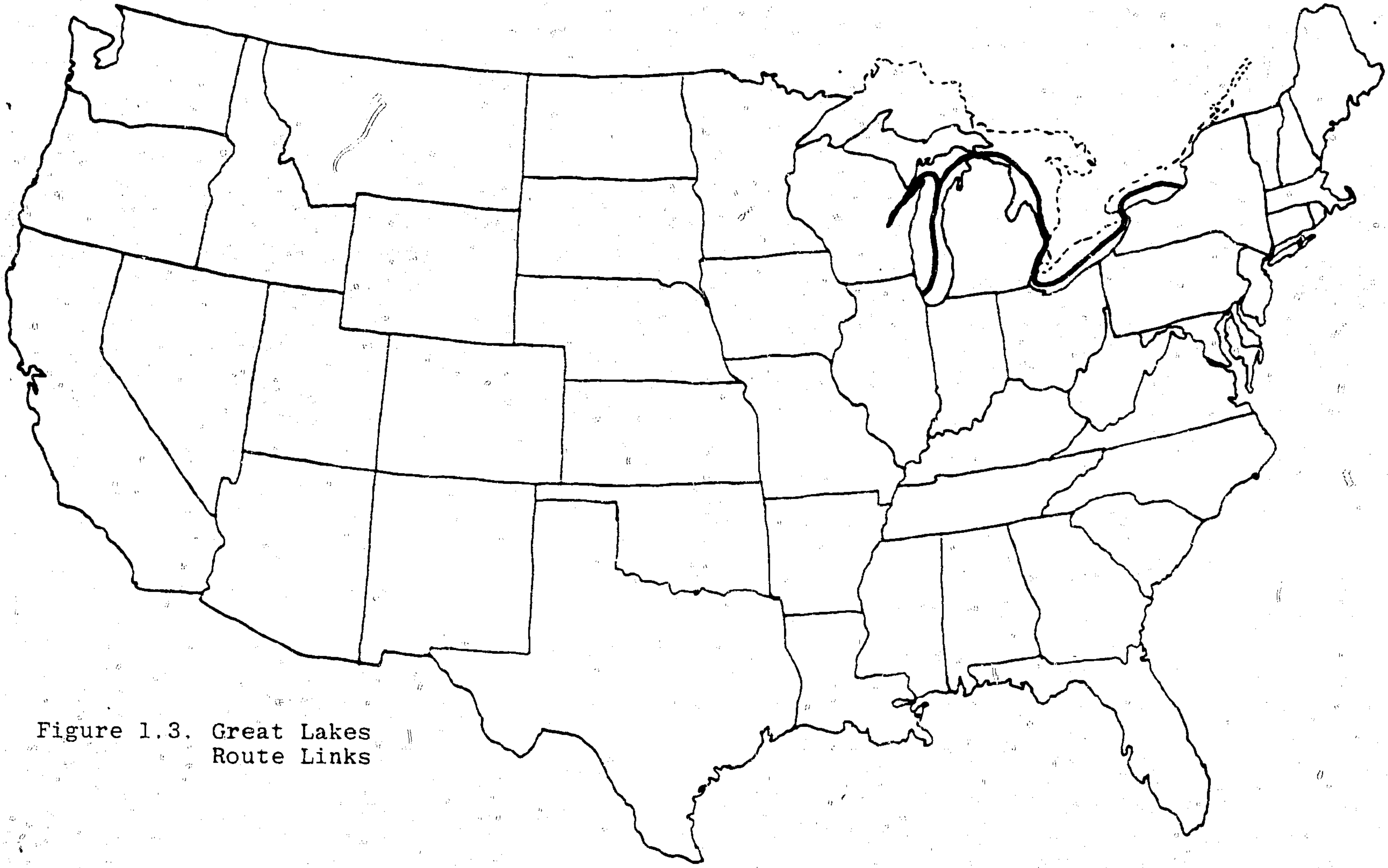

Figure 1.3. Great Lakes Route Links

mileage and the controlling depths of these routes, available from the literature, are presented in Tables A.1 and A.2 of Appendix A. The focus of this report is restricted to the portion of the U.S. east of the Rocky Mountains since the mountains are a barrier which makes intermodal shipment across them untenable without extensive rail links.

Semi-protected ocean segments (e.g., Bangor, Maine, to New York City) and open ocean segments (e.g., New York City to the mouth of the Delaware River) can be used as spent fuel transport routes if properly outfitted tug-barge units are available.* Shipment on different route links can be accomplished without changing barges, although tugs may be changed as needed to meet different navigational requirements. All waterways considered in this study are usable for spent fuel transport since all of them are open for an average of nine months out of the year and a single reactor shipping campaign can be completed in less than four months.

1.3 Definition of Intermodal Routes

In order to assess the utility of intermodal transport as a means of removing spent fuel from a reactor, the location of the reactor with respect to navigable water must be determined. Sites defined as serviceable by intermodal transport include one or more of the following:

a) direct access to a navigable waterway

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* Routes along the eastern coast are chosen for maximum protection. However, this does not preclude the use of fully open ocean routes in the future as integrated tug-barge units are used more extensively.

b) a short distance, i.e., less than 20 miles between the reactor site and an intermodal transfer point that is negotiable by heavy haul trucks *

c) a rail link between the reactor site and a suitable intermodal transfer point

All reactors which are operating, under construction, with construction licenses pending, or which are planned were considered in this study. A listing of all of these sites which tabulates their status and their access to a navigable waterway or rail link (determined from NRC licensing documentation and other sources) is given in Table A.3 of Appendix A.

Intermodal routes were defined for each reactor site less than 100 miles from navigable water and for which the overland distance on the route is less than 10% of the total trip distance. Definition of an intermodal route requires specific knowledge of:

a) the overland mileage between the reactor and the intermodal transfer point

b) the waterborne mileage on each water link

c) the overland mileage between the receiving facility and the intermodal transfer point

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* Heavy haul trucks are defined as units especially designed to haul large, cumbersome loads, such as railcar size spent fuel casks, over a variety of terrains, including public roadways (under permit).

The results of this definition process are given in Table A.4 of Appendix A. The receiving facility locations considered are in Barnwell, S.C. (B) and Oak Ridge, Tennessee (O).* A summary of these results are presented in Table 1.1. It shows that the majority of reactors on line or expected to be on line by 1985 have feasible intermodal transport routes. No intermodal routes are defined for sites on the Pacific Coast, sites not near navigable water, nor for sites for which the overland distance to and from water is greater than 10% of the total distance to the receiving facility.

Table 1.1. Summary - Scope of Intermodal Access

	No. of Operating Reactors 1977	No. of Operating Reactors 1985	No. of Reactor Sites 1985
Total	62	191	111
No. with Intermodal Access	55	153	89
Fraction Serviceable by Intermodal Transport	0.9	0.8	0.8
No. of Tug-Barge Units Required for Heavy Use Scenario	9	25 - 30	-

1.4 Definition of Generic Routes

Each intermodal route defined in Table A.4 (Appendix A) embodies some uncertainties in estimated rail distances to suitable embarkation points. Also, each route has other

* Routes to the Morris, Illinois facility were not defined in this study. However, the results of the study are considered applicable because of the expected similarity in average route lengths.

peculiarities, such as varying weather conditions, controlling depth variations, or marine traffic conditions, which render them to a certain extent unique. Detailed consideration of each route was not within the scope of this study. A set of generic routes derived from characteristics of the feasible intermodal routes and minimizing their peculiarities is compiled for use in the risk analysis models.

All generic routes can be identified by one or more of the following indicators:

a) mileage on major waterborne links

b) mileage on overland connections to a suitable intermodal transfer point

c) mileage in specific marine environments (such as where contact with major marine traffic is possible)

Seven generic routes are defined in Table 1.2 using the criteria above and the information in Table A.4 of Appendix A. The eighth generic route (No. 4 in Table 1.2) was not defined on the same bases as the other routes. This route represents an identified near-term real requirement for waterborne spent fuel transport, i.e., linking utility sites without suitable rail access to railheads at major ports. An intermodal transfer would be made at the major port and the remainder of the trip would be made by rail.

Table 1.2. Generic Intermodal Routes*

Generic Route Number	Receiving Facility*	# of Reactor Sites	Overland Distance From Reactor Site to Water	Waterborne Link Distance (Miles): Upper Mississippi System	Tennessee River System	Great Lakes	Lower Mississippi System	GIW	AIW South	AIW Middle	AIW North	Hudson & NY SBC	Atlantic Ocean		Overland Distance to Receiving Facility	Generic Route Description	Total Exposure Miles by Water	Number of Locks	Exposure to Major Shipping miles
1	O	15	7	619	652	376	-	-	-	-	-	-	-		4	Great Lakes to Chicago, Upper Mississippi System to Tennessee River. Tennesse River to Oakridge. Overland to Receiving Facility	1647	22	376
2	O	20	31	577	652	-	-	-	-	-	-	-	-		4	Upper Mississippi System (Mississippi, Ohio, Illinois, Cumberland) to Tennessee River. Tennessee River to Oakridge. Overland to Receiving Facility	1229	38	0
3	O	9	60	-	652	782	139	-	-	-	-	-	-		4	GIW to Closest Entry to Lower Mississippi System. Mississippi System to Tennessee River. Tennessee River to Oakridge. Overland to Receiving Facility	1573	30	300
4	O	12	0-10	-	-	-	-	-	-	110	-	-	-		450	AIW South to Portsmouth, VA. Overland to Receiving Facility	110	0	110
5	B	10	26	-	-	13	-	-	735	326	180	224	-		15	Great Lakes to New York State Barge Canal, Canal to Hudson River to New York City. AIW to Savannah River Savannah River to Barnwell. Overland to Receiving Facility	1478	25	550
6	B	9	0	-	-	-	-	-	735	326	180	-	228		15	Atlantic Ocean South to New York City AIW to Savannah River. Savannah River to Barnwell. Overland to Receiving Facility	1469	0	800
7	B	16	26	-	-	-	-	-	735	233	20	-	-		15	AIW South to Savannah River. Savannah River to Barnwell. Overland to Receiving Facility	908	0	275
8	B	7	8	-	-	-	-	-	684	-	-	-	-		15	AIW North to Savannah River. Savannah River to Barnwell. Overland Overland to Receiving Facility	684	5	300

* See page 1-3 for key to table.

1.5 Equipment Requirements for Extensive Utilization of Spent Fuel Shipment by Barge

An intermodal shipment of spent fuel from a single reactor site requires the use of a tug, a barge, and various pieces of transfer equipment (see Section 2.0). Given this information, the quantity of equipment needed for large-scale implementation of intermodal spent fuel transport in the U.S. was calculated.

First, a weighted average which considered route distances and number of reactor sites on a route was taken across the eight generic routes to approximate a single "typical route". Characteristics of the typical route, including a breakdown of overall trip time, are given in Table 1.3. Since an average waterborne trip both ways takes 34 days, a single tug-barge unit could complete ten trips a year.

The number of barge trips required per reactor per year to remove spent fuel can be determined by considering present generation core sizes and cask capacities. An average 1000 MWe PWR has 193 fuel assemblies of which one-third, or 65, are removed yearly. The largest rail car size casks presently available hold 7-12 PWR fuel assemblies, or an average of 10. With 2 casks per barge, an average of 3.25 trips would be required yearly per PWR to remove its spent fuel.

Although 80% of all operating reactor sites in 1985 will have feasible intermodal routes, it is unlikely that intermodal transport will be used for all of them for a variety of reasons, including cost. In a heavy use scenario,

Table 1.3. Characteristics of the Typical Intermodal Route [h]

Waterborne Distance One Way (mi)	1311
Overland Distance One Way (mi)	33
Locks[a]	
- Distance Between Locks[b] (mi)	55
- Avg. Lock Waiting Time (hr)	3
- Max. Lock Waiting Time (hr)	6
Trip Time[c] Contributors	
- Traveling Time[d] (days)	16
- Total Lock Waiting Time[e] (avg) (days)	6
- Total Lock Waiting Time[f] (max) (days)	12
- Total Turnaround Time[g] (days)	12
Average Round Trip Time (days)	34 (10 trips/ barge-yr)[i]
Maximum Round Trip Time (days)	40 (8.5 trips/ barge-yr)[i]

(a) Only on river trips.

(b) An average of 38 mi. on Upper Mississippi and 72 mi. on the Tennessee River

(c) All estimates for round trips

(d) Using barge speed of 7 mph (from Section 7.0)

(d) From reference A.1

(f) From reference A.1 with all locking operations taking a maximum time

(g) Average of all turnaround methods considered (from Section 7.0)

(h) All tabulated data is for one-way transport unless otherwise indicated.

(i) Does not consider tug-barge unit maintenance outages and other procedural delays perhaps half of these sites (40% of all reactor sites) would use intermodal transport methods. If 40% of the 191 anticipated reactors require 3.25 two-way trips per year to remove their spent fuel and a single tug-barge unit can complete 10 trips a year,* then a total of 25 tug-barge units would be required to implement national usage of intermodal transport. Nine barge-tows would be required to service a similar percentage of reactors in 1977.

Should the amount of traffic on the waterways significantly increase by 1985, six days might be added to the two-way trip time, as shown in Table 1.3 (maximum lock-waiting time). In this case, a single tug-barge unit could complete 8.5 trips a year, and 30 tug-barge units would be required for large-scale implementation of intermodal transport.

* does not consider tug-barge unit maintenance outages and other possible operational delays

2.0 INTERMODAL TRANSPORT SYSTEMS

2.1 Purpose and Summary

A variety of transport system designs are currently being considered for transport of spent nuclear fuel by water. These designs utilize equipment ranging from readily available barge and rigging equipment to equipment specifically designed for intermodal spent fuel transport. The purpose of this section is to provide operational descriptions of several of these candidate intermodal transport systems and their equipment and man-power requirements. A summary of the attributes of several different systems is given below.

It is recognized that the man-power requirements discussed below for intermodal transfer are conservative and represent an upper limit on exposure for occupational dose calculations.

Available Barge and Tug Equipment

Available equipment (AE) systems suitable for carrying railcar size spent fuel casks* make use of existing barge and tow equipment. An identified near term need for intermodal transport using AE barge-tow systems is to provide a link between utilities with no rail access and railheads at major

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* The NL Industries' 10/24 and GE IF 300 casks currently licensed, along with the TN 12 cask soon to be introduced in this country, are the major railcar size casks of interest. The GE IF 300 "wet" cask uses water as a coolant for the spent fuel elements while the NLI 10/24 and TN 12 "dry" casks utilize helium and air respectively as a coolant.

ports. By using waterborne access at the utility site, rail size casks can be used for spent fuel shipping. The increased capacity of rail casks over legal weight truck casks would allow a reduction in total campaign time. Two types of cask transfer methods, both of which utilize the roll-on/roll-off principle,* were considered in this study.

a) Heavy Haul Truck (HHT) Method

Trucks are removed from the railcars forming a cask-pallet which is transferred to rubber tired dollies. An HHT then pulls the cask-pallet onto and off of the barge.

b) Floating Bridge (FB) Method

The wheels are left on the railcar, and a yard engine transfers the railcar over a floating railroad bridge span connecting the barge and the railhead.

The HHT method has two advantages: low capital cost and use of commonly available equipment. Its disadvantages include longer transfer time and higher personnel radiation doses. The FB method has the opposite set of advantages and disadvantages: faster transfer time and lower personnel radiation doses, but a higher capital cost.

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* Roll-on/roll-off refers to the fact that casks are transferred to and from barges on wheels without benefit of cranes.

Specially Designed Barge and Tow Equipment

A significant increase in the operational efficiency of intermodal transport can be achieved if equipment is used which is specifically designed for the needs of waterborne transport and intermodal transfer between rail and water. Special equipment for use in various phases of the intermodal trip has been currently designed.

One concept is an integrated tug-barge (IBT) unit which would provide greater flexibility of operation. Through the use of specially designed barges, an IBT can carry up to four rail size casks and can utilize simple loading facilities.

A second concept is a specially designed HHT featuring a gooseneck arrangement and rear dollies which form an integrated trailer with the cask-pallet. These gooseneck trucks would reduce transfer handling time.

2.2 Barge-Tow System Descriptions

2.2.1 Available Equipment (AE) Barge-Tow Systems

An AE tug-barge system used to transport spent fuel will consist of a single barge and a tugboat to provide motive power (Figure 2.1). The tugboat can be used to either push or pull barges. For extended waterborne journeys, several different tugs may be used. For example, a trip from Lake Michigan to Oak Ridge, Tennessee would involve transit on Lake Michigan, on canals through Chicago, and on the

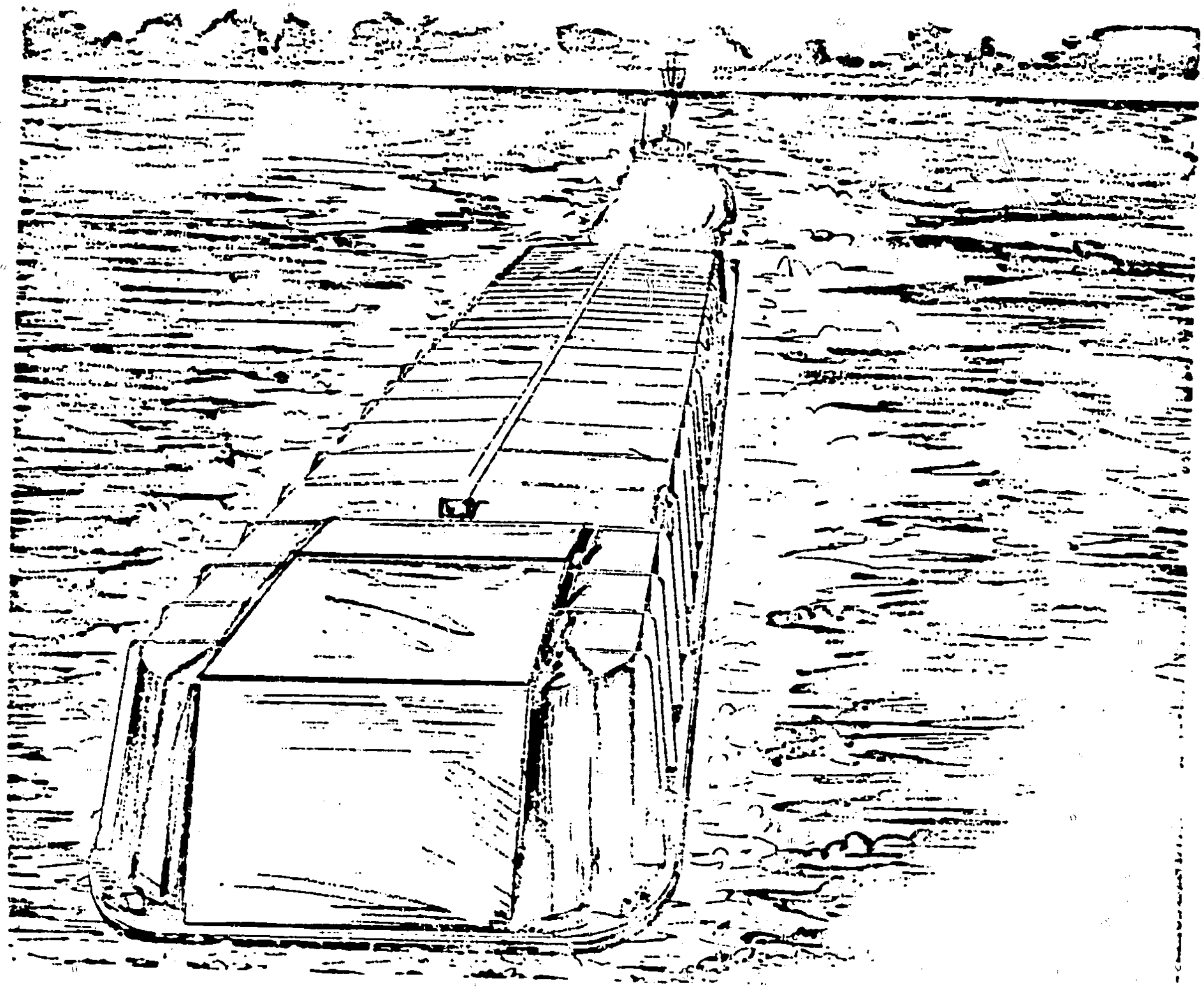

Figure 2.1. Tug Boat Configuration with Barges Being Pushed

Illinois, Mississippi, and Tennessee River links. The most appropriate unit for the lake transit would be the open water tug, which can push or pull the barge unit. Transit through Chicago requires a tug with a special telescoping bridge that allows passage under a number of low bridges on the Chicago River. A standard tug can be used for the remainder of the journey. Tugs with a draft of 9 feet are acceptable in most intracoastal waterways and river systems. However, some inland water links may require the use of a tug with a draft of considerably less than 9 feet. Note that the same barge is used throughout the entire journey, and it therefore must be appropriate for all types of water conditions encountered.

The barges used in spent fuel transport must be seaworthy in the most demanding environment anticipated for the waterborne portion of the journey. The requirements for tug-barge system construction, operation and navigational equipment are covered in the Draft ANSI 552 Guide.

2.2.2 Integrated Tug-Barge Systems

Ordinarily, tugs push barges in open water and are anchored to the barge by hausers or chains. Current operating procedures for rough weather require that the tug pull the barge on a tow line, but this method is highly vulnerable to the loss of a barge in open water. Current designs ameliorate this problem without introducing the maintenance problems and costs associated with single unit transport ships.

A number of designs have been developed for linking special barges and tugs to provide a broad range of services not previously considered possible with barge-tug combinations. One design calls for an ordinary tug and a specially notched barge as shown in Figure 2.2 (from Reference 2-1), which would allow some rough weather capability. A second design utilizing a semi-rigid or rigid link between a special tug and a special barge is shown in Figure 2.3 (from Reference 2-2). The tug used in this design is similar to an ordinary tug except for the shape of its hull and the addition of semi-rigid linking mechanisms.

The barge used in either of these designs is a special purpose vessel having a capacity of at least four casks (capacity greater than 1000 DWT) and its own transfer equipment for loading and unloading at primitive transfer facilities.

2.3 Intermodal Transfer Description

2.3.1 Transfer Techniques

All AE intermodal transfer techniques analyzed in this study utilize the roll-on/roll-off transfer concept and avoid the use of heavy duty cranes.

The simplest method of intermodal transfer, as described in Reference 2-3 uses the current generation of casks, a set of dollies, and a large tractor (or truck) which would normally be used for moving heavy equipment. The casks, with all their support equipment and all personnel shields needed to comply with regulatory radiation dose limitations, would be mounted on railcars. Thus, when its trucks are removed, the railcar becomes a complete, self-sustaining cask-pallet.

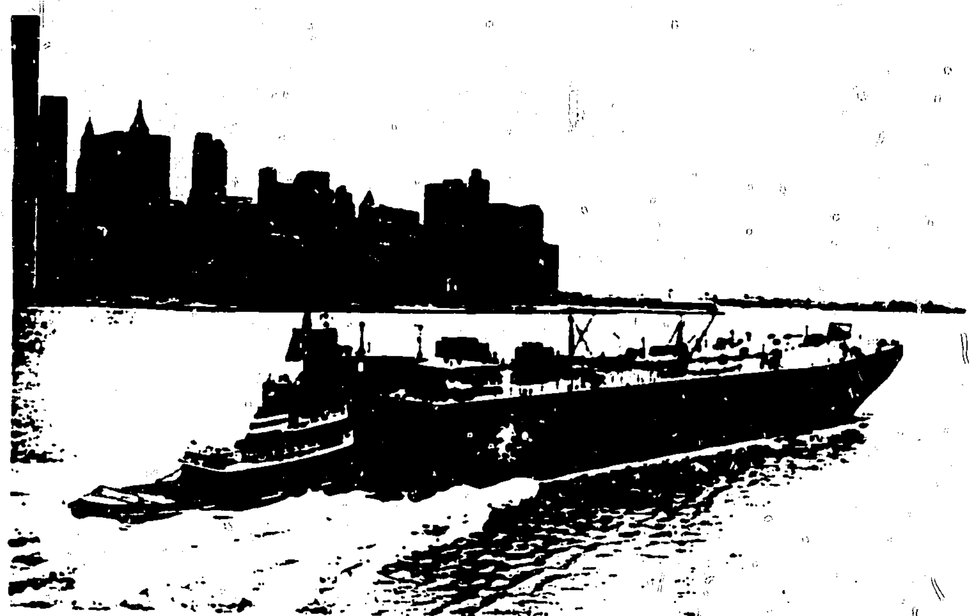

Figure 2.2. Tugboat Configuration with Barge

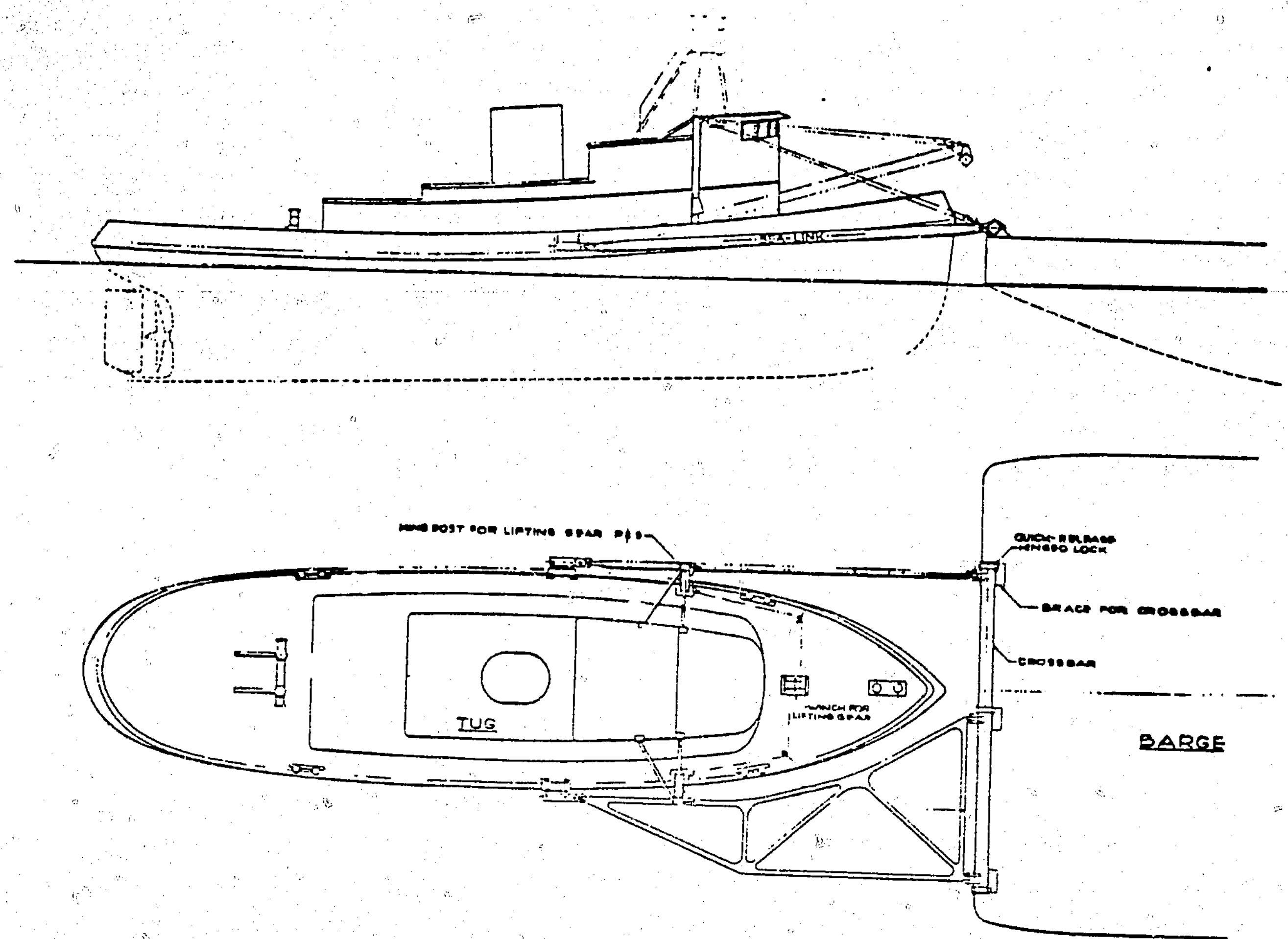

Figure 2.3. Two Cask Arrangement on a Class I Carfloat Type Barge

There are two methods for transferring the cask-pallet to the barge: a) remove the railcar trucks, replace them with rubber tires, and haul the cask-pallet onto the barge with an HHT (Figure 2.4); or b) leave the railcar intact, connect the barge and the railhead with a special, floating rail transfer bridge, and push the cask-pallet onto the barge with a yard engine (Figure 2.5). The first method is hereafter referred to as HHT (Heavy Haul Truck) and the second is referred to as FB (Floating Bridge).

As is pointed out in Reference 2-4, the FB method can accomodate significant changes in water level, and it stabilizes and secures the barge with respect to weight movements during the transfer.

HHT Transfer Equipment and Personnel Requirements

Equipment requirements for HHT transfer are as follows:

a) two special railcar units

b) several sets of hydraulic jacks and cribbing material

c) two sets of front and rear, multi-wheeled, heavy duty, steerable, rubber tired dollies with rated capacities in excess of 150 tons

d) one heavy haul truck capable of at least 50,000 lbs. force of drawbar pull

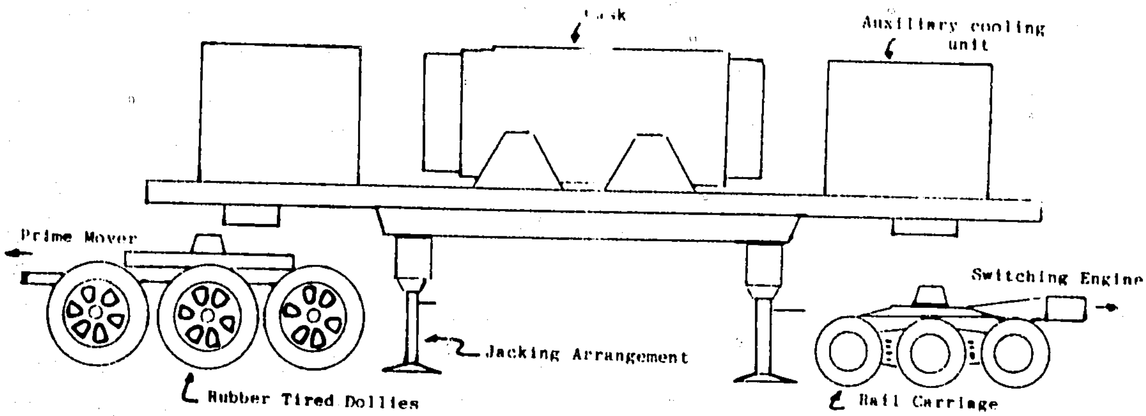

Figure 2.4. HHT Roll-On/Roll-Off Transferral Process

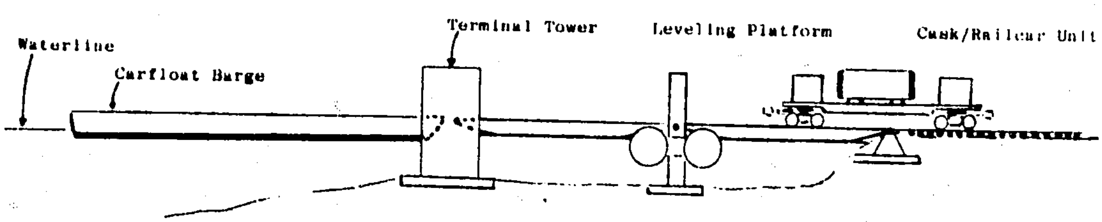

Figure 2.5. Floating Bridge Roll-On/Roll-Off Transferral Process

e) one barge slip with a rail siding at each end of the waterborne portion of the journey

f) one yard engine to move the railcar units and their trucks

g) one flatbed barge and tug

As discussed above, the NLI 10/24 cask and the IF 300 cask arrive by rail at the transfer point mounted with their support equipment on a single railcar. A complete railcar unit includes the cask, integral cask support, expansion tanks, heat exchange equipment, and a personnel shield (Figure 2.6). The cars measure 54' to 59' in length by 10' in width and weigh 150 to 170 tons with a full cask (NL 10/24). Jack beams are attached across the bottom of the railcar to avoid problems in jack placement and weight balance during loading and unloading.

Personnel requirements for HHT loading and unloading include the following at each end of the waterborne leg of the journey:

a) one nine-man loading/unloading crew consisting of seven workers, one foreman and one superintendent (Multiple shifts can be used to provide faster overall transfer time.)

b) one boat crew of two or three workers who stay with the tow and barge at all times

c) two health physics personnel to monitor radiation

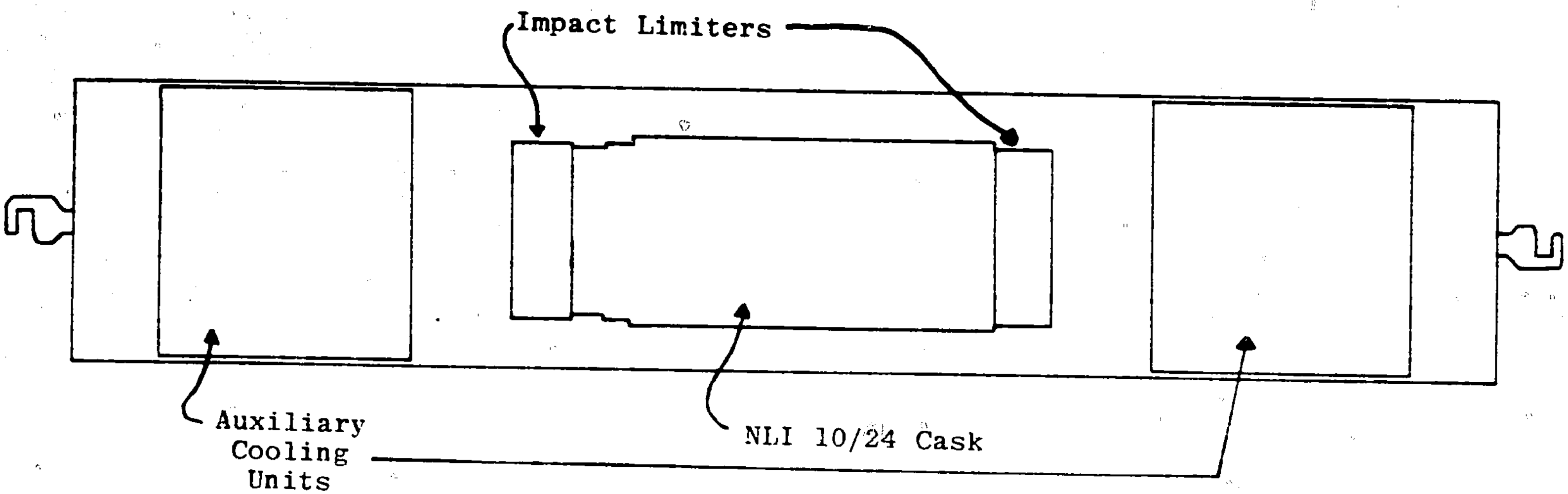

Figure 2.6. Top View of Integrated Cask and Rail Car Unit NLI 10/24 Spent Fuel Shipping Cask

d) one three-man train crew of one engineer, one foreman, and one brakeman to move railcars as necessary

The above personnel requirements are predicated on the assumption that exposure of the workmen can be kept below the level which requires the classification of personnel as radiation workers. The use of non-radiation workers removes a number of procedural delays and eliminates added costs for backup crews, special suiting, and reporting procedures. Health physics personnel will provide administrative control to insure compliance with regulatory dose limits for personnel.

FB Transfer Equipment and Personnel Requirements

Equipment requirements for FB transfer for each IMP are as follows:

a) two special railcar units

b) one floating rail transfer bridge

c) one yard engine

d) one barge slip with a proper railhead

e) one empty railcar used for spacing (if necessary)

f) one carfloat barge and tow

Personnel requirements for direct loading and unloading include at each end of the waterborne leg:

a) one three-man crew to operate the FB span

b) one boat crew of two or three men for the tow and barge

c) one three-man train crew

d) one health physics representative

Since radiation exposure is a function of the time spent at a given distance from the cask surface, it will be less for the FB method than for the HHT method because the close-in time needed in the HHT method for jacking operations and securing of the casks to dollies is eliminated in the FB method. The health physics function is similar to that for the HHT process but is not as stringent.

2.3.2 AE Transfer Procedures

In an HHT transfer of a full cask the following steps occur in sequential order upon receipt of the special railcar at the rail siding:

a) The railcar is positioned at the end of the docking facility by the train crew.

b) An inspection is made of the railcar and its load by health physics personnel to ascertain cask integrity prior to loading.

c) The HHT hauling vehicle and dollies are assembled.

d) The jacking system is inserted beneath the railcar; the railcar is jacked from its trucks, and the trucks are removed.

e) The dollies are placed under the railcar which is then lowered into place and secured.

f) The barge is secured in its slip, and a transfer ramp is installed.

g) The hauling vehicle is used to move the cask and dollies onto the barge, after which the cask is removed from the dollies and secured. The barge is trimmed as necessary to insure load stability during this time.

h) The load is reinspected by health physics personnel for cask integrity and the tie-downs are inspected by the barge crew prior to acceptance of the shipment by the tow operators.

The entire process is repeated for the loading of a second cask, and, with minor differences, the same procedure is followed in reverse for cask unloading.

In an FB transfer, the following occur in sequential order upon receipt of the special railcar at the rail siding:

a) The railcar is positioned at the end of the floating rail transfer bridge by the train crew.

b) The railcar and its load are inspected by health physics personnel.

c) The barge is positioned in its slip and trimmed to level in front of bridge span.

d) The span is adjusted to be level with respect to barge deck.

e) The railcar is rolled onto the barge by the yard engine while the barge is trimmed as necessary to insure load stability.

f) The railcar is secured using chocks and tiedowns. The load is reinspected by health physics personnel and the tiedowns are inspected by the tow operator prior to acceptance of the shipment.

2.3.3 Advanced System Transfer Procedures

Cask transfer procedures in the advanced system are similar to those for the AE system. The casks are transferred using a roll-on/roll-off technique. The required equipment consists mainly of specialized rubber-tired trucks with several design features to avoid the need of jacking operations during loading and unloading.

Cask palleting is slightly different than that for the AE system. The cask and pallet no longer form an integral railcar unit. The pallet is such that, with the cask mounted, it forms a unit which can be directly picked up by a "gooseneck" arrangement of a specially designed HHT (Figure 2.7), avoiding the need for rigging equipment such as jacks and cribbing. Therefore, if transfer is made to or from railcars, the cask and pallet are hauled onto a heavy duty railcar by the HHT, set down, and secured. Alternatively, the cask may be placed on the railcar using a crane with a capacity of 170 tons. The HHT "gooseneck" unit stays on the barge and it is used at both ends of the journey (Figure 2.8).

Four casks may be carried by the IBT system with the casks arranged in a balanced cluster on the barge deck.

Crews required for the IBT transfer process are smaller than those required for the AE HHT process since the rigging crew is much smaller and no train crew is necessary.

2.4 Procedures and Operation During Waterborne Transit

In-transit procedures vary with the type of water environment to which the barge and tow are exposed. While no inspection is required during transit, one member of the boat crew should be designated to verify the integrity of the radioactive cargo by package checks

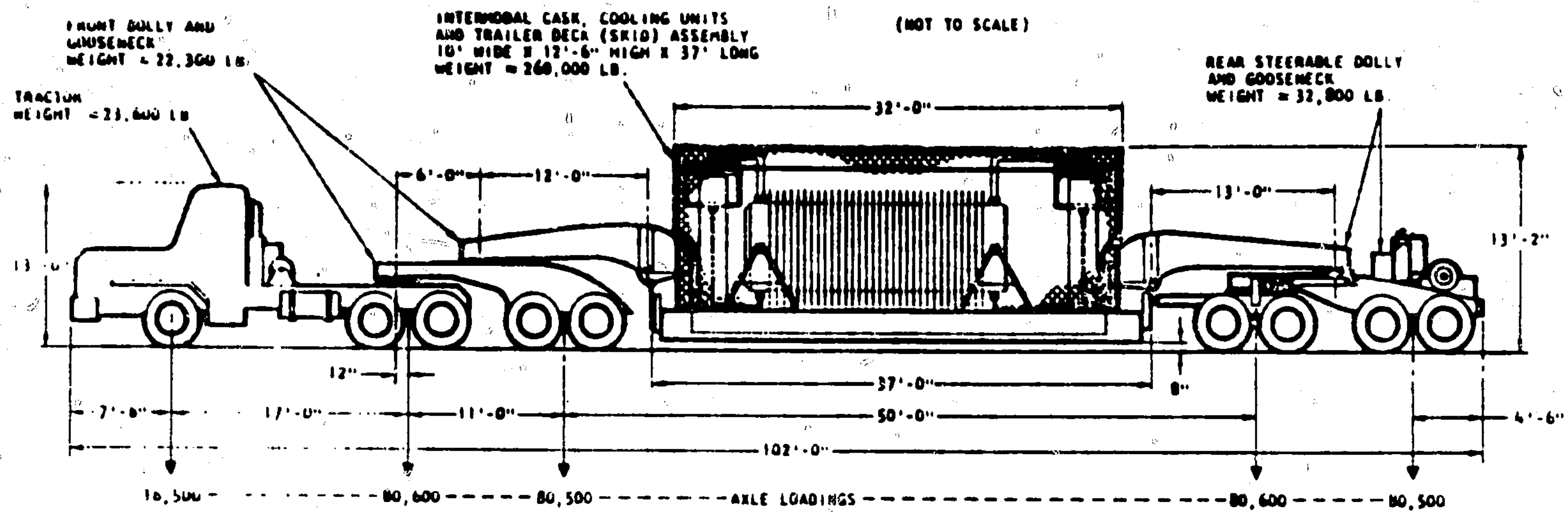

Figure 2.7. Intermodal Transport of NL 10/24 Cask Using Skid With Gooseneck Attached

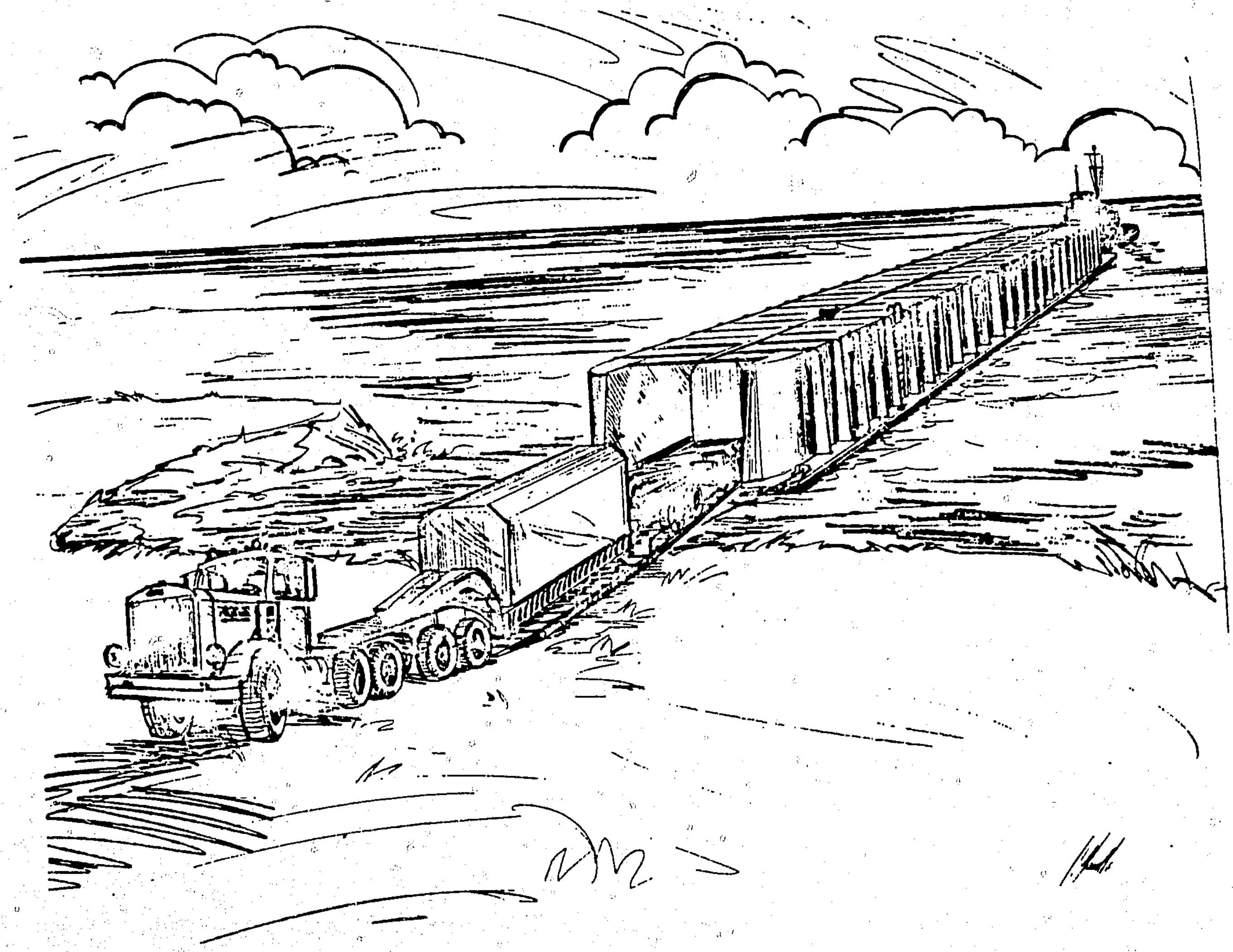

Figure 2.8. Illustration of Cask Removal from Barge Using Gooseneck Unit

Communication with appropriate shore based stations regarding the status of the radioactive cargo is required periodically. Delays and estimates of delay times would be reported to allow for the placing of crews at the debarkation points. Mishaps of a serious nature would be reported immediately to the nearest NRC office and to the Coast Guard. If docking is to be made at a port from open water or intra-coastal water, the captain of the port would be notified in advance of docking so that he can be prepared to inspect the cargo and ascertain its integrity on arrival. Some advanced tug-barge systems can operate in open water under poor weather conditions, but all AE barge systems operating in open water are limited to normal sea state conditions.

REFERENCES

2-1. Allied Gulf Nuclear Services, "Barge for Transportation of Spent Nuclear Fuel," Preliminary Design Drawing, August 1971.

2-2. R.W. Peterson et al, "Current Status and Future Considerations For A Transportation System For Spent Fuel and Radioactive Waste," AGNS Report Y/OWI/SUB-77/42513.

2-3. Williams Crane and Rigging, "Feasibility Study, Spent Fuel Removal, Surry Nuclear Power Station, Virginia Electric Power Co.," Report to AGNS, March 1975.

2-4. E.J. Bourgeois, Letter and Drawing Transmittal to A.J. Unione, February 1977.

3.0 RULES AND REGULATIONS

This section presents an overview of the regulations affecting packaging and intermodal transportation of spent nuclear fuel. Regulations considered include those of the Nuclear Regulatory Commission (NRC), Department of Transportation (DOT) and Coast Guard. Coast Guard regulations are administered by the Materials Transportation Bureau. The subject material is very extensive and reference to the source documents is recommended.

3.1 Background

There are four basic safety requirements(3-1) which must be met when transporting radioactive materials:

a) Adequate containment of the radioactive material
b) Adequate shielding of the radiation emitted by the material
c) Safe dissipation of heat generated in the spent fuel
d) Prevention of nuclear criticality, i.e., the prevention of the accumulation of enough fissile material in one location to result in a nuclear chain reaction

The first three requirements may be summarized as generalized containment. The last item and, to some extent, item c are related to maintaining the integrity of the containment.

The adequacy of the regulations is not addressed here. Rather the adequacy of the regulatory framework is assumed, and only its requirements are identified.

The International Atomic Energy Agency (IAEA) published the first codified regulations regarding the safe transport of radioactive material in 1961.(3-2) These served as a format for structuring U.S. regulations for which the responsible agencies and departments are the NRC, DOT, Coast Guard, and Postal Service. International shipment must be consistent with IAEA standards, and the DOT serves as the U.S. "competent authority" for this interface.

NRC regulations are contained in the various chapters of Title 10 of the Code of Federal Regulations (10CFR). These deal with licenses for accepting or possessing radioactive material. Non-exempt material* may be transferred in approved containers only between licensees. 10CFR20 deals with standards for radiation protection, 10CFR70 with special nuclear material, 10CFR71 with packaging of radioactive material for transport and the transportation thereof, and 10CFR73 with physical protection of plants and material including material in transit.

DOT packaged transportation regulations are contained in various chapters of Title 49 of the Code of Federal Regulations (49CFR). Labelling, marking, and placarding requirements are specified in part 172. Part

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* Material which cannot be shipped through the mails.

173 contains general shipping and packaging requirements for all modes of transportation. Part 174 is devoted to specific, additional rail requirements, part 175 to aircraft requirements, part 176 to marine vessels, and part 177 to motor vehicles.

Various states*, through formal agreement with NRC, have regulatory authority over byproduct material, source material, and special nuclear material in less than critical quantities. The rules adopted by these states are consistent with DOT and NRC requirements for interstate shipping of radioactive materials.

The branch of the DOT which administers the majority of the transportation regulations concerned with safety in the transportation of radioactive and other hazardous materials is the Office of Hazardous Materials Operations (which is part of the MTB). Through a Memorandum of Understanding between DOT and NRC, rules and regulations of the two agencies are framed to be complementary and avoid duplication.

In addition to these regulations, there is an American National Standards Institute (ANSI) Draft Guide on the water transportation of irradiated nuclear fuel.[3-3] In the following discussion, reference will be made to Federal regulations and occasionally to the ANSI Draft Guide.

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* Alabama, Arizona, Arkansas, California, Colorado, Florida, Georgia, Idaho, Kansas, Kentucky, Louisiana, Maryland, Mississippi, Nebraska, Nevada, New Hampshire, New Mexico, New York, North Carolina, North Dakota, Oregon, South Carolina, Tennessee, Texas, and Washington.

3.2 Discussion of the Four Requirements of Transportation

3.2.1 Containment

Requirements for Type B and 'Large Quantity' package standards are given in 10CFR71 subpart C, and accident conditions are given in 10CFR71 Appendix B. The corresponding DOT requirements appear in 49CFR173.393 and 49CFR173.398 (c).

The package standards permit no significant chemical, galvanic or other reaction between components or components and contents. Packages will be equipped with positive closure tie-down devices capable of withstanding a force 10 times the weight of the package in the direction of vehicle motion, 2 times the package weight in the vertical direction and 5 times the package weight in the transverse direction.* A tie-down must be designed such that its failure would not impair the ability of the package to meet other requirements. The package shall be capable of withstanding five times its normal weight when supported by the ends as a simple beam. The package shall withstand an extreme pressure of 25 psig with no loss of contents.

Accidents must not affect the shielding such that the dose rate 3 feet from the package exceeds 1000 mrem/hr. In addition, they shall not result in releases, except for gases and contaminated coolant, that exceed 0.01 Ci Group I radionuclides, 0.5 Ci Group II, 10 Ci Group III and IV and

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* The Draft ANSI Guide[3-3] (pg. 22) specifies 1.5 g loading in any horizontal direction for tie-downs between package and hull structure.

1.0 Ci inert gases (10CFR71 subpart C and Appendix C). Packages must remain subcritical under accident conditions.

The test conditions which these criteria must satisfy sequentially are: a 30 ft free drop onto an unyielding surface, impacting in the manner that causes maximum damage; a 40 inch free drop onto a vertically oriented steel probe eight or more inches high and six inches in diameter that has a flat horizontal top and rounded edges with a radius of curvature of 0.25 inch or less; a 30 minute, 1475°F fire with emissivity 0.9, a package absorptivity of 0.8, and no artificial cooling; and water immersion to a depth of 3 feet for more than 8 hours. Compliance can be shown by tests or other assessments on sample packages or scale models (10CFR71.34(2)).

3.2.2 Radiation Shielding

49CFR173.393(i) requires that the radiation level at the surface of the package must not exceed 200 mrem/hr on contact nor have a TI exceeding 10 (10 mrem/hr at 3 ft).* The specified normal dose rates for shipment in exclusive use vehicles 49CFR173.393(j) are 1000 mrem/hr at 3 ft from the external surface of the package, 200 mrem/hr at any point on the external surface of the car or vehicle (closed transport vehicle only), and 10 mrem/hr at any point 6 ft from the vertical planes projected by the outer lateral surface of the car or vehicle. If open transport is used, the stipulation is 10 mrem/hr at any point 6 ft from the vertical planes projected from the outer edge of the vehicle.

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* For further details see 49CFR173.389(i).

Another specification is that the dose-rate in any normally occupied point in the car or vehicle does not exceed 2 mrem/hr. For carrying radioactive material by vessel, 49CFR176.700(e) specifies that a person may not remain unnecessarily in a hold or compartment in the immediate vicinity of a package containing radioactive material, nor exceed a 7-day whole-body dose of 100 mrem nor more than 500 mrem whole-body dose per year. The radiation level in an area continuously occupied by people or animals must not exceed 0.5 mrem/hr. All special instructions with regard to the shipment must be given to the person in charge of the vessel, and the aggregate transportation index of any group packages must not exceed 50 nor shall the TI for the loaded vessel exceed 200.

3.2.3 Dissipation of Heat

49CFR173.393(c)(2) requires that the maximum accessible package temperature be less than 122°F (ANSI[(3-3)] indicates 130°F) in the shade, fully loaded with still air and ambient temperature (when in thermal equilibrium). If the package is a sole use shipment, the maximum accessible external surface temperature must not exceed 180°F.

3.2.4 Criticality Control

10CFR171.33 requires that a package be designed and constructed, such that the most reactive contents it could carry would remain subcritical under the most severe accident conditions.

Packages used for shipping fissile materials are divided into Classes I, II and III. Fissile Class I places no restrictions on the number of such packages transported on a vehicle. Fissile Class II limits the number of packages that can be shipped. Fissile Class III requires special arrangements between the shipper and carrier to provide nuclear criticality safety.

49CFR172.310 and 49CFR173.403 define requirements for placarding and marking of radioactive packages being shipped.

49CFR176 subpart M provides detailed requirements for the stowage of radioactive material on vessels. Subpart M consists of 49CFR176.700 - general stowage requirements, 49CFR176.710 - care following leakage of radioactive materials, and 49CFR176.715 - contamination control (namely the affected area cannot be reused until the dose rate from an accessible surface is reduced to less than 0.5 mrem/hr).

49CFR176.83 presents the separation requirements from other radioactive and hazardous materials. These are complicated requirements and will not be condensed here. Similarly, 49CFR176.99 provides a table indicating the types of barges that may carry radioactive material.

46CFR42.40 defines freeboard requirements for Type A and B vessels (which includes barges). Vessel stability requirements are presented in 46CFR93.70-10. Reference should also be made to the Draft ANSI Guide[3-3] pg. 18-21.

REFERENCES

3-1 A. Fairbarn, "The Development of the IAEA Regulations for the Safe Transport of Radioactive Materials," Atomic Energy Review, Vol. 11, No. 4, 1973.

3-2 IAEA, "Regulations for the Safe Transport of Radioactive Materials," Safety Series No. 6, Revised Edition, 1973.

3-3 American National Standards Institute, Subcommittee N552, "Draft Proposed Guide for Water Transportation of Irradiated Nuclear Fuel," ANSI N-14, ANS N552, Draft #3, October 1976.

4.0 RADIATION EXPOSURE FROM NORMAL OPERATIONS

4.1 Purpose and Summary

The purpose of this section is to calculate the radiation doses resulting from the normal activities involved in the shipment of spent fuel by barge. These doses may be received by transport workers and the general public as a consequence of barge movement and off-site transfer. The results show:

a) Radiation doses received by rigging and barge crews involved in intermodal cask transportation are within the guidelines for non-radiation workers.

b) Radiation doses to an individual member of the public are well within federal guidelines. The estimated dose to the population along a barge route is 5.1×10^{-2} man-rem/reactor year.

4.2 Radiation Exposure to Transport Workers

The major contributing sources of radiation doses to operating personnel in a waterborne spent fuel transport campaign are:

a) exposures to the barge crew during waterborne transportation

b) doses to the working crew, including riggers, drivers, railroad and supervisory personnel, received during intermodal transfer

It is the responsibility of the licensee/shipper to assure that no employee of the transfer organization receives a dose that exceeds the dose limits set forth in the regulations. These regulations define a maximum exposure for non-radiation workers (see Chapter 3) as:

a) 500 mrem per calendar year
b) 312 mrem per calendar quarter
c) 100 mrem in any seven consecutive days
d) a rate of exposure to the crew of a marine vessel of less than 0.5 mrem/hr. in any normally occupied living space during the journey

4.2.1 Radiation Exposure During Intermodal Transfer

The highest radiation doses to personnel involved in intermodal shipment occur during transfer operations. In particular, transfers between barge and rail by HHT require a significant amount of close-in work to remove casks from the barge especially in cases where railcar units are assembled. The radiation doses calculated for this process also represent upper bound estimates of radiation doses for the other transfer operations.

4.2.1.1 Exposure Times for Transfer Processes

Estimates of working times needed to complete various procedures in the loading/unloading process are available from actual contractor experience with intermodal transport of large reactor components(4-1). The times required for the various procedures are listed in Table 4.1 by occupation. Exposure times for a loading crew utilizing floating bridge access are not listed, but they would be much less than those given in the table.

4.2.1.2 Dose Rate Estimates for Transfer Operations

The dose rate estimates at various points around a cask vary with cask design and shielding thickness. The greatest dose rate allowed at 6 ft. from the cask pallet is 10 mrem/hr. This rate is used to determine the source strength of a "plate source"* at the cask pallet surface which is then used to estimate doses received by transport workers and members of the public. Since there is heavier shielding at the ends of the car frame and other iron supports, the dose rate from that area is assumed to be negligible. A set of dose rates is calculated with only one cask on the barge and a second set with two casks on the barge separated by a distance of ten feet. A dose point vertical height of 3 feet (roughly one-half a worker's height) is used in the calculation.

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* As a plate source the cask radiates for dose calculation purposes as a rectangular plate (17.6 ft. long by 6 ft high). The dose rate at coordinates (x_o, y_o, z_o) is given by the integral

$$R = \iint \frac{S\,dxdy}{(x - x_o)^2 + (y - y_o)^2 + z_o^2}$$

which is numerically integrated over the plate surface using a source strength equivalent to 10 mrem/hr at 6 ft from the surface (the maximum allowed dose rate).

Table 4.1. Radiation Exposure Times of Personnel Involved in Intermodal Transfer of a Spent Fuel Cask From Rail to Barge Using Roll-on/Roll-off by HHT[4-1]

Operation	Exposure Time For Crew [f] (hr)	Occupation							
		Rigger		Driver		Supervisor		Health Physicist	
		Near [a] (hr)	Far [b] (hr)	Near [a] (hr)	Far [b] (hr)	Near [a] (hr)	Far [b] (hr)	Near [a] (hr)	Far [b] (hr)
1. Receive railcar(s) at intermodal transfer point 2. Check radiation level and inspect cask 3. Check barge ballast and lower transition ramp	4	-	4	-	4	-	4	1[c]	3
4. Assemble hauling vehicle and rigging equipment	4	-	4	-	4	-	4	-	4
5. Place jacks under carframe 6. Jack carframe free from trucks 7. Remove trucks, place hauling vehicle under carframe 8. Jack carframe onto hauling vehicle and secure	4	0.6	3.4	1[d]	3	-	4	-	4
9. Move hauling vehicle onto barge	4	-	4	4[d]	-	-	4	-	4
10. Jack carframe free of hauling vehicle 11. Remove hauling vehicle from beneath carframe 12. Lower carframe to barge deck 13. Remove jacks from under carframe	4	0.5	3.5	1[d]	3	-	4	-	4
14. Secure carframe to barge deck	4	0.8[e]	3.2		4	0.9[e]	3.2		4

(a) assumed to be at a distance of 3 feet unless noted
(b) assumed to be at a distance of 20 feet unless noted
(c) at a distance of 6 feet
(d) at a distance of 10 feet from front of cask
(e) at a distance of 8 feet
(f) estimated upper bound

Table 4.2a summarizes the dose rates sustained at given distances during transfer. Table 4.2b gives does rates at longer distances, showing the marked attenuation of the dose rate. Table 4.3 summarizes the dose rate by occupation using the assumptions of exposure time from Table 4.1. Table 4.4 summarizes the total dose by occupation for a two-cask transfer procedure.

4.2.1.3 Discussion of Transfer Dose Results

The radiation doses presented in Tables 4.2 and 4.3 are conservative. In practice, transfer worker doses would be considerably less since: a) casks do not necessarily contain maximum activity fuel; b) additional shielding would be used if a large amount of close-in work were required; and c) most transfer operations are not as elaborate as the one described.

Assuming one third of a PWR core was removed every year, the number of casks transferred would vary between 6 and 10, depending on cask capacity. If a pair of casks is loaded in two working days, the riggers would receive their allowable weekly dose in two days. If shipment of pairs of casks were spaced at least a week apart, a single crew might be used for an entire spent fuel shipment campaign since their dose limit is 312 mrem per quarter. It is likely that shipments will be spaced due to the long turnaround times encountered in waterborne transportation (see Section 7.0).

Table 4.2a. Dose Rates From a Full Cask Modeled as a Plate Source for Relatively Short Distances[a,b]

Perpendicular Distance From Plate (ft)	Dose Rate Variation With Distance From One End of Plate (c) (mrem/hr)					Averaged Dose Rate At A Perpendicular Distance From the Plate (mrem/hr)
	Beyond Edge of Plate	Edge of Plate	3 ft	6 ft	Midpoint of Plate Length	
3	6.4	13.5	20.6	23.4	24.0	17.6
4	5.5	10.1	14.6	16.8	17.3	12.9
6	4.0	6.2	8.4	9.7	10.0	7.7
8	3.0	4.2	5.4	6.1	6.3	5.0
10	2.2	3.0	3.7	4.1	4.2	3.4
12	1.7	2.2	2.6	2.9	3.5	2.6
14	1.3	1.6	1.9	2.1	2.1	1.8
16	1.0	1.2	1.4	1.5	1.6	1.3
18	0.8	0.9	1.0	1.1	1.2	1.0
20	0.6	0.7	0.8	0.8	0.9	0.8

(a) Cask is a dry cask assumed to be loaded with 10 PWR fuel assemblies

(b) Dose rates are for cask at elevation of 3 feet

(c) Plate dimensions are 17.2 ft. long x 6 ft. high

Table 4.2b. Dose Rates From a Full Cask Modeled as a Plate Source for Relatively Long Distances

Perpendicular Distance From Plate (ft)	Dose From Mid Point of Plate Length (mrem/hr)
20	0.872
30	0.224
40	0.0561
50	0.0125
60	0.0024
70	3.84×10^{-4}
80	5.02×10^{-5}
90	5.40×10^{-6}
100	4.67×10^{-6}

Table 4.3. Dose Estimates by Occupation for Personnel Involved in Intermodal Transfer of a Cask From Rail to Barge Using Roll-on/Roll-off By HHT[(a)]

Operation	Occupation							
	Rigger		Driver		Supervisor		Health Physicist	
	Near (mrem)	Far (mrem)	Near (mrem)	Far (mrem)	Near (mrem)	Far (mrem)	Near (mrem)	Far (mrem)
1. Receive railcar(s) at intermodal transfer point 2. Check radiation level and inspect cask 3. Check barge ballast and lower transition ramp	-	3.2	-	3.2	-	3.2	7.7	2.4
4. Assemble hauling vehicle and rigging equipment	-	3.2	-	3.2	-	3.2	-	3.2
5. Place jacks under carframe 6. Jack carframe free from trucks 7. Remove trucks, place hauling vehicle under carframe 8. Jack carframe onto hauling vehicle and secure	10.4	2.7	2.2	2.4	-	3.2	-	3.2
9. Move hauling vehicle onto barge	-	3.2	8.8	-	-	3.2	-	3.2
10. Jack carframe free of hauling vehicle 11. Remove hauling vehicle from beneath carframe 12. Lower carframe to barge deck 13. Remove jacks from under carframe	8.7	2.8	2.2	2.4	-	3.2	-	3.2
14. Secure carframe to barge deck	4.0	2.6	-	3.2	4.0	2.6	-	3.2

(a) Doses are for exposure during transfer of one cask and do not include the effect of a second cask. The effect of a second cask during transfer is estimated by increasing the dose at far distances by a factor of 1.3 for operations numbered 1 through 8 involving the first cask and operations numbered 9 through 14 involving the second cask.

Table 4.4. Radiation Dose by Occupation Accumulated During Intermodal Transfer of Two Full Spent Fuel Casks From Rail to Barge Using Roll-on/Roll-off by HHT

Occupation	Dose (mrem)	% of Weekly Allowable Dose[(a)]	% of Quarterly Allowable Dose[(b)]	% of Yearly Allowable Dose[(c)]
Rigger[(d)]	86.9	86.9	30.0	17.4
Driver[(d)]	59.5	59.5	19.8	11.9
Supervisor[(d)]	42.8	42.8	14.3	8.6
Health Physicist[(e)]	50.0	50.0	3.8	1.0

(a) 100 mrem per week for non-radiation or radiation worker.
(b) 312 mrem per quarter for non-radiation worker, 1250 mrem for radiation worker.
(c) 500 mrem per year for non-radiation worker, 5000 mrem per year for radiation worker.
(d) Non-radiation worker classification.
(e) Radiation worker classification.

If the barge journey is short for an intermodal journey, the same crew could be used to unload the casks at the transfer point. If the amount of time required to unload the casks is about the same as for loading, doses to the rigging crew will double.

The use of a more automated way of loading the barge, such as the floating bridge, would eliminate the jacking operation which would reduce the maximum daily dose to transfer crews by 70%. A similar reduction would result from using a gooseneck HHT for loading.

The dose estimates calculated above can be assumed to represent a bounding case for doses received during a normal turnaround operation, excluding the exposure the truck driver received during transport of a loaded cask from the utility site to the barge.

4.2.2 Dose to Boat Crews During the Journey

The tug boat crew will be about 40 to 60 ft from the nearest cask during the conveyance portion of the trip. Using the dose rates calculated in Table 4.2a and assuming an average barge journey of 1300 miles* at 4 mph†, the total dose to each crew member would be approximately 4.1 mrem per one way trip. The maximum total dose to each crew member would then be 49 mrem per year.

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* See Section 1, Table 1.5 for average barge journey lengths.

† Actual carrier experience (Section 7.0) indicates that barge speeds of 7 miles per hour are more likely, but the low estimate of speed based on WASH-1238[4-2] is used for dosage conservatism. For a spent fuel reactor campaign from one reactor requiring 3-5 barge trips per year, the maximum dosage received would be 20 mrem/year/worker.

4.3 Dose to the Public

The method used to calculate total dose to the public from a barge carrying spent fuel is the same as that used in WASH-1238.(4-2) Table 4.5 (from Reference 1-2) gives the dosage an individual will receive as a function of distance from the shipping route. Using Table 4.5 the maximum individual dose incurred at a distance of 100 ft from the barge is 1.9×10^{-3} mrem/R-yr which is a factor of 4×10^{-6} times the allowable federal guideline as quoted in 10CFR20.105.

In WASH-1238 it was assumed that there are approximately 165 people per route mile uniformly distributed between 100 ft. and 2600 ft. on each side of the route. Assuming that 1/26th of the 165 people are grouped at 100 ft. intervals on each side of the route, the total man-rem dose per barge mile on one side of the route is 9.0×10^{-6} man-rem/mile, or a total of 1.8×10^{-5} man-rem/mile for each cask shipped. An average waterborne journey is 1300 miles in length, 2 casks are carried per barge; 3.25 journeys per year are required to remove a reactor's spent fuel. WASH-1238 also assumes that no persons reside within half a mile on either side of 2/3 of the average barge route; therefore, the cumulative dose (D) per reactor year of operation is:

$$D = 1.8 \times 10^{-5} \frac{\text{man-rem}}{\text{inhab.-barge-mi}} \left(1300 \frac{\text{barge-mi}}{\text{cask trip}}\right)\left(2 \frac{\text{cask trips}}{\text{barge trip}}\right)$$

$$\left(\frac{1}{3} \frac{\text{inhab.-barge-mi}}{\text{barge-mi}}\right)\left(3.25 \frac{\text{barge trips}}{\text{R-yr}}\right)$$

$$= 5.1 \times 10^{-2} \left[\frac{\text{man-rem}}{\text{R-yr}}\right]$$

Table 4.5. Dosage to Individuals Per Barge Trip as a Function of Distance From the Centerline of a Shipping Route (4-2)

Distance From Centerline of Shipping Route (ft)	Individual Dose at Given Distance (mrem)/Barge Trip
100	5.8×10^{-4}
200	2.5×10^{-4}
300	1.5×10^{-4}
400	1.0×10^{-4}
500	7.1×10^{-5}
700	4.0×10^{-5}
900	2.5×10^{-5}
1000	2.0×10^{-5}
1300	1.1×10^{-5}
1500	7.8×10^{-6}
1700	5.5×10^{-6}
2000	3.4×10^{-6}
2300	2.1×10^{-6}
2600	1.3×10^{-6}

Note: Doses at some intermediate distances have been omitted to shorten the table.

REFERENCES

4-1. W. Kemp Norman, Williams Crane and Rigging, Inc., Richmond, VA., Private communication to R. Stuart, May 2, 1977.

4-2. USAEC (NRC) Directorate of Regulatory Standards, "Environmental Survey of Transportation of Radioactive Materials To and From Nuclear Power Plants," WASH-1238, December 1972.

5.0 ACCIDENT PROBABILITY ANALYSIS

5.1 Purpose and Summary

This section presents an analysis of the frequency of postulated accidental radioactive releases during intermodal transport of spent fuel, and includes the following:

a) descriptions of all mechanisms by which radioactivity can be released during an accident involving dry and wet spent fuel casks

b) estimates of the frequency of radioactive release events involving dry and wet casks based on construction and evaluation of fault trees

c) comparison of estimated radioactive release accident frequencies for spent fuel transport by intermodal means to the estimated frequencies for transport by rail

The estimated frequency of occurrence of any radioactive release during intermodal transport of spent fuel in a dry cask was found to be less than once per 800,000 reactor years of operation. The frequency of severe release accidents was estimated to be less than once per 23,000,000 reactor years of operation.

The probability of a release occurring during the waterborne portion of an intermodal trip was estimated to be approximately 5% of the total probability of release per trip. This small fraction results from the reduced frequency of high impact energy accidents and a significantly reduced frequency of fires and explosions.

It is estimated that the difference between the probability of a release accident with extensive use of intermodal transport in the U.S. (40% of all fuel shipped) and the same probability with minimal use of this form of transport (5% of all fuel shipped, i.e., essentially transport by rail only) is less than a factor of two. The results of this analysis show that this is well within the uncertainties in the input probabilities; therefore, the use of intermodal transport does not appear to significantly affect the overall likelihood of radioactive releases during spent fuel transport.

5.2 Descriptions of Dry and Wet Cask Designs

5.2.1 NLI 10/24 Dry Cask

The National Lead Industries NLI 10/24 rail transported spent fuel shipping cask[5-1] is designed for zero release under both normal and accident conditions as defined by 10CFR71 Appendix A and B. The cask weighs approximately 2.2×10^5 lbs when filled with 10 PWR fuel assembles. The fuel is shipped "dry" in a helium atmosphere with no need for pressure relief to the atmosphere. No forced convection cooling is required, but water cooling is used to provide lower fuel temperatures and reduce cooldown time at the receiving facility. Neutron shielding is provided by a 9-inch water jacket. Table 5.1 briefly summarizes some of the cask characteristics and Figure 5.1 shows a three dimensional view of the cask assembly. Figure 5.2 is a two-dimensional section drawing of the cask.

Fuel is transported in the inner cavity which is supported by a shipping basket constructed of Ag-In-Cd alloy plate (shown as "aluminum fuel basket" in Figure 5.2) to prevent a criticality if fresh fuel were put in the cask by accident, and the cask filled with pure water.

The inner cavity is a cylinder with 3/4 inch stainless steel walls which is filled with helium at approximately atmospheric pressure after loading. If a cask were loaded with BWR fuel having a fill pressure of 200 psi and all the fuel rods failed, the cavity pressure would rise to 80.5 psi. Immersion of the cask in a 1475^{O}F fire of 30 minute duration as prescribed in 10CFR71 would raise the pressure to 104.5 psig. No pressure relief is needed or supplied to relieve cavity pressures inasmuch as the containment vessel can withstand more than 200 psig internal pressure.

Immediately outside of the inner cylinder are 20 axial cooling channels which are 0.3 square inch in cross sectional area. These channels are grouped into two independent systems of 10 channels each which are water filled and connected to independent diesel-powered cooling systems. Backup power is supplied by the rail carriage or by the barge electrical supply system during the course of the intermodal journey.

Table 5.1. Characteristics of the NLI 10/24 Dry Cask[5-1]

Characteristic		PWR Fuel	BWR Fuel
Fuel Data (1 assembly)			
Envelope	(in)	8.60 sq. x 171.5	5.44 sq. x 176.25
Enrichment	(w/o U-235)	3.35	2.65
Avg. burnup	(MWD/MTU)	35,500	29,700
Avg. specific power	(Kw/Kg)	36.3	25
Weight of uranium	(Kg)	454	197
Decay heat	(Kw)	9.72	3.7
Total Weight of Uranium (full cask load)	(Kg)	4,540	4,728
Total Decay Heat (full cask load)	(Kw)	76	76
Cask Capacity	(assemblies)	10	24
Cask Weight (loaded)	(lbs)	218,000*	218,000
Cask Data			
Cavity dimensions	(in)	45.0 dia x 179.4	
Envelope	(in)	88.0 dia x 204.5	
Weight (empty)	(lbs)	200,000	
Max. normal operating pressures†			
Cavity	(psig)	80.5	
Water jacket	(psig)	300	
Max. design pressure			
Cavity	(psig)	200 (approx.)	
Water jacket‡	(psig)	345	

* Including impact limiters

† The maximum normal operating pressures listed here are based on operation without auxiliary cooling and total fission gas release.

‡ The water jacket relief valve is set for 320 psig.

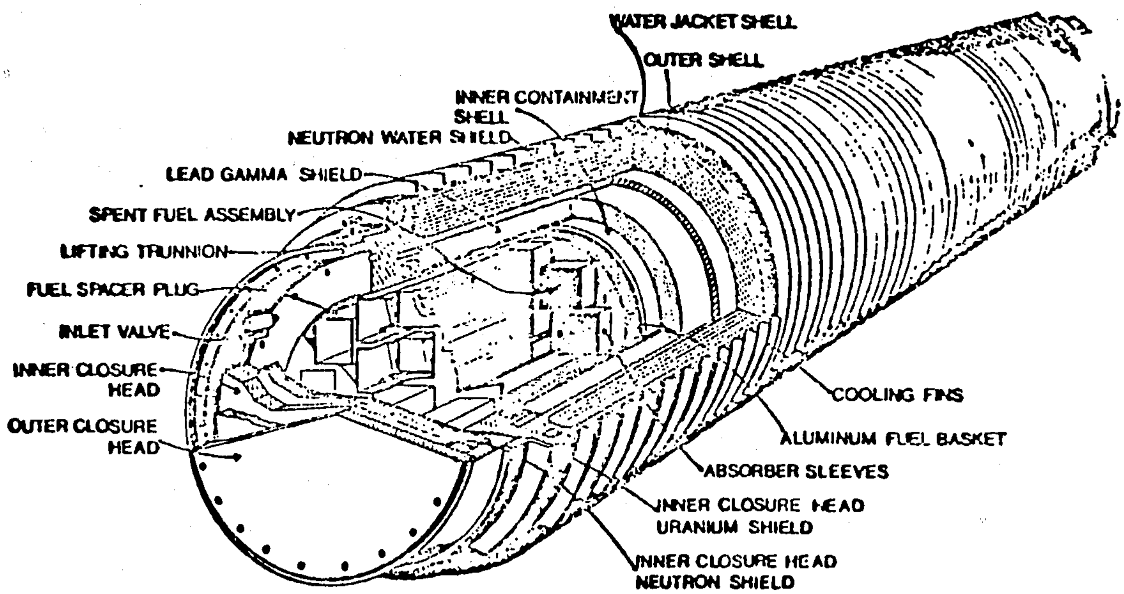

Figure 5.1. NLI 10/24 Dry Cask Assembly(5-1)

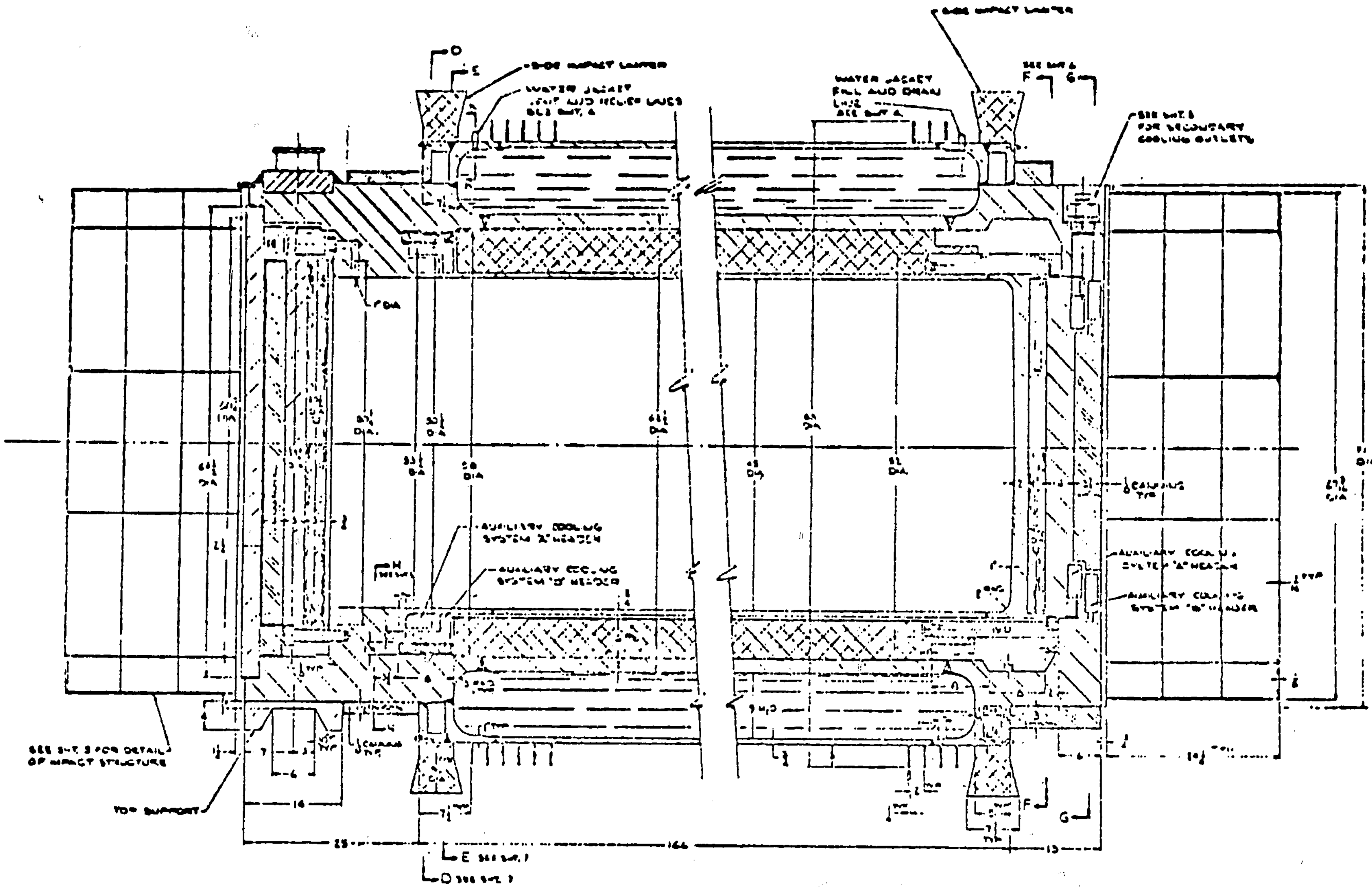

Figure 5.2. Section Drawing of the NLI 10/24 Dry Cask[5-1]

The active cooling is not a prerequisite to licensing; it is used to keep the cask cool in order to reduce cooling times required for loading and unloading. Table 5.2 lists temperatures of various portions of the cask for situations involving loss of one or both of the auxiliary cooling systems.

The inner cylinder and its cooling channels are surrounded by a 6-inch thick lead gamma-ray shield. This lead shield is, in turn, surrounded by a 2-inch thick stainless steel cylinder which forms the inner wall of a 9-inch thick water jacket, i.e., the neutron shield. The outer wall of this neutron shield is a 3/4-inch thick stainless steel jacket. Expansion tanks are provided to maintain a solid water shield. Under maximum normal operating temperatures, the water jacket operating pressure is 300 psig. The water jacket is designed to withstand a pressure of 345 psig and the pressure relief valve is set at 320 psig.

Table 5.2. NLI 10/24 Dry Cask Temperature Data for a Maximum Heat Load* with Partial or Total Loss of Auxiliary Cooling(5-1)

Location	Loss of 1 Cooling Loop	Loss of 2 Cooling Loops
Outer Surface	227°F	407°F
Inner Shell	268°F	541°F
Aluminum Basket (max.)	451°F	757°F
Fuel Assembly (avg.)	690°F	899°F

* Maximum heat load is 97.2 kW for a full load of PWR fuel. The cask is currently licensed for 70 kW full load heat output.

The ends of the cask are closed by inner and outer closure heads. A penetration through the head end of the cask body connects the cask exterior to the space between the inner and outer closure heads. This penetration is used to drain the space between these closure heads when the cask is removed from the spent fuel storage pool. The penetration is also used for pressure testing the secondary containment system prior to shipment of the loaded cask.

The cask cavity closure head (inner closure head) is a stainless steel forging with a center section filled with depleted uranium and covered by a stainless steel plate welded to the forging. The bulk of the required gamma shielding is contained in the inner closure head to provide protection for the operator during handling operations. The closure head is held in place by sixteen 1 3/4-inch high-strength studs, and the inner head seal is a metallic ring. The studs and the ring can easily withstand the temperatures expected as a result of the hypothetical fire accident.

The cask body closure head (outer closure head) is a 2-inch thick flat stainless steel plate which is held in place by twenty-eight 1 1/8-inch high-strength studs. There are no penetrations through the outer closure head itself since the single necessary service penetration is made through the cask body, as described above.

5.2.2 IF 300 Wet Cask

The General Electric IF 300 irradiated fuel shipping cask, like the NLI 10/24 cask, is designed to be transported by rail car and can be used for most types of light water reactor fuels. The fuel is enclosed in a water-filled cavity; hence the designation "wet" cask.* Like the NLI 10/24, the IF 300 cask is designed to be zero-release under all normal and most accident conditions in accordance with NRC and DOT regulations; however, the IF 300 is not designed for zero release under the hypothetical accident conditions of 10CFR71, Appendix B. Nevertheless, releases produced under these conditions do not exceed the allowable releases under present NRC and DOT regulations.

Fuel loads which can be contained in the IF 300 are shown in Table 5.3. A section view of the cask and skid assembly is shown in Figure 5.3. Cask weight when loaded is between 135,000 lb. and 140,000 lb. depending on the particular type of fuel being shipped. Weight of the skid assembly is approximately 45,000 lbs.

The IF 300 cask body is a uranium shielded stainless steel clad annular cylinder closed at one end. Fuel is loaded through the top end, and closure is accomplished using a bolted and sealed head. The head shielding is similar to the cask body. All external and internal surfaces of the cask, including the inner and outer shells, side fins, flanges end fins and head seal, are stainless steel.

During normal operation, the water-filled inner cavity will be at approximately 55 psig pressure. Heat transmission from the fuel to the cavity walls is accomplished by natural circulation of the water.

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* This cask is also licensed to be shipped air filled but at a lower heat output.

Table 5.3. Characteristics of the GE IF 300 Wet Cask*(5-2)

Characteristic		PWR Fuel	BWR Fuel
Fuel Data (1 assembly)			
Envelope	(in)	8.75 sq. x 169.5	5.75 sq. x 180.25
Enrichment	(w/o U-235)	4.0	3.5
Avg. burnup	(MWD/MTU)	35,000	35,000
Avg. specific power	(Kw/Kg)	40	30
Weight of uranium	(Kg)	457	198
Decay heat	(Kw)	11.0	4.3
Total Weight of Uranium (full cask load)	(Kg)	3199	3564
Total Decay Heat (full cask load)	(Kw)	62	62
Cask Capacity	(assemblies)	7	18
Cask Weight (loaded)	(lbs)	135,000	140,000
Skid Weight	(lbs)	~45,000	~45,000
Total Shipping Package Weight	(lbs)	~180,000	~185,000
Cask Data			
Cavity dimensions	(in)	37.5	37.5
Envelope	(in)	64 x 204	64 x 209
Weight (empty)	(lbs)	125,000	130,000
Max. normal operating pressures			
Cavity	(psig)	200	
Water jacket	(psig)	50	
Max. design pressure			
Cavity	(psig)	400	
Water jacket	(psig)	200	

*Updated by R. Jones of General Electric Co., San Jose, Calif., 3-15-78.

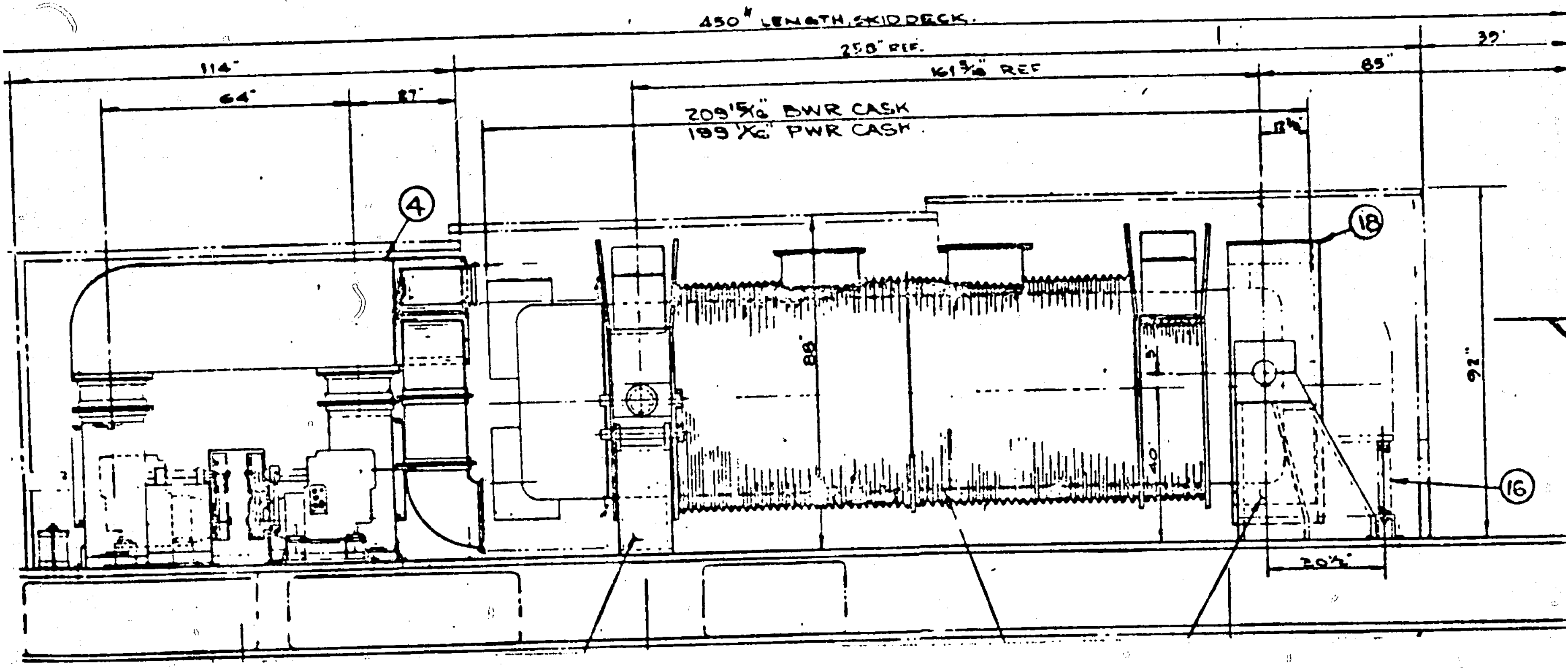

Figure 5.3. Wet Cask Side View - Showing Cask, Cooling System, Skid and Mounting Cradle[5-2].

Normal cooling is accomplished by an external forced-air-jet impingement system, but this system is not required to maintain cask integrity or prevent venting. Over-pressure protection for the cask cavity is provided by a high-temperature pressure relief valve. Discharge pressure for these valves is 375 psig, and the valves are set for a steam or gas blowdown reset pressure of < 5%, i.e., the valves will reseat at a pressure $\geq$ 356 psig. Cavity pressures and representative temperatures are given in Table 5.4. This relief valve is mounted within the upper of two valve boxes located on the cask exterior (see Figure 5.4a) and each of these boxes also contains a nuclear service valve for filling, draining, and sampling the cask cavity. Each vent/fill/drain valve has quick disconnect fittings. Each valve handle is lockwired during transit to prevent loosening.

Table 5.4. GE IF 300 Wet Cask Temperature Data[a,b]

Location	Normal	Loss of Mechanical Cooling
Neutron shield surface (max)	235°F	350°F
Cavity water	296°F	389°F

a Heat load is 210,000 Btu/hr = 61.5 Kw

b Ambient temperature = 130°F (still air)

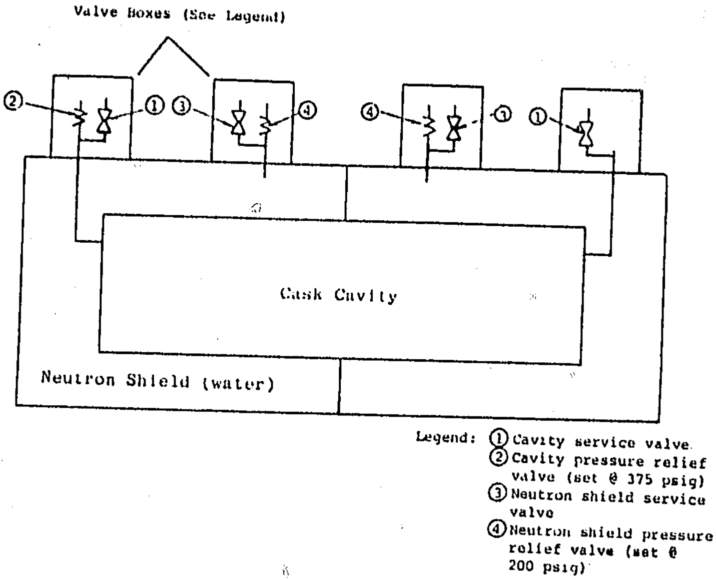

Figure 5.4a. Wet Cask Schematic Drawing

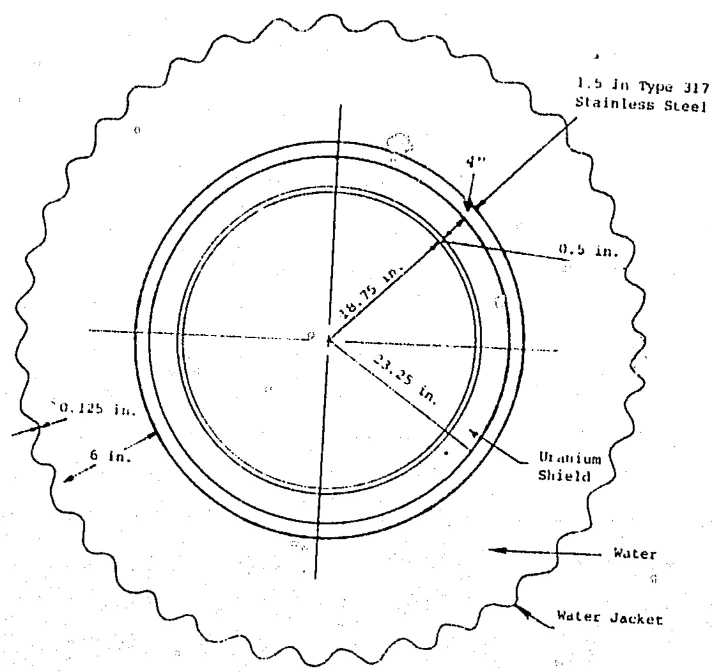

Figure 5.4b. Wet Cask Cross Section(5-2)

The neutron water shield is partitioned to form two functioning separate compartments each protected from over-pressure by a 200 psig relief valve and serviced by a fill and drain valve. The two sets of service and relief valves are located in separate valve boxes - not the same as those used for the cask cavity valves.

The depleted uranium shielding surrounds the inner cavity and is shrink-fitted, providing shielding against gamma radiation (Figure 5.4b). The uranium shield consists of 8 to 10 annular castings, each with a 37.5-inch ID and a 4-inch thick wall. Bottom end shielding uses a 3.75-inch thick uranium casting. The cast outer shell is a stainless steel cylinder with a 46½ inch ID and a 1½ inch thick wall. This outer shell is shrink-fitted to the uranium castings, thus forming a·composite or laminated vessel.

The cylindrical portion of the cask is encircled by a thin-walled, corrugated, stainless steel water jacket. This jacket extends axially from the upper valve box to a point slightly above the cask bottom, thus masking the active fuel zone. The water contained in this structure functions as a neutron shield. The jacket surface is corrugated for heat transfer purposes.

There are four large valve boxes on the exterior of the cask body as previously described: two for the corrugated water jacket, and two for the cask cavity. A large amount of impact protection and fire protection is afforded to the cavity pressure relief fill-valving: each valve box is protected from impact by a 1¼-inch thick stainless steel structural rings, a heavy lid, large side castings, and numerous small fins. Several structural members are also used to support the water jacket sections.

The IF 300 cask can be equipped with either of two different heads - one for use with PWR fuel loads and one for use with BWR fuel loads. Shielding in the heads consists of 3 inches of depleted uranium. The outer shell and flange is a single piece machined casting of stainless steel. A circular stainless steel plate is welded in place to form the inner liner and the head cover. Each head has radially mounted fins designed to offer impact protection to the cask and contents. The fins are stainless steel and are welded in place. The cask body and head are joined using studs in the body flange. Cask sealing is accomplished using a Grayloc metallic gasket.

5.3 Fault Tree Analysis

5.3.1 Background

As a preliminary to this analysis, the fault tree analysis of a dry cask by Fullwood et al.,[5-3] and the fault tree analysis of a wet cask by Hodge and Jarrett[5-4] were reviewed for applicability.

Fullwood's fault tree analysis concentrated on the air release pathway and considered only the NLI 10/24 dry cask. Since dry casks have no pressure relief system, all accidental releases postulated to occur required violation of the containment boundary.

In keeping with the philosophy of WASH-1400, failure was defined as an accident resulting in a radioactive release. Four postulated radioactive hazards were defined:

a) failure of the outer containment boundary and loss of neutron shielding

b) failure of the outer and inner containment boundaries with no rod failures beyond those assumed to occur during reactor operation (<1%)

c) failure of the outer and inner containment boundaries and mechanical fracture of a significant amount of fuel rods cladding (≈50%) within the containment

d) failure of the outer and inner containment boundaries and cladding damage within the cask with post failure overheating of the fuel

Categories (b), (c) and (d) represent air releases of increasing severity, (minor, severe and very severe, respectively) while category (a) may be a hazard to emergency response crews.

Hodge and Jarrett[(5-4)] utilize a generic fault tree to define the general event of an air release to the atmosphere from a wet cask. The causal events used are environmental and functional. In their evaluation of the fault tree, three sets of input probabilities were used to generate three potential levels of consequences.

Hodge and Jarrett did not distinguish a category of release involving only loss of neutron shielding; hence, their analysis is not strictly comparable to Fullwood's. Hodge and Jarrett did note that the wet cask has a failure mode that does not require failure of the containment boundary, i.e., a release during extended heating due to operation of the pressure relief valves.

5.3.2 Failure Criteria

A fault tree analysis of both the wet and dry casks was performed using the same generic radioactive release categories used in Reference 5-3, excluding category 1 which Fullwood et al. showed to be a minor hazard.

Two types of postulated releases are modeled in this report: those requiring failure of the containment boundary of the cask, and those not requiring failure of the containment boundary. Failure of the containment boundary is defined as the penetration of all boundaries between the cask interior and the outside. The penetration may be small, consisting of a seal failure or a crack failure of the end cap, or large, consisting of puncture of the cask body or cap.

Penetration of the cask body must be considered a low probability event by comparison to other failures, since all cask designs must meet stringent federal licensing requirements for impact and puncture resistance. Furthermore, a previous study by Shapper et al.[(5-5)] suggests that penetration of the outer and inner cask containment boundaries during the waterborne portion of the journey is extremely difficult because of the relatively slow speeds at which barge collisions occur. However, extrapolation of Fullwood's ballistic penetration analysis[(5-3)] indicates that the kinetic energy necessary to produce cask damage can be present in extreme situations due to the large masses of the vehicles involved. Therefore though shown to be unlikely (in Appendix B) penetration of the cask by moving stubs consisting of dense portions of another vessel is postulated, as is penetration by missiles resulting from fires and explosions.*

Radioactive releases not requiring failure of the containment boundary are identified only for the wet cask. Such releases can be produced during extended exposure to a thermal environment by operation of the pressure relief valve, since the vapor given off will contain a) gases released from failed fuel and b) possibly some dissolved radioactive material from failed rods. The requirement for pressure relief implies that failure of the pressure relief valving could result in leakage through the containment boundary if the valving fails open, or in a potential seal rupture if the valving fails closed and the cask is heated. The second event could also occur with a dry cask if the interior of the cask were not dryed according to procedures and the cask were involved in a fire.

No mechanism by which releases to the liquid pathway can occur without violation of the outer and inner containment boundary is postulated for either the wet or the dry cask. The effect of heating fuel in a failed cask prior to immersion would enhance the amount of radioactive material dissolved. Thermal effects of this type are not treated in this study because they are not considered a significant effect.†

* footnotes on recent impact tests
† See Fullwood et al[(5-3)] Appendix C "Thermal Analysis"

5.3.3 Fault Logic for the Dry Cask

The failure event for release from a dry cask is shown in Figures 5.5 - 5.7. Releases may be to the air (RDA) or to the water (RDL). The three air release categories shown correspond to categories (b), (c) and (d) in Section 5.3.1.

RDA1. Loss of containment boundary integrity, but no rod failures beyond those assumed to occur during reactor operation (<1%)

RDA2. Loss of containment boundary integrity with significant mechanical rupture (≈ 50%) of fuel cladding within the containment

RDA3. Loss of containment boundary integrity, significant mechanical failure of fuel claddings within the containment with post accident over-heating of the failed rods in a sustained thermal environment

Figures 5.6 and 5.7 respectively describe the sequence of events leading to minor and major loss of dry cask containment boundary integrity. A minor breach can involve cracking of the end cap or failure of both closure seals. A major breach involves penetration of the cask body by missiles or stubs or catastrophic failure of the end cap.

Liquid release (RDL) is postulated to occur if the cask is immersed after violation of the containment boundary

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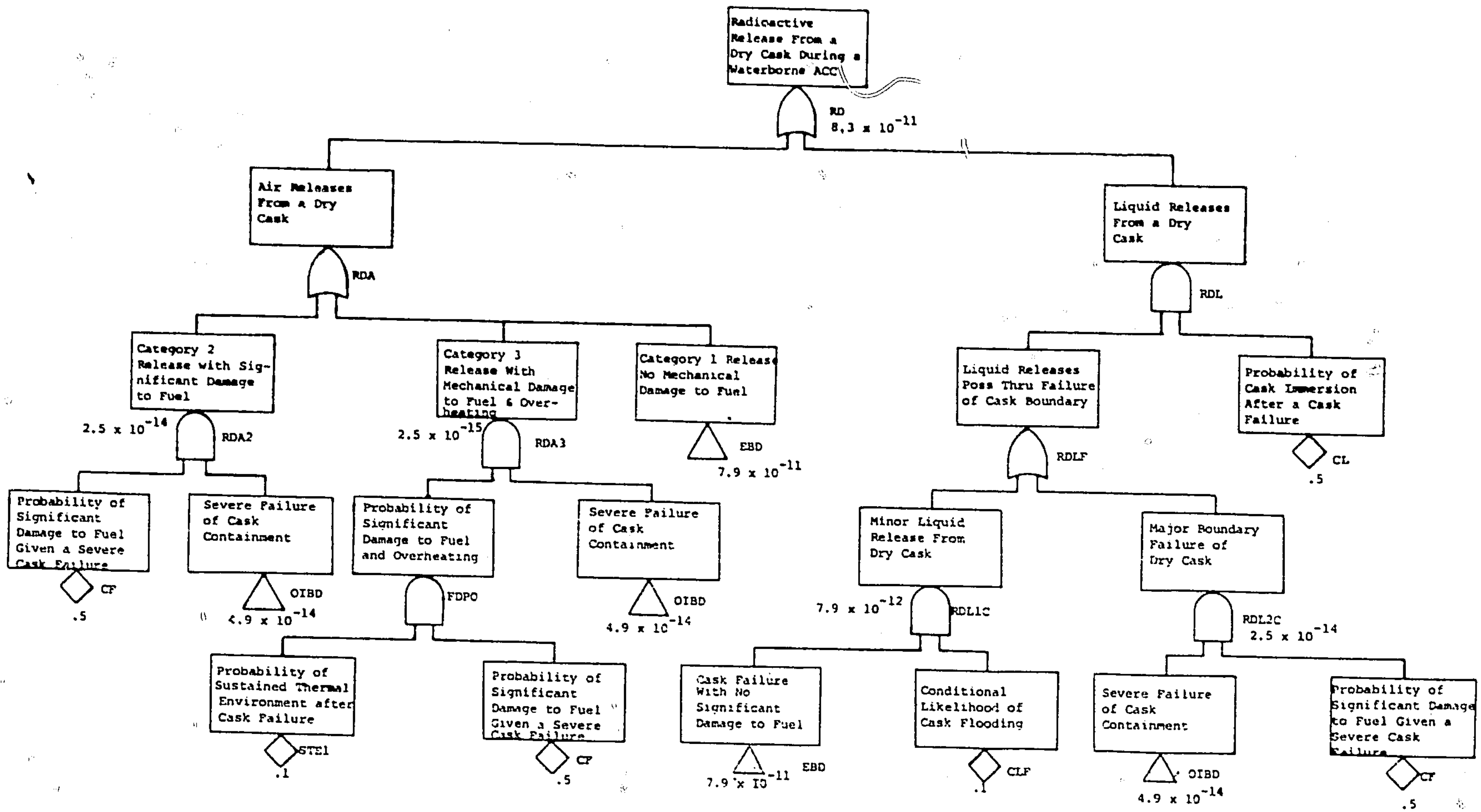

Figure 5.5. Radioactive Release From a Dry Cask During a Waterborne Accident

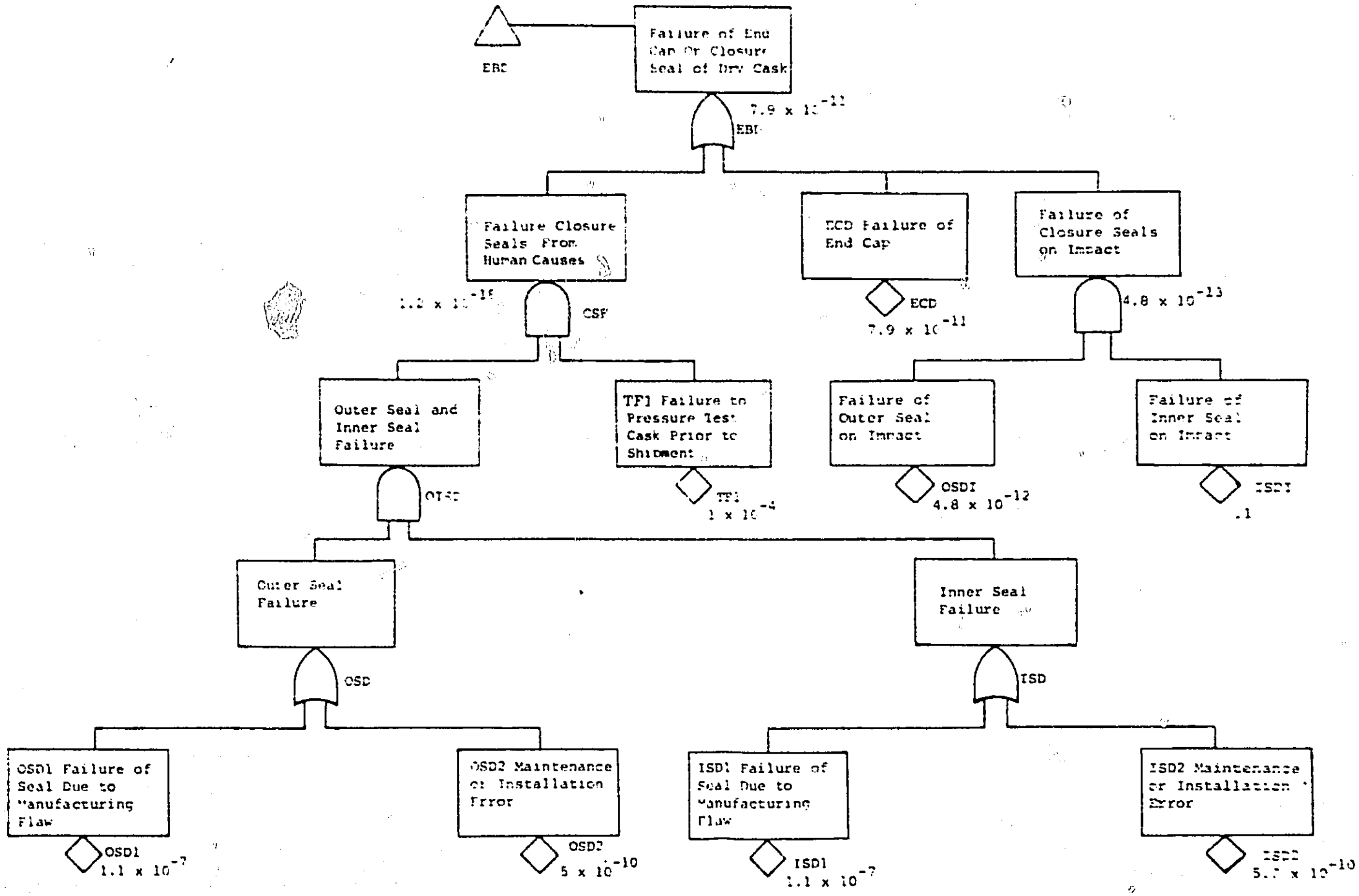

Figure 5.6. Radioactive Release From a Dry Cask During a Waterborne Accident Due to a Minor Breach of the Cask Boundary

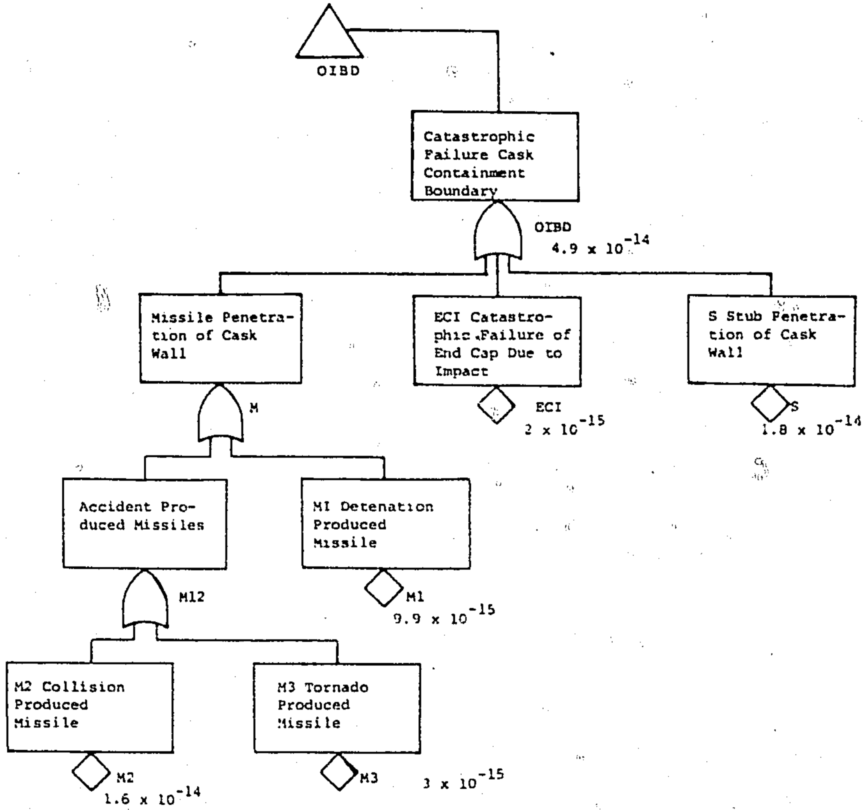

Figure 5.7. Radioactive Release From a Dry (or Wet) Cask During a Waterborne Accident Due to a Major Breach of the Cask Boundary

takes place. Two release classes are considered:*

RDL1. A minor breach of cask containment integrity, such that the major release-producing mechanism is diffusion or pressure forced exit of contaminated liquid.

RDL2. A major breach of cask containment boundary integrity, such that flushing of the cask by water occurs several times daily.

5.3.4 Fault Logic for the Wet Cask

In general, the release pathways described for the wet cask in this section are similar to those described for the dry cask in Section 5.3.3. The fault logic for air release pathways for the wet cask is shown in Figures 5.8 and 5.9. The air release pathways resulting from violation of the outer and inner containment boundary (RWA1, RWA2 and RWA3 in Figure 5.8) are identical to those described for the dry cask. In addition, an air release category corresponding to an accident involving boiling and pressure release of coolant (RWA4) is included in the logic.

Figure 5.9 shows the failure logic for a minor breach of wet cask integrity. The major difference from the dry cask logic shown in Figure 5.6 is the inclusion of pressure relief failure in a thermal environment as a cause of closure seal failure. A second difference is that the wet cask

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* The consequence analysis in Section 6 considers only the release resulting from immersion of a dry cask with a major breach of containment (equivalent to RDL2).

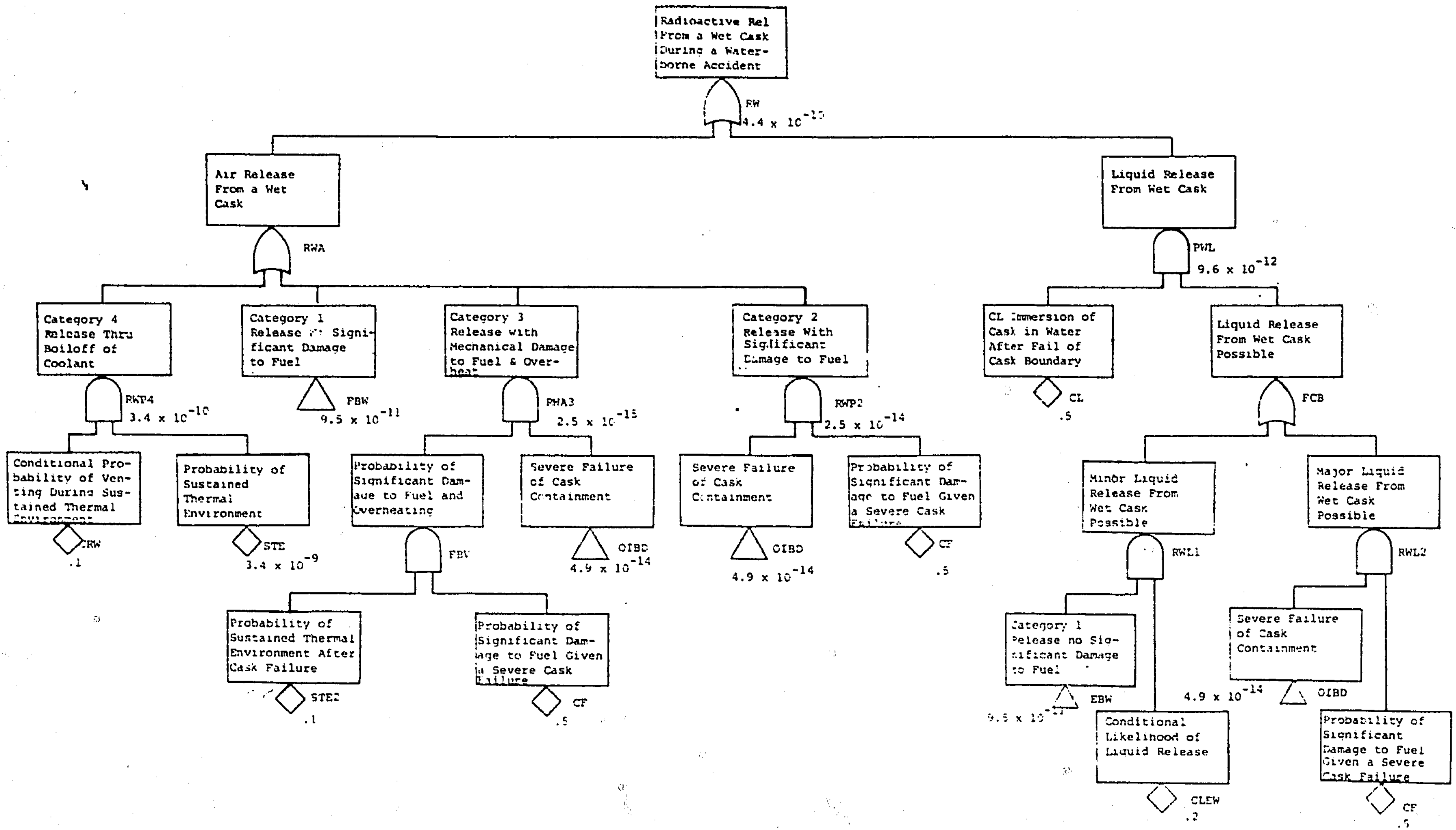

Figure 5.8. Radioactive Release From a Wet Cask During a Waterborne Accident

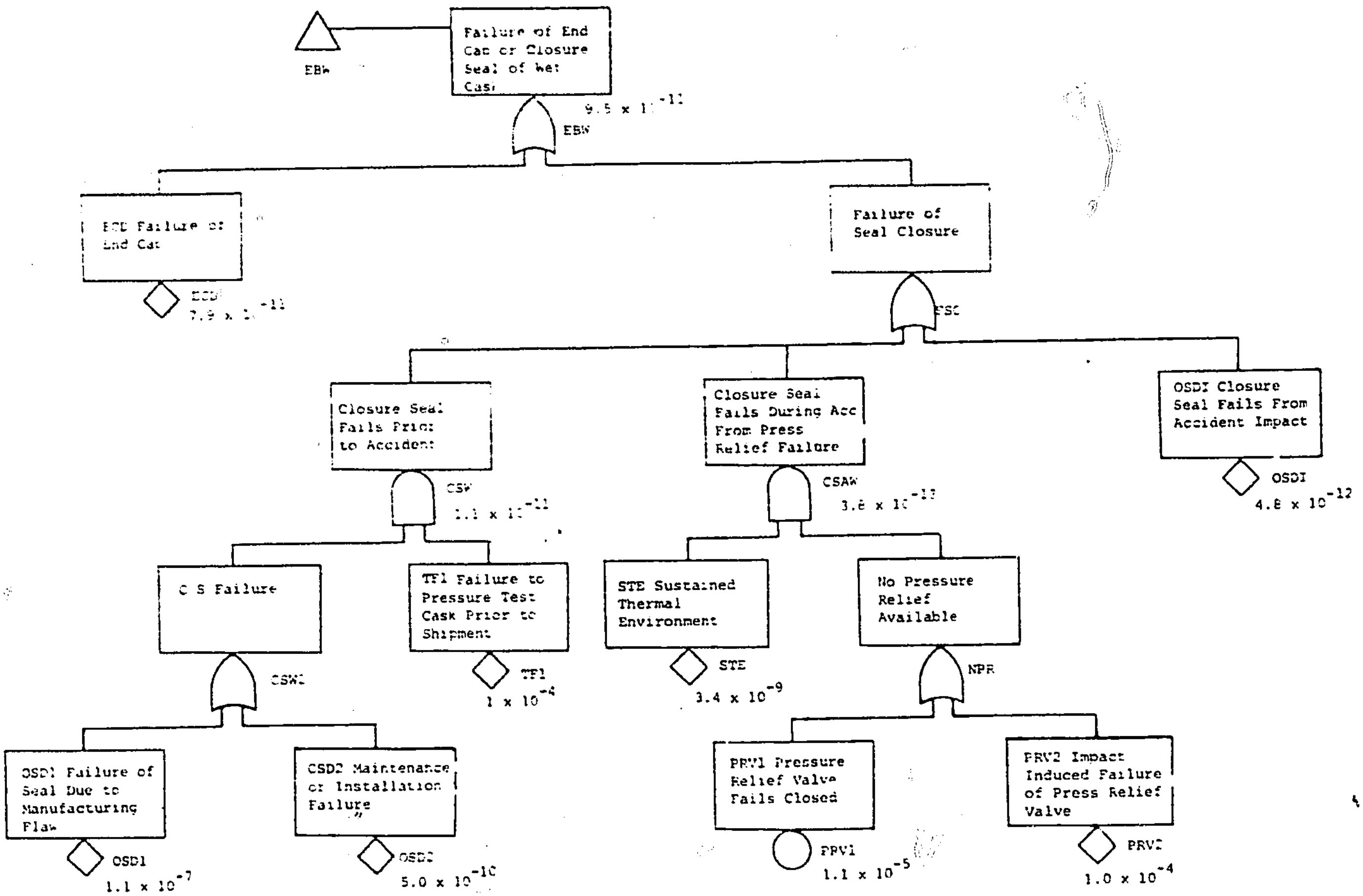

Figure 5.9. Radioactive Release From a Wet Cask During a Waterborne Accident Due to a Minor Breach of the Cask Boundary (End Cap Failure)

cask requires only a single closure seal failure for loss of integrity. The logic for a major breach of wet cask integrity is the same as shown in Figure 5.7 for the dry cask.

5.4 Data Sources

Failure frequencies for components of the fault trees are taken from a variety of sources. Frequencies of accident occurrence involving barge transport were taken from marine accident files of the Coast Guard Data File. The procedure for extracting data from Coast Guard Reports is described in Appendix B and by Erdmann et al.(5-6) The historical frequency of incidents involving significant impacts, explosions, or sustained thermal environments was normalized to a per barge mile basis (1/b-mi) by utilizing Army Corps of Engineers estimates of the total barge mileage for deck barges like those to be used in spent fuel transport.

Since Fullwood's analysis(5-3) described failures of the dry cask, many failure probabilities were extracted from Fullwood's references. Appendix B discusses the derivation of conditional probabilities of cask penetration from existing missile and stub penetration data. These data were used by Fullwood to obtain similar estimates of penetration probabilities for a rail accident. Conditional probabilities of penetration were assumed to be similar for the dry and wet casks.

Other sources of failure rate data on equipment include: WASH-1400, for estimates of equipment and human failure rates; Harris and Fullwood(5-7), for estimates of fatigue failure rates; and previous documents on the risk of spent fuel transport, such as Shappert et al.(5-5)

Component failure probabilities used in the evaluation of air and liquid release probabilities for both dry and wet cask designs are summarized in Table 5.5. The values for each component are discussed below.

M1. Penetration of Cask Boundary by Detonation-Produced Missiles

Accidents that result in large, damaging fires and explosions and that involve barges of the type used to transport spent fuel (flat deck cargo type) are estimated to occur at a rate of 1.7×10^{-9} to 5.1×10^{-9} per barge mile (b-mi). Napadensky et al.(5-8) assessed the conditional probability of producing a large missile in a detonation accident as being less than 1% per accident. From Appendix B, the probability of missile penetration, given missiles are produced, is approximately 3.4×10^{-5}/accident. A safety factor of 10 was used in consideration of the fact that missiles produced by explosions move at a higher velocity than those produced by collision only.* The total probability of an M1 occurrence is in the range of 5.8×10^{-15} to 1.7×10^{-14}/b-mi.

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* This is consistent with Reference 5-3 in which the probability of missile penetration from train wreck-produced missiles was assessed as 2.3×10^{-5} to 1.3×10^{-4}/accident.

Table 5.5. Summary of Failure Data Used in Dry and Wet Cask Fault Tree Assessment

Failure Event	Event Description	Failure Rate Range Per Mile of Barge Travel (1/b-mi)	Failure Rate (1/b-mi)	Reference or Calculation source	Failure Event	Event Description	Failure Rate Range Per Mile of Barge Travel (1/b-mi)	Failure Rate (1/b-mi)	Reference or Calculation Source
M1	Penetration of cask boundary by detonation produced missile	5.8×10^{-15} 1.7×10^{-14}	1.1×10^{-14}	App.B 5-8	PRV1	Unavailability of pressure relief during accident (failure closed)	3.5×10^{-6}(1/d) -3.5×10^{-5}(1/d)	1.1×10^{-5}(1/d)	5-10
M2	Penetration of cask boundary missile produced during collision or ramming	$1.2 \times 10^{-14}-2.1 \times 10^{-14}$	1.6×10^{-14}	App.B	PRV2	Failure of pressure relief by impact		1.0×10^{-4}(1/d)	App.B
M3	Penetration of cask boundary by tornado produced missile		2.0×10^{-15}	5-3	TF1	Failure to test closure seal integrity prior to journey		1.0×10^{-4}(1/d)	5-17
S	Penetration of cask boundary by stub	$1.4 \times 10^{-14}-2.4 \times 10^{-14}$	1.8×10^{-14}	App.B	CF	Failure of 50% of fuel claddings mechanically at failure of cask containment		0.5	5-3
STE	Existence of sustained thermal environment	$1.7 \times 10^{-9}-5.1 \times 10^{-9}$	3.4×10^{-9}	App.B	CLF	Flooding of dry cask after immersion due to minor break of cask		0.1	
ECD	Failure of end cap by other than impact		7.9×10^{-11}	5-3, 5-11	STE1	Exposure to a high thermal environment after catastrophic failure of cask containment		0.1	App.B
ISD1	Inner closure seal failure (dry cask only) from manufactured in defect		1.1×10^{-7}	5-3, 5-16	CRW	Venting of cask coolant due to immersion in a sustained thermal environment		0.1	5-17
ISD2	Inner closure seal failure (dry cask only) from maintenance or installation failure		5.0×10^{-10}	5-3, 5-16	CL	Immersion of cask in a waterborne accident		0.5	
OSD1	Outer closure seal failure from manufactured-in defect		1.1×10^{-7}	5-3, 5-16	CLEW	Release of radioactivity from wet cask during immersion given a minor break in containment		[illegible]	
OSD2	Outer closure seal failure from maintenance or installation failure		5.0×10^{-10}	5-3, 5-16	ISDI	Failure of closure seal due to accidental impact given outer seal failure		0.1	
OSDI	Failure of outer closure seal due to accidental impact	$3.4 \times 10^{-12}-6.1 \times 10^{-12}$	4.8×10^{-12}	App.B	ECI	Impact produced fracture of end cap		5×10^{-14}	App.C

M2. Penetration of Cask Boundary by Collision-Produced Missiles

From Appendix B, the probability of a severe collision or ramming which generates large missiles is 3.4×10^{-10} to 6.1×10^{-10}/b-mi. The conditional probability of penetration given a missile impact is 3.4×10^{-5}/impact. Therefore, the probability of collision produced missile penetration is 1.2×10^{-14} to 2.1×10^{-14}/b-mi.

M3. Penetration of Cask Boundary by a Tornado-Produced Missile

The probability of cask penetration by a tornado missile was evaluated by Fullwood(5-3) as 8.0×10^{-12} per car mile (/c-mi) for rail accidents based on an assessment of the likelihood of a design basis tornado. From WASH-1300(5-9) the likelihood of a design basis tornado at any point in the U.S. is assessed to be 10^{-7} per year. For an average long waterborne route of 1312 miles covered at an average barge speed of 4 mph this amounts to a probability of approximately 3×10^{-12}/b-mi of encountering a design basis tornado.

Fullwood's analysis assumed that a design basis tornado would contain projectiles of sufficient size to penetrate the cask body. This is thought to be overly conservative and a factor of .01 is used to define the probability of large projectiles being encountered in a design basis tornado.

Finally Fullwood's analysis was done for penetration of the cask water jacket only. Based on the decreased probability of penetration of the cask interior given penetration of the cask neutron shield defined by Fullwood an additional factor of .1 is used. Therefore the probability of penetration by a tornado produced missile in this study is taken to be 3×10^{-15}/b-mi.

S. Penetration of Cask Boundary by Stubs

In Fullwood's work on cask penetration by stubs it was assumed that certain components such as pieces of rail or partially buried rail car axles could act as fixed stubs with the potential to penetrate a moving cask. In this work, conditions are hypothesized to exist in which the moving cask encounters some portion of the colliding vessel or a fixed abutment. If it can be assumed that the solid protrusion contacting the cask is not simply pushed out of the way, then the protrusion may be considered a fixed stub, and the probability of stub penetration of a cask may be calculated.

The frequency of an accident which generates moving stub contact has already been evaluated (in Appendix B) as 3.4×10^{-10} to 6.1×10^{-10}/b-mi, and the conditional probability of penetration, from Appendix B, is 4.0×10^{-5}/stub impact. Thus the overall probability of stub penetration is 1.4×10^{-14} to 2.4×10^{-14}/b-mi.

STE. Sustained High Temperature Environment

The probability of STE, assessed directly from Appendix B data taken from the Coast Guard is 3.4×10^{-9}/b-mi.

ECD. Fracture of End Cap

Harris(5-7) estimated the rupture probability of piping of less thickness than the end fitting under pressure to be 3.5×10^{-8}/yr. However, Harris assumed that radiographic inspection had been performed. Fullwood, et al.(5-3) estimated the failure probability of the end cap in a rail accident as 4.7×10^{-4}/vessel-yr. The geometric mean of the two values is 4.1×10^{-6}/yr. However, some derating should be used in consideration of the fact that the vessel is not pressurized. Therefore, a value of 0.1 is used. Normalizing this to 5.2×10^{3} miles of yearly operations for a given route* produces an estimated probability of ECD occurrence of 7.9×10^{-11}/b-mi.

ECI. Impact Produced Failure of End Cap

Failure of any portion of the cask body by accident produced stimuli is estimated to be no higher than 2×10^{-14}/b-mi. The end cap is assumed to be built to similar standards with more protection and much smaller target area. Therefore, a derating factor of .1 is used for an overall likelihood of impact failure of an end cap of 2×10^{-15}/b-mi.

* A campaign to servide a 1000 MWe PWR requires 3-4 shipments of spent fuel per year. Using 4 trips per year and an average journey of 1300 mi. between utility site and receiving facility yields an exposure distance of 5.2×10^3 b-mi/yr.

ISD1,OSD1. Failure of a Defective Closure Seal

Fullwood[5-3] evaluated the probability of failure of a defectively manufactured closure seal to be 1.1×10^{-7}/c-mi. from data supplied by RADC.[5-10] This value is conservative because the seals used in spent fuel casks are of better than average quality.

ISD2, OSD2. Failure of Closure Seal Due to Incorrect Installation

The probability of accidents involving cargo damage, excluding only the most minor category of occurrences, is 5.0×10^{-6}/b-mi (Appendix B). The probability of the seal not being installed correctly is conservatively set at 1.0×10^{-4}/seal extracted from Gilbert and Fullwood[5-11] which yields an overall probability of an ISD2, OSD2 occurrence of 5.0×10^{-10}/b-mi.

TF1. Failure to Test Cask Pressure Seal Integrity Prior to Cask Shipment

Gilbert and Fullwoods' estimate of 1.0×10^{-4}/occurrence is used directly here as 1.0×10^{-4}/journey.

ISDI, OSDI. Failure of Inner or Outer Closure Seals Due to Accident Impact

It is conservatively estimated that a seal will fail in 10% of the accidents where the cask is severely impacted. Therefore, from Appendix B, a value of 4.8×10^{-12} is used as the probability of OSDI. Failure of the inner seal is assumed to occur 10% of the cases where failure of the outer seal occurs. Therefore, ISD1 has a value of .1.

PRV1. Unavailability of Pressure Relief Valving (Wet Cask)

Failure of pressure relief valving in the closed position is estimated in WASH-1400[5-12] to be in the range of 3.5×10^{-6} to 3.5×10^{-5}/demand. The average probability experienced in the nuclear industry is 1.1×10^{-5}/demand, which is used as the overall failure probability.

PRV2. Unavailability of Pressure Relief Valving From Impact-Induced Failure (Wet Cask)

This is a conditional probability of failure due to impact of the pressure relief valving. PRV2 is estimated to be an order of magnitude more probable than puncture of the main cask body. Thus, the estimate used here for PRV2 is 1×10^{-4}/demand.

CF. Conditional Probability of Significant Mechanical Failure (50% of the Fuel Element Claddings) Given A Failure of the Inner Cask Boundary

Fullwood[5-3] estimated that 50% of the contained fuel claddings would rupture from mechanical stimuli given a failure of the cask boundary such as that postulated for his failure categories 3 and 4 which correspond to RDA2, RWA2 and RDA3, RWA3, respectively, in this study. Thus, CF is estimated to be 0.5 in the absence of sufficient data.

CLF. Cask Flooding After Immersion with a Minor Breach of Cask Boundary (Dry Cask)

It is estimated that a breach will be severe enough to eliminate back pressure and allow flooding of the cask in about 10% of cases involving minor breach of cask containment.

STE1. Sustained Thermal Environment Following an Accident Involving a Penetration Failure of a Cask

An upper bound on the probability of this conditional event can be taken from the data in Appendix B as .07. For conservatism a value of .1 is used in this study.

CRW. Conditional Coolant Boiloff (Wet Cask)

Shappert et al.[(5-5)] indicated that RWA4 could possibly occur if the cask were allowed to remain in a high temperature environment for 71 hours (severe accident category). The probability of such a fire was estimated to be 0.1, which is also used here.

CL. Conditional Post Accident Immersion of Cask

This event refers to cask immersion after the cask boundary has been breached, and its probability is evaluated as 0.5 in the absence of any further information.

CLEW. Cask Flooding After Immersion With a Minor Breach of Cask Boundary (Wet Cask)

During an accident involving immersion of a wet cask, the cask may already be filled with coolant. In this case, a small release through diffusion mechanisms is more likely for the wet cask than for the dry cask which must fill with water in all cases. A probability of 0.2 is used for the conditional probability of a minor release from a wet cask during an immersion accident.

5.5 Accident Analysis Results and Discussion

5.5.1 Quantitative Results of Fault Tree Evaluations for Dry and Wet Casks

The probability of each postulated release event defined in Section 5.3 is evaluated, per mile of travel, in Table 5.6 for the dry cask and in Table 5.7 for the wet cask.

Given that an accident has occurred involving an air release, the most probable form of failure of a dry cask is a minor failure of the cask containment boundary as defined in Section 5.3.1. The most probable release from a wet cask could occur because of pressure relief venting after an extended exposure of the cask to a thermal environment.

The fractional contribution of the severe and very severe release events to the total probability of any release involving a dry cask is less than .05%. Similarly, the

Table 5.6. Summary of Dry Cask Release Frequencies for Waterborne Transport and Comparison With Release Frequencies for Rail Transport

Release Category	Release Description	Probability of Occurrence in a Waterborne Accident per Barge Mile of Travel (1/b-mi)	Probability of Occurrence in a Rail Accident per Car Mile of Travel (1/c-mi)
RD	release of radioactivity to the environment	$8.3x10^{-11}$	$9.4x10^{-9}$
RDA1	air release, minor failure of cask containment, no significant mechanical damage to fuel (<1% broken claddings)	$7.9x10^{-11}$	$9.0x10^{-9}$
RDA2	air release, major failure of cask containment, significant mechanical damage to fuel (≈50% broken claddings)	$2.5x10^{-14}$	$4.0x10^{-10}$
RDA3	air release, major failure of cask containment, significant mechanical damage to fuel, overheating of fuel	$2.5x10^{-15}$	$2.0x10^{-12}$
RDL1	liquid release, minor failure of cask containment, no significant mechanical damage to fuel	$4.0x10^{-12}$	-
RDL2	liquid release, major failure of cask containment significant mechanical damage to fuel	$1.2x10^{-14}$	-

Table 5.7. Summary of Wet Cask Release Frequencies for Waterborne Transport and Comparison with Release Frequencies for Rail Transport

Release Category	Release Description	Probability of Occurrence in a Waterborne Accident per Barge Mile of Travel (1/b-mi)	Probability of Occurrence in a Rail Accident per Car-Mile of Travel (1/c-mi)
RW	release of radioactivity to the environment	4.4×10^{-10}	3.8×10^{-8}
RWA1	air release, minor failure of cask containment, no significant mechanical damage to fuel (<1% broken claddings)	9.5×10^{-11}	9.0×10^{-9}
RWA2	air release, major failure of cask containment, significant mechanical damage to fuel (≈50% broken claddings)	2.5×10^{-14}	4.0×10^{-10}
RWA3	air release, major failure of cask containment, significant mechanical damage to fuel, overheating of fuel	2.5×10^{-15}	2.0×10^{-12}
RWA4	air release, immersion of cask in thermal environment for sufficient period of time to require pressure relief venting (>1 hr fire with no reestablishment of cooling for >11 hrs.)	3.4×10^{-10}	2.9×10^{-8}*
RWL1	liquid release, minor failure of cask containment, no significant mechanical damage to fuel	9.5×10^{-12}	-
RWL2	liquid release, major failure of cask containment with significant mechanical damage to fuel	1.2×10^{-14}	-

* determined using ratio of rail to intermodal probability for RWA1.

fractional contribution of all major release events to the total probability of any release from a wet cask is approximately .01%.

Because of the possibility of a design basis accident involving venting, the overall probability of release from the wet cask is higher than the probability of release from the dry cask. However, the difference is approximately a factor of five, which is not statistically significant since all probabilities used in the evaluation are order of magnitude estimates.

The probability of an air release from either type of cask during waterborne shipment versus rail shipment suggests a lesser likelihood of an air release during waterborne shipment. Waterborne shipment presents the possibility of a release to the hydrosphere. The probability of a severe water release (RDL2) and the probabilities of minor, severe, and very severe air releases (RDA1, RDA2, and RDA3) from a dry cask per reactor year of operation are given in Table 5.8 for each of the generic routes of Section 1.0 and for an average long waterborne route. The average long waterborne route is the mean of the generic route distances weighted by the number of utility sites accessible by each route. An equivalent rail distance for comparison was determined for each waterborne route. The equivalent rail distance corresponds to the total of the waterborne distance and the intermodal transfer distance (see Section 7.0) multiplied by 0.7. The probability of a release occurring during the land portion of an intermodal trip is assumed to be the same per mile as the probability of release during rail shipment.

Table 5.8. Probability of Radioactive Release From a Dry Cask per Reactor Year Using Intermodal and Strictly Rail Forms of Transport

Generic Route Number	Waterborne Distance (mi)	Rail or Other Overland Mode Distance (mi)	Equivalent Rail Distance (mi)	Frequency of a Minor Air Release: Intermodal Shipment (1/R-yr)	Frequency of a Minor Air Release: Rail Shipment (1/R-yr)	Frequency of a Severe Air Release: Intermodal Shipment (1/R-yr)	Frequency of a Severe Air Release: Rail Shipment (1/R-yr)	Frequency of a Very Severe Air Release: Intermodal Shipment (1/R-yr)	Frequency of a Very Severe Air Release: Rail Shipment (1/R-yr)	Frequency of Severe Liquid Release (1/R-yr)
1	1647	11	1161	7.5×10^{-7}	3.4×10^{-5}	1.4×10^{-8}	1.5×10^{-6}	8.5×10^{-11}	7.6×10^{-9}	6.4×10^{-11}
2	1229	35	685	1.3×10^{-6}	2.6×10^{-5}	4.6×10^{-8}	1.2×10^{-6}	2.4×10^{-10}	5.8×10^{-9}	4.8×10^{-11}
3	1573	64	1146	2.3×10^{-6}	3.4×10^{-5}	9.3×10^{-8}	1.5×10^{-6}	4.3×10^{-10}	7.5×10^{-9}	6.1×10^{-11}
4	110	450	560[a]	1.3×10^{-5}	1.6×10^{-5}	5.9×10^{-7}	7.3×10^{-7}	2.9×10^{-9}	3.6×10^{-9}	4.3×10^{-12}
5	1478	41	1063	1.6×10^{-6}	3.1×10^{-5}	5.3×10^{-8}	1.4×10^{-6}	2.8×10^{-10}	6.9×10^{-9}	5.8×10^{-10}
6	1469	15	1039	8.2×10^{-7}	3.0×10^{-5}	1.9×10^{-8}	1.4×10^{-6}	1.2×10^{-10}	6.5×10^{-9}	5.8×10^{-10}
7	988	41	720	1.5×10^{-6}	2.1×10^{-5}	5.3×10^{-8}	9.4×10^{-7}	2.7×10^{-10}	4.7×10^{-9}	3.9×10^{-10}
8	684	23	495	8.5×10^{-7}	1.5×10^{-5}	3.0×10^{-8}	6.1×10^{-7}	1.6×10^{-10}	3.2×10^{-9}	$2.7\times10^{-}$[illegible]
National[b] Average Route	1311	33	941	1.3×10^{-6}	2.8×10^{-5}	4.3×10^{-8}	1.2×10^{-6}	2.3×10^{-10}	6.1×10^{-9}	5.1×10^{-11}

[a] Equivalent rail mileage not derated with respect to waterborne distance since waterborne link is short and direct

[b] The average route mileage excludes short waterborne link route 4 and is weighted by the number of utility sites accessible by each route.

As shown in Table 5.8, the predicted probabilities indicate that an accidental release from a dry cask is less likely per reactor year using the intermodal mode of shipment as opposed to strictly rail shipment. For most generic intermodal routes, the probability of release during the land portion of the trip is greater than the probability of release during the waterborne portion.

The probability of a severe air release and severe release to water during intermodal transport are essentially a function of the likelihood of a cask puncture. Major contributions to the likelihood of a cask puncture are the probability of missiles penetration (detonation and collision) and stub penetrations, which are evaluated in Appendix B. However, in Appendix B it is noted that there is uncertainty concerning the adequacy of penetration modeling. In particular, the likelihood of a large missile being produced in low speed collisions or in detonation is not clearly established. Nor is the likelihood clearly established of encountering a projection of sufficient density, strength and immobility to be called a stub.

The results of penetration modeling indicate that all cask puncture phenomena have a probability of occurrence of less than 10^{-10} per reactor year or 10^{-4} to 10^{-3} less than the most probable form of release producing phenomena.

Therefore, puncture producing events must be considered low probability events and even though the modeling is inexact, it provides a conservative limit on the risk from puncture initiators.

5.5.2 Comparison of Accident Release Probabilities for Various Scenarios

The three following spent fuel transport scenarios are used in normalizing the release probabilities estimated in the previous section to a national scale:

a) Five percent (5%) of all spent fuel transported yearly will be moved by intermodal transport. The remaining 95% will be transported by rail (85%) and by legal weight truck (10%). This scenario is in keeping with previous analyses of spent fuel transport.[5-4]

b) Forty percent (40%) of all spent fuel transported yearly will be moved by intermodal transport. This scenario is based on projections that 80% of all units operating in 1985 will be accessible for barge transport. However, route economics and waterway closure for up to 5 winter months a year could considerably reduce use of waterborne transport.

c) Eighty percent (80%) of all spent fuel transported yearly will be moved by intermodal transport. This is an upper bound scenario anticipating that all units accessible by barge will use intermodal transport.

Table 5.9 compares the overall probability of accident release for all three of the above described spent fuel shipping strategies using dry cask probability data, and

Table 5.9. Probability of Radioactive Release Per Year from Spent Fuel Shipping

Spent Fuel Transport Strategy	Probability of Release Per Year				
	Any Release	Minor Air Release	Severe Air Release	Very Severe Air Release	Severe Water Release
land transport 95%, intermodal transport 5% (units on line in 1977)	1.7×10^{-3}	1.7×10^{-3}	7.1×10^{-5}	3.6×10^{-7}	1.5×10^{-10}
land transport 95%, intermodal transport 5% (units on line in 1985)	5.3×10^{-3}	5.1×10^{-3}	2.2×10^{-4}	1.1×10^{-6}	5.1×10^{-10}
land transport 60%, intermodal transport 40% (by 1985)	3.5×10^{-3}	3.3×10^{-3}	1.4×10^{-4}	7.2×10^{-7}	3.9×10^{-9}
land transport 20%, intermodal transport 80% (by 1985)	1.3×10^{-3}	1.3×10^{-3}	5.2×10^{-5}	2.7×10^{-7}	7.8×10^{-9}

Figure 5.10 illustrates the predicted differences in the probabilities of accidental radioactive release per year for these three strategies as a function of metric tonnage shipped. Figure 5.10 also indicates the decrease in overall accident release probability achieved by using increasing amounts of waterborne transport. Table 5.9 shows that the decrease in accident risk occurs across the spectrum of risk categories and that the probability of a water release during intermodal transit never exceeds the probability of a very severe air release.

The probability of accidental release per year is compared to the probability of release of a similar spent fuel shipping mix calculated by Hodge & Jarrett[5-4] in Figure 5.11. The figure also shows that the probability of release calculated in Reference 5-3 and in this report are much lower than those in Reference 5-4. It is noteworthy that the same wet cask design was considered in both Reference 5-4 and in this report.

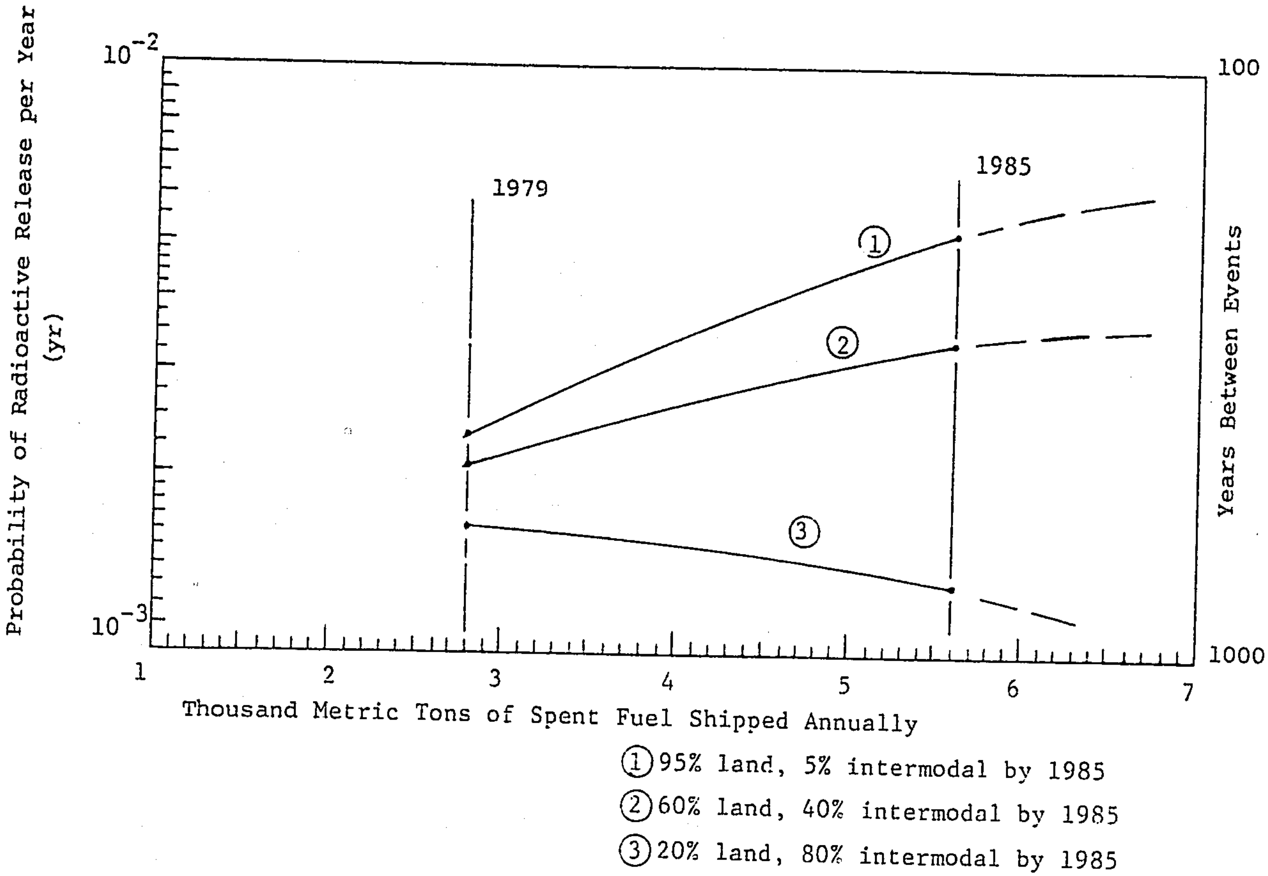

Figure 5.10. Probability of a Radioactive Release per Year For All U.S. Reactors Resulting From a Spent Fuel Shipping Accident as a Function of Amount of Fuel Shipped*

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* Using dry cask accident probability data and assuming that spent fuel is being shipped at the rate of discharge.

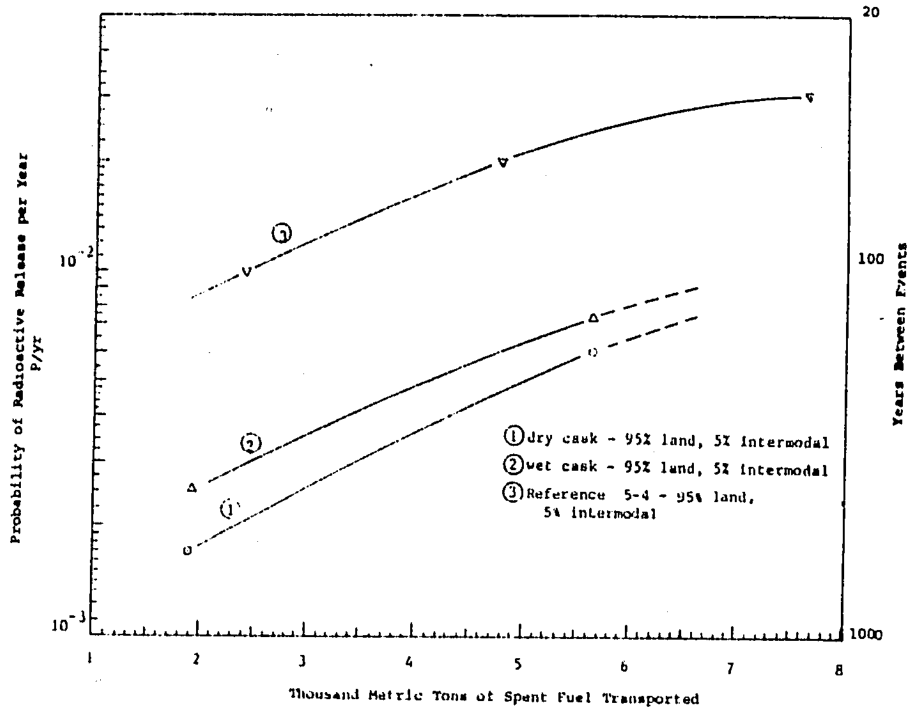

Figure 5.11. Probability of a Radioactive Release per Year for Various Cask Transport Cases as a Function of Metric Tons of Spent Fuel Shipped

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6.0 ACCIDENT CONSEQUENCE ANALYSIS AND RISK ASSESSMENT

6.1 Purpose and Summary

In Section 5.0, a broad spectrum of release producing accidents involving large spent fuel casks was defined, and the likelihood of each accident was determined probabilistically. All accident release events postulated in this report were assumed to result in the release of some radioactivity from the cask, either to the air or to water. The probability of each event was estimated for intermodal shipment of spent fuel casks and for cask shipment exclusively by rail.

None of the release events postulated for intermodal transport accidents in the probabilistic evaluation in Section 5.0 has a probability of occurrence greater than 5×10^{-6}/Reactor-year (R-yr), and all severe release events postulated had a probability of occurrence of less than 1×10^{-7}/R-yr.

In this section the consequences of each accident postulated in Section 5.0 are estimated and the resultant risk to the public is evaluated. The methodology for determining air release consequences was taken from WASH-1400[6-1] while the methodology for determining water release consequences was taken from NRC regulatory guides.[6-2]

Using the intermodal accident probabilities of Section 5.0, an estimate was made of the contribution to the public risk from each release category defined and the cumulative public risk from intermodal transport of spent fuel.

A similar risk estimate was compiled for spent fuel handled exclusively by rail based on the rail accident probabilities of Section 5.0.

Risk to the public was evaluated for spent fuel shipping strategies involving different levels of intermodal shipment and was based on projections of the number of reactors expected to be on line by 1985. The results of this risk assessment are summarized below:

1. The average risk to the public from all postulated release accidents (air and water releases) is 1.2×10^{-6} man-rem/R-yr if spent fuel is transported between utility sites and receiving facilities by intermodal means using waterborne transport as the major transport mode.

2. The average risk to the public from radioactive release accidents is approximately 4.0×10^{-7} man-rem/R-yr if spent fuel is transported exclusively by rail. This is a factor of 3 smaller than the risk from intermodal transport due entirely to the fact that with waterborne transport there is the added risk of a release to water. The difference is not statistically significant since the uncertainty in these results is likely to be larger than one order of magnitude.

3. Estimated risk to the U.S. public from spent fuel transportation accidents for a 1985 population of reactors (from Section 1.0) is 7.9×10^{-5} to 1.3×10^{-4} man-rem/year, depending on the extent of utilization of waterborne transport. The higher estimate corresponds to heavy use of waterborne transport (i.e., servicing 40% of all operating reactors) while the lower estimate corresponds to a light use scenario (i.e., servicing 5% of all operating reactors).

4. Comparison of this study's results with those of WASH-1400 indicates that while the risk from transportation of spent fuel may vary by a factor of 2 depending on the mode mix used, the risk from transportation of spent fuel by any mode considered in this report is smaller than the risk from light water reactor operation by a factor of more than 10

5. Comparison of this study's results with other estimates of spent fuel transport risk from the literature reveal that the risk estimates of this study are bounded by the results of other studies and that the highest and lowest risk estimates are separated by less than an order of magnitude.

6.2 Cask Radioactive Inventory

All consequence calculations were performed using the conservative assumption of cask contents being recycled spent fuel assemblies from a 1000 MWe PWR irradiated 33×10^3 megawatt days/metric ton of uranium and cooled for 150 days. Inventories derived from Pu recycle do not represent the inventory of current shipped fuels, but their use was intended to conservatively represent potential future shipment inventories. Table 6.1 (from Reference 6-3) lists cask nuclide constituents along with their cask inventory (in curies) for a dry cask containing ten fuel assemblies. The inventory of a wet cask is 70% of the listed values, since a wet cask holds only seven assemblies.

Table 6.1. Major Isotopic Constituents of a Dry Cask Assuming that Fuel is Recycled From a 1000 MWe PWR at 33×10^3 MWD/MT Burnup and Cooled for 150 days(6-3)

[illegible]	[illegible]	[illegible]	[illegible]
H-3	$4.1 \times 10^{[illegible]}$	[illegible]	$1.0 \times 10^{[illegible]}$
Kr-85	3.1×10^4	Cs-134	$8.4 \times 10^{[illegible]}$
Sr-89	3.0×10^5	Cs-137	5.0×10^5
Sr-90	2.0×10^5	Ba-137m	$4.6 \times 10^{[illegible]}$
Y-90	2.0×10^5	La-140	2.1×10^3
Y-91	5.4×10^5	Ce-141	$2.1 \times 10^{[illegible]}$
Zr-95	1.1×10^6	Ce-144	3.0×10^6
Nb-95	2.2×10^6	Pr-144	3.0×10^6
Ru-103	4.5×10^5	Pm-147	4.7×10^5
Rh-103m	4.5×10^5	Pu-238	8.5×10^4
Ru-106	3.1×10^6	Pu-239	3.3×10^3
Rh-106	3.1×10^6	Pu-240	8.7×10^3
Sn-123	2.2×10^4	Pu-241	2.7×10^6
Sb-125	5.9×10^4	Pu-242	7.3×10^1
Te-127m	3.5×10^4	Am-241	7.1×10^3
Te-127	3.4×10^4	Am-243	2.3×10^3
Te-129m	1.4×10^4	Cm-242	1.1×10^6
Te-129	8.6×10^3	Cm-244	6.1×10^5

6.3 Air Release Source Terms

6.3.1 Air Release Due to a Minor Failure of the Cask Container Boundary with No Significant Fuel Damage (< 1% Cladding Failure) (RDA1, RWA1)*

It was assumed that no major deviation from normal thermal conditions exists during an accident in this release category. The impact of a failure of the inner containment boundary was considered. It is assumed that no significant (< 1%) cladding failure will occur during the shipment or as a result of the containment boundary failure. Thus, the release consists of the accumulated gases in the helium filled cavity for a dry cask or the accumulated insoluble gases for a wet cask.

Ritzman[(6-4)] has estimated the fractional release of fission gas from a cask containing 1% failed fuel as approximately 3×10^{-8}, based on a rod temperature of 700°F, an empirical diffusion coefficient of 1×10^{-22}/sec, and a release time of one week.

A more conservative estimating technique was used by Fullwood[(6-5)] based on the percentage of the fission gases being released to the fuel gap and plenum over the operating life of the fuel (approximately three years in this case).

Fullwood assumed that the release fraction of the r-th nuclide (η_r) of the fission gases from a failed rod is a

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* Release categories are defined in Section 5.0

linear function of time, τ, and an exponential function of temperature, T, as shown in equation (1).

$$\eta_r = L(\tau) \cdot E(T) \tag{1}$$

More specifically, the amount of fission gas released from a broken rod in a cask was assumed to be a linear function of the time the rod is in the cask, and an exponential function of the differences between the fuel temperature under reactor operating conditions, T_R(^oK), and fuel temperature under conditions in the cask, T_D(^oK) or

$$\eta_r = \eta_r(\text{reactor}) \cdot \frac{\tau_{cask}}{\tau_{reactor}} \cdot \exp(-T_R/T_D) \tag{2}$$

where

η_r(reactor) = release fraction of the r-th fission gas nuclide released from the fuel over its operating life

τ_{cask} = time spent in the cask by the broken fuel

$\tau_{reactor}$ = time spent in the reactor by the fuel

One week was used as the average residence time in the cask (for a cask involved in an accident during transport) and η_{Kr-85}(reactor) = 0.3.[6-6] A fuel pellet temperature of 2550^oF under operating conditions* and 700^oF† under decay heating conditions in the cask was assumed. The fraction of Kr-85 given off from a broken fuel rod in a cask using equation (2) is

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* This is approximately the maximum fuel rod volumetric average temperature which produces a Kr-85 release to the plenum of 0.3 during the core lifetime of a fuel rod.[6-7]

† will be less for a wet cask

$$\eta_{Kr-85}(\text{broken rod}) = (0.3)(\frac{1}{169})\ e^{-1672/644}$$

$$= 1.3 \times 10^{-4}$$

Assuming that 1% of the rods have failed during operation, the fractional release of Kr-85 from the entire cask inventory is

$$\eta_{Kr-85} = 1.3 \times 10^{-6}$$

The value of η_r(reactor) for the other fission gases in the cavity is η_{I-131}(reactor) = 0.02 and η_{H-3}(reactor) = 0.01 (from Reference 6-6). Substituting these values in equation (2) and assuming 1% rod failure yields

$$\eta_{I-131} = 8.8 \times 10^{-8}$$

and

$$\eta_{H-3} = 4.4 \times 10^{-8}$$

The scaling suggested by Ritzman was considered more realistic, but Fullwood's scaling provides a conservative upper limit to the quantities of fission gases released.

6.3.2 Air Release Caused by Major Breach of Cask Containment Boundary with Subsequent Mechanical Damage to 50% of the Fuel (RDA2, RWA2)

Heat transfer characteristics were assumed to be unchanged in this accident; but in this release category 50% of the fuel is assumed to be damaged during cask containment failure. In this case, all of the fission gas collected in the fuel rod plenum in the three year operating life of the fuel will be given off, since the rod damage occurs in the accident.

Using estimates of fission gas isotopic fractions in the clad gap provided by WASH-1250[6-6], the following release fractions were obtained:

$$\eta_{H-3} = 5.0 \times 10^{-3}$$

$$\eta_{Kr-85} = 1.5 \times 10^{-1}$$

$$\eta_{I-131} = 1.0 \times 10^{-2}$$

6.3.3 Air Release Caused by Major Breach of Cask Containment with Subsequent Overheating of Fuel (RDA3, RWA3)

This category represents the extreme in accident consequences for both the dry and wet cask designs and is similar to the "beyond design basis accident" analyzed in WASH-1238.[6-8]

A major difference between this release and that for RDA2, RWA2 is that some semivolatiles, such as cesium, can be released in the presence of a high thermal environment when poor heat transfer conditions exist in the cask. Under the severe thermal conditions given in WASH-1238, 50% of the fuel rods were assumed to fail due to high temperature creep effects. Temperatures inside the cask were assumed to exceed 1200^{o}F and to be sufficient to volatilize any uncombined (metallic) cesium available at the surface of the fuel.

Original estimates from WASH-1238 indicated that the release fraction η_{Cs} is approximately 4.5×10^{-5}. A more recent analysis in WASH-1238 Supplement II[6-9] placed

η_{Cs} at 1.5×10^{-4} by considering the amount of metallic cesium present and the amount which would not recombine with UO_2 before perforation occurs. The latter estimate was used in the analysis of RDA3 and RWA3 for the release fractions of Cs-134 and Cs-137 since it is based on a large body of experimental data; however, it is still considered conservative because it does not correct for the condensation and plateout of cesium which would reduce the actual release to the environment.

6.3.4 Air Release Due to Prolonged Exposure to Thermal Environment; Loss of Coolant Through Vaporization and Pressure Relief, but No Loss of Containment Boundary Effectiveness (RWA4)

This was actually a design basis accident as analyzed by the manufacturer's safety analysis report.(6-10) It was also treated in Reference 6-9. With no containment failure the steam remaining in the cavity provides a medium for convective heat transfer sufficient to keep fuel rod cladding temperatures at or below 965°F. At these temperatures, additional rod perforations from creep rupture are not expected. The main loss mechanisms therefore include the loss of fission gas and the leakage of cesium to the coolant from mechanically broken pins, followed by subsequent loss to the atmosphere during blowdown.

In Reference 6-9 one accident scenario is considered in which 10% of the rods inside a wet cask are damaged and the cask is immersed in a thermal environment which vaporizes all of the coolant. A cesium release fraction of 3.4×10^{-6} is given to account for leaching of some cesium from broken rods by the coolant during the accident and release of that cesium through pressure relief of the cask as the coolant is vaporized. The release fraction given in Reference 6-9 is overly conservative since it does not reflect the fact that cesium in the coolant will not necessarily be in a form which can be vaporized and released during pressure relief.

The over-conservatism of Reference 6-9 stems from the fact that the main thrust of that analysis was to determine the amount of cesium given off at a later time in their scenario, when all the coolant has been lost by pressure relief from the cask, and an even more severe thermal environment exists in which the cask is dry, unbroken rods are perforated and cesium is volitalized directly. By comparison with the amount of cesium released directly by volatilization, the amount of cesium leached by the coolant and given off during pressure relief is not significant.

Since the cesium in the cask coolant probably exists in an oxidized form, it would be inefficiently given off with steam vapor. Several estimates from the literature [6-11,6-12] cite the fraction of a non-volatile species present in a solution which can be given off as 1×10^{-4} to 1×10^{-5}. Therefore, the fraction of cesium released in the RWA4 accident is the product of the fraction released from the broken fuel to the coolant[6-7] and the fraction releasable from solution in the coolant to the coolant vapor [6-11,6-12], or $(3.4 \times 10^{-6}) \bullet (1 \times 10^{-4}) = 3.4 \times 10^{-10}$. This number was used in this analysis to estimate the fraction of cesium given off from a wet cask in which 10% of the rods were broken.

It was difficult to estimate the extent of mechanical damage to rods in an accident involving collision and fire but with no violation of the cask boundary. A lower bound was selected as the case where no fuel rod breakage resulted from the accident, so that the 1% clad failures assumed were those that occurred during reactor operation. The upper bound assumed was a total of 10% rod breakage. The release fraction was assumed to be distributed log normally and the geometric mean of the two bounds was calculated and used as the release fraction for each nuclide constituent in the calculation of air release source terms for the RWA4 accident. All of these release fractions are shown in Table 6.2.

A summary of release accident source constituents, release fractions, and corresponding source strengths is given in Table 6.3 for all accidents.

6.4 Air Release Consequence Calculations

Consequences of air release accidents, including individual doses (rem) and population doses (man-rem), were calculated with a modified version of the consequence code used in the (Draft) Reactor Safety Study[(6-1)]. The code was simplified for use in this analysis in that plume rise and evacuation were not considered. The code uses a probabilistic combination of weather conditions

Table 6.2. Air Release Fraction (η) for Various % Cladding Failure in a Pressure Venting Loss of Coolant Accident Involving a Wet Cask (RWA4)

	NUCLIDE	η
1% Rods Broken	H-3	3.6×10^{-7}
	Kr-85	1.1×10^{-5}
	I-131	7.2×10^{-7}
	Cs-134	3.4×10^{-11}
	Cs-137	3.4×10^{-11}
10% Rods Broken	H-3	1.7×10^{-3}
	Kr-85	5.0×10^{-2}
	I-131	3.3×10^{-3}
	Cs-134	3.4×10^{-10}
	Cs-137	3.4×10^{-10}
Geometric Mean*	H-3	2.5×10^{-5}
	Kr-85	7.4×10^{-4}
	I-131	4.9×10^{-5}
	Cs-134	1.1×10^{-10}
	Cs-137	1.1×10^{-10}

* Used in the source term release calculations for RWA4

Table 6.3. Air Release Source Terms From Dry and Wet Cask Release Categories (for PWR Pu recylce fuel @ 33 x 10^3 MWD/MT burnup, cooled for 150 days)

Release Category	Nuclide Released	Air Release Fraction(η)	Air Release Source*(Ci)
RDA1	H-3 Kr-85 I-131	4.4×10^{-8} 1.3×10^{-6} 8.8×10^{-8}	1.8×10^{-4} 4.1×10^{-2} 8.8×10^{-7}
RDA2	H-3 Kr-85 I-131	5.0×10^{-3} 1.5×10^{-1} 1.0×10^{-2}	2.1×10^{1} 4.7×10^{3} 1.0×10^{-1}
RDA3	H-3 Kr-85 I-131 Cs-134 Cs-137	5.0×10^{-3} 1.5×10^{-1} 1.0×10^{-2} 1.5×10^{-4} 1.5×10^{-4}	2.1×10^{1} 4.7×10^{3} 1.0×10^{-1} 1.3×10^{2} 7.5×10^{1}
RWA1	H-3 Kr-85 I-131	4.4×10^{-8} 1.3×10^{-6} 8.8×10^{-8}	1.3×10^{-4} 2.9×10^{-2} 6.2×10^{-7}
RWA2	H-3 Kr-85 I-131	5.0×10^{-3} 1.5×10^{-1} 1.0×10^{-2}	1.5×10^{1} 3.3×10^{3} 7.0×10^{-2}
RWA3	H-3 Kr-85 I-131 Cs-134 Cs-137	5.0×10^{-3} 1.5×10^{-1} 1.0×10^{-2} 1.5×10^{-4} 1.5×10^{-4}	1.5×10^{1} 3.3×10^{3} 7.0×10^{-2} 8.9×10^{1} 5.3×10^{1}
RWA4	H-3 Kr-85 I-131 Cs-134 Cs-137	2.5×10^{-5} 7.4×10^{-4} 4.9×10^{-5} 1.1×10^{-10} 1.1×10^{-10}	7.3×10^{-2} 1.6×10^{1} 3.4×10^{-5} 6.5×10^{-5} 3.9×10^{-5}

* Air release source term values for wet cask releases are 70% of the equivalent dry cask releases because the wet cask inventory is 70% of dry cask inventory.

and deposition parameters. The population distribution was assumed to be similar to that surrounding an average nuclear reactor, i.e., no population area near the source, and an average population distribution moving out radially from the source. Probabilistic results are given in Table 6.4 for all the air release sources defined in Section 6.3.

As discussed above, the consequence code sampled a set of release consequences utilizing probabilistic weather and wind conditions in each iteration. The average consequences, given in Table 6.4, were the average of all iterated calculations using all potential weather conditions and a cross-section of population distributions. The maximum consequence, also shown in Table 6.4, was the worst combination calculated and provided an upper bound.

The risk to the public from air release accidents occurring during intermodal transport of spent fuel is given in Table 6.4 as the integral of whole-body doses. The whole-body dose risk from spent fuel shipping using dry or wet casks is approximately 1.4×10^{-8} man-rem/R-yr. The risk from air release accidents is approximately an order of magnitude larger for spent fuel shipping by rail only, being 3.7×10^{-7} man-rem/R-yr and 3.8×10^{-7} man-rem/R-yr for dry and wet casks, respectively.

Table 6.4. Summary of Air Release Consequence Calculation Results

Air Release Category: Designation	Air Release Category: Description	Dose Type	Population Dose Per Accident (Man-rem): Average	Population Dose Per Accident (Man-rem): Maximum	Risk to the Public From Intermodal Transport (man-rem/Reactor-year): Average	Risk to the Public From Intermodal Transport (man-rem/Reactor-year): Maximum
RDA1	minor air release dry cask, no significant fuel damage	WBD(50 year)	2.5×10^{-7}	8.4×10^{-6}	3.3×10^{-13}	1.1×10^{-11}
		Lung	2.3×10^{-7}	7.4×10^{-6}	3.0×10^{-13}	9.7×10^{-12}
		WBD(30 day)	2.5×10^{-7}	8.4×10^{-6}	3.3×10^{-13}	1.1×10^{-11}
		Thyroid	2.0×10^{-6}	3.3×10^{-5}	2.6×10^{-12}	4.3×10^{-11}
RDA2	severe air release, dry cask, significant mechanical fuel damage	WBD(50 year)	2.9×10^{-2}	9.7×10^{-1}	1.2×10^{-9}	4.2×10^{-8}
		Lung	2.6×10^{-2}	8.5×10^{-1}	1.1×10^{-9}	3.7×10^{-8}
		WBD(30 day)	2.9×10^{-2}	9.6×10^{-1}	1.2×10^{-9}	4.1×10^{-8}
		Thyroid	2.3×10^{-1}	3.7×10^{0}	9.9×10^{-9}	1.6×10^{-7}
RDA3	very severe air release, dry cask, significant fuel damage plus over-heating of fuel	WBD(50 year)	5.5×10^{1}	1.1×10^{3}	1.2×10^{-8}	2.5×10^{-7}
		Lung	5.5×10^{1}	1.1×10^{3}	1.2×10^{-8}	2.4×10^{-7}
		WBD(30 day)	4.2×10^{1}	1.0×10^{3}	9.5×10^{-9}	2.3×10^{-7}
		Thyroid	3.7×10^{1}	9.9×10^{2}	8.3×10^{-9}	2.3×10^{-7}
RWA1	minor air release, wet cask, no significant fuel damage	WBD(50 year)	1.8×10^{-7}*	6.0×10^{-6}	3.5×10^{-13}	1.1×10^{-11}
		Lung	1.6×10^{-7}	5.1×10^{-6}	3.1×10^{-13}	9.5×10^{-12}
		WBD(30 day)	1.7×10^{-7}	5.7×10^{-6}	3.3×-0^{-13}	1.1×10^{-11}
		Thyroid	1.3×10^{-6}	2.2×10^{-5}	2.5×10^{-12}	4.1×10^{-11}
RWA2	severe air release wet cask, significant fuel damage	WBD(50 year)	2.0×10^{-2}	6.8×10^{-1}	1.2×10^{-9}	4.2×10^{-8}
		Lung	1.8×10^{-2}	6.0×10^{-1}	1.1×10^{-9}	3.7×10^{-8}
		WBD(30 day)	2.0×10^{-2}	6.8×10^{-1}	1.2×10^{-9}	4.2×10^{-8}
		Thyroid	1.6×10^{-1}	2.6×10^{0}	9.8×10^{-10}	1.6×10^{-7}
RWA3	very severe air release, wet cask, significant fuel damage plus over-heating of fuel	WBD(50 year)	3.8×10^{1}	7.9×10^{2}	1.2×10^{-8}	2.5×10^{-7}
		Lung	3.8×10^{1}	7.9×10^{2}	1.2×10^{-8}	2.5×10^{-7}
		WBD(30 day)	2.9×10^{1}	7.0×10^{2}	9.3×10^{-9}	2.3×10^{-7}
		Thyroid	2.5×10^{1}	6.9×10^{2}	8.0×10^{-9}	2.2×10^{-7}
RWA4	air release, wet cask pressure vent loss of coolant accident	WBD(50 year)	1.3×10^{-4}	4.0×10^{-3}	8.5×10^{-10}	2.6×10^{-8}
		Lung	1.1×10^{-4}	3.5×10^{-3}	7.2×10^{-10}	2.3×10^{-8}
		WBD(30 day)	1.2×10^{-4}	3.8×10^{-3}	7.8×10^{-10}	2.5×10^{-8}
		Thyroid	1.7×10^{-4}	3.8×10^{-3}	1.0×10^{-9}	2.5×10^{-8}
Dry cask Total Risk From Air Release		WBD(50 year)			1.4×10^{-8}	2.9×10^{-7}
Wet cask Total Risk From Air Release		WBD(50 year)			1.4×10^{-8}	3.2×10^{-7}

* estimated using RDA1 results

6.5 Consequences Due to Accidental Releases to the Hydrosphere From a Spent Fuel Shipping Cask (Cask Immersion Accident)

In Section 5.0, it was shown that the probability of a liquid release accident was small ($P = 5.1 \times 10^{-11}$/R-yr). However, in order to complete an estimate of public risk from intermodal waterborne transport of spent fuel, it was necessary to evaluate the consequences of a radionuclide release to the hydrosphere resulting from a spent fuel transportation accident.

6.5.1 Source Term for a Cask Immersion Accident

A source term for accidents in which radionuclides are released to water was developed on the basis that the cask is sufficiently damaged to allow free flow of water through it and a significant fraction of the rods have been broken inside. Criteria for development of a liquid release source term are given in Appendix C. Essentially, a breakdown of release fractions into prompt and delayed source terms similar to that employed by the NRC in NUREG-0140[(6-13)] was used.

The significant nuclide constituents of a liquid release accident were estimated using the expression

$$K_{Hi} = I_{ci} \cdot \eta_{Li} \cdot \alpha_i \cdot 10^{-6} \qquad (4)$$

where

K_{Hi} = the hazard index which for a particular nuclide is an individual whole body dose resulting from ingestion of one millionth of the contents of the cask (rem)

I_{ci} = the dry cask inventory of the nuclide (Ci)

η_{Li} = fraction of the nuclide released during the accident (dimensionless)

α_i = the 50 year whole body dose commitment factor for the nuclide ingested (rem/μCi)

10^{-6} = a conversion factor (Ci/μCi)

Hazard indexes for the dry cask nuclides released to the hydrosphere are given in Table 6.5. In the liquid pathway analysis, only those nuclides identified as critical on Table 6.5 were considered. Nuclides were eliminated as major contributors if the sum of their hazard index and those of the remaining non-critical nuclides did not equal 1% of the total hazard index (or dose).

6.5.2 Consequences to the Individual of a Cask Immersion Accident

A barge accident resulting in a release from a spent fuel cask to water can occur in a variety of aquatic environments including lakes, estuaries, open oceans and rivers. Of the aquatic environments a river used as a source of drinking water and fresh water fish by the population along its shores is assumed to represent a worst case for the purpose of estimating the consequences of a liquid release accident. Thus,

Table 6.5. Liquid Release Nuclides with the Largest Hazard Indices

Nuclide	I_{ci} (Ci)	η_{Li} (24 hour)÷	η_{Li} (30 day)‡	α_i (rem/µCi)	Hazard Index K_{Hi} (rem)	Potentially Significant Dose Contributor*
Sr-89	3.0×10^{5}	.002	.0038	8.7×10^{-3}	9.9×10^{0}	Yes
Sr-90	2.0×10^{5}	.002	.0038	1.7×10^{-1}	1.3×10^{2}	Yes
Y-90	2.0×10^{5}	.001	.0028	2.5×10^{-7}	1.4×10^{-4}	
Y-91	5.9×10^{5}	.001	.0028	3.6×10^{-6}	5.9×10^{-3}	
Nb-95	2.2×10^{6}	.001	.0028	1.8×10^{-6}	1.1×10^{-2}	
Ru-103	4.5×10^{5}	.002	.0038	8.6×10^{-5}	1.1×10^{-3}	
Ru-106	3.1×10^{6}	.002	.0038	3.2×10^{-4}	3.8×10^{0}	Yes
Sn-123	2.2×10^{4}	.002	.0033	7.4×10^{-4}	6.2×10^{-2}	
Sb-125	5.9×10^{4}	.02	.0218	4.1×10^{-4}	5.3×10^{-1}	
Te-127m	3.4×10^{4}	.02	.0218	1.1×10^{-3}	8.2×10^{-1}	
Te-129m	1.4×10^{4}	.02	.0218	2.9×10^{-3}	8.9×10^{-1}	
I-131	1.0×10^{1}	.02	.0218	3.5×10^{-3}	7.6×10^{-4}	
Cs-134	8.4×10^{5}	.02	.0218	7.5×10^{-2}	1.4×10^{3}	Yes
Cs-137	5.0×10^{5}	.02	.0218	4.3×10^{-2}	4.7×10^{2}	Yes
Ce-141	2.3×10^{5}	.001	.0028	6.6×10^{-7}	4.3×10^{-4}	
Ce-144	3.0×10^{6}	.001	.0028	2.6×10^{-5}	2.2×10^{-3}	
Pu-238	8.5×10^{4}	.001	.0028	1.7×10^{-2}	4.0×10^{0}	Yes
Cm-242	1.1×10^{6}	.001	.0028	1.4×10^{-3}	4.3×10^{0}	Yes
Cm-244	6.1×10^{5}	.001	.0028	3.0×10^{-2}	5.1×10^{1}	Yes

* Nuclides are excluded as critical dose contributors if when added to the remaining non-critical nuclides they contribute less than 5% of the hypothetical hazard index dose.

÷ Release fraction for a 24 hour release includes only the prompt release source from Appendix C.

‡ Release fraction for a 30 day release includes the prompt plus delayed release source from Appendix C.

the product of the integrated population dose for a liquid release accident in a river and the probability of a major liquid release accident was used to produce a conservative estimate of the population risk due to liquid releases during barge transport. Population consequences were specifically estimated for a release from a spent fuel cask to a river with a medium flow rate* which is used as a water supply by 6×10^5 persons†.

Because of the low probability of occurrence of a liquid release event during spent fuel transport and the small fraction of cask inventory released, conservative techniques were used to produce first order estimates of the dispersion of radionuclides and individual doses to the population at risk from various liquid pathways‡.

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* A hypothetical river with a $2.8 \times 10^2 (m^3/sec)$ flow rate and an average flow area of $1 \times 10^3 m^2$.

† The EPA's fuel cycle impact analysis(6-14) assumes a population density of 2.0×10^3 persons/km on major U.S. rivers. The release is assumed to be effective 300 km downstream such that the at risk population is 6×10^5 persons. The distribution is arrived at by dividing the number of people in the U.S. living in large river watersheds by the length of rivers over 600 miles in length.

‡ While large scale averaging of dispersion, uptake, ingestion, and population makeup parameters could underestimate the maximum individual doses sustained in an accident, the values used for these parameters are believed to be conservative enough to overestimate the overall population dose.

The methodology used to estimate individual doses was essentially that put forth by the NRC in its guide for calculation of doses due to routine releases of reactor effluents RG 1.109.(6-2) The ensuing sections discuss individual doses from a liquid release which enters the food chain through the drinking water, fish, and irrigated food pathways, and which also causes exposure to the public from shoreline desposits.

6.5.2.1 Estimation of Nuclide Concentrations in Liquid Pathways

In order to determine the quantity of radionuclide available through various dose pathways after a release to water, it is necessary to estimate the concentration of the nuclide at a point downstream from the accident where the contaminated water enters the food chain.

In a river, there are a number of factors which affect the downstream concentration of a nuclide including the source strenth, the size of the river (average velocity, width, and flowrate), the turbulent dispersion of the flow, the nuclide decay rate, and the distance downstream from the source. The ratio of the downstream concentration to the initial concentration of the nuclide is the dilution factor.

Downstream dilution in a medium flow rate river (280 m^3/sec) is estimated in the EPA's fuel cycle impact analysis(6-14) simply by assuming that mixing is complete,

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taking the reciprocal of the flow rate and allowing an additional dilution factor of 10 due to downstream tributary inflow. Thus from EPA methodology

$$\frac{X}{Q} = 4.0 \times 10^{-4} \ (\frac{sec}{m^2})$$

The equivalent coefficient used in the NRC's liquid pathway dose equations in RG 1.109 is M/F where M is the dilution factor and F is the flow rate of contaminated effluent. For the case of releases from a spent fuel cask into a river, F is the flow rate through the cask.

A rigorous methodology for estimated downstream nuclide concentration (C_M) in a river is presented in RG 1.113.(6-15) However, the results of Appendix D suggest that the flow can be considered completely mixed and the concentration uniform across the channel within 20 mi downstream of the source. Thus in the medium flow river of the EPA study the steady state downstream concentration is

$$C_M = C_I \cdot \frac{F}{280} \qquad (5)$$

where C_I is the initial concentration of nuclide leaving the cask. Since

$$M = \frac{C_M}{C_I} \qquad (6)$$

then

$$\frac{M}{F} = 3.6 \times 10^{-3} \ (\frac{sec}{m^3}).$$

Assuming a further factor of 10 for tributary dilution as was done in the EPA methodology the dilution factor is

$$\frac{M}{F} = 3.6 \times 10^{-4} \left(\frac{sec}{m^3}\right)$$

which is essentially identical to the EPA dilution coefficient.

NRC dose equations for liquid pathways are expressed as functions of the downstream concentration of an individual nuclide, C_i ($\mu Ci/\ell$). The downstream concentration is given by the equation

$$C_i = 3.86 \times 10^{-4} \cdot Q_i \cdot \frac{M}{F} \cdot e^{-\lambda_i \tau_c} \qquad (7)$$

where

Q_i = amount of nuclide released during accident (Ci/mth)*

λ_i = decay constant for nuclide (hr^{-1})

τ_c = average transit time between point of release and point of entry of contaminated water into dose pathways (hr)

3.86×10^{-4} = a conversion factor $\left(\frac{m^3 - mth - \mu Ci}{\ell - sec - Ci}\right)$

In this study the accidental release of nuclides from a spent fuel cask to water is modeled as a release to a river for a period of 30 days. The 30 day release is considered an upper bound on the time needed for cask recovery. Table 6.6 shows the downstream concentration for nuclides during a 30 day release which are potentially significant contributors to one or more of the liquid dose pathways.

* Ci/mth = curies/month

Table 6.6. Downstream Concentration of Critical Nuclides Following a Spent Fuel Cask Release to a River* (30 day release time assumed)

Critical Nuclide	Q_i† (Ci/mth)	λ_i (hr^{-1})	τ_c (hr)	C_i (Ci/ℓ)
Sr-89	1.14×10^3	5.7×10^{-4}	1.5×10^2	1.45×10^{-4}
Sr-90	7.6×10^2	2.9×10^{-6}	1.5×10^2	1.06×10^{-4}
Ru-106	1.18×10^4	7.9×10^{-5}	1.5×10^2	1.62×10^{-3}
Cs-134	1.83×10^4	3.4×10^{-5}	1.5×10^2	2.53×10^{-3}
Cs-137	1.09×10^4	2.6×10^{-6}	1.5×10^2	1.51×10^{-3}
Cm-244	1.71×10^3	4.5×10^{-6}	1.5×10^2	2.37×10^{-4}

* with a flow rate of 280 m^3/sec

† the dry cask inventory of a nuclide multiplied by the 30 day release fraction $Q_i = I_{Ci} \cdot \eta_{Li}$ (30 day)

6.2.5.2 Drinking Water Pathway

The individual dose from the drinking water pathway is estimated using the equation (from RG 1.109)

$$RD_{wbd} = U_D \cdot \sum_{i=1}^{N} C_i \cdot \alpha_{D_{wbd_i}} \qquad (8)$$

where

$\alpha_{D_{wbd_i}}$ = the whole body dose accumulation factor for an ingested nuclide (rem/μCi)

U_D = the quantity of nuclide contaminated water ingested by an average adult member of the exposed population (ℓ)

Table 6.7 shows the contribution of significant nuclides to the whole body dose for an individual exposed to nuclide contaminated water for a period of 30 days. The whole body dose accumulation factors for nuclide ingestion are taken from Killough.(6-16) The quantity of water ingested monthly is extrapolated from RG 1.109 which gives a yearly ingestion quantity of 370 liters (ℓ).

Table 6.7. Individual Whole Body Dose From Drinking Water Pathway Following a Spent Fuel Cask Release to a River

Critical Nuclide	C_i (μCi/ℓ)	$\alpha_{D_{wbd_i}}$ (rem/μCi)	U_D (ℓ)	RD_{wbd_i} (rem)
Sr-89	1.45×10^{-4}	8.7×10^{-3}	3.0×10^{1}	3.78×10^{-5}
Sr-90	1.06×10^{-4}	1.7×10^{-1}	3.0×10^{1}	5.41×10^{-4}
Cs-134	2.53×10^{-3}	7.5×10^{-2}	3.0×10^{1}	5.69×10^{-3}
Cs-137	1.51×10^{-3}	4.3×10^{-2}	3.0×10^{1}	1.95×10^{-3}
Cm-244	2.37×10^{-4}	3.0×10^{-2}	3.0×10^{1}	2.13×10^{-4}

$RD_{wbd} = 8.43 \times 10^{-3}$

6.2.5.3 Fish Ingestion Pathway

The individual dose from ingestion of fresh water fish harvested downstream from a cask release source in a river is estimated using the equation from RG 1.109

$$RF_{wbd} = U_F \cdot \sum_{i=1}^{N} C_i \cdot \alpha_{D_{wbd_i}} \cdot B_{F_i} \qquad (9)$$

where

U_F = quantity of nuclide contaminated fish ingested by an individual of the exposed population (kg)

B_{F_i} = bioaccumulation factor for freshwater fish (ℓ/kg)

Table 6.8 shows major dose contributors to the whole body dose from ingestion of freshwater fish. Bioaccumulation factors for strontium, cesium and ruthenium are taken from RG 1.109. The adult fish intake for a one-month period is 0.57kg and is extrapolated from RG 1.109 data. Notably because cesium has a high bioaccumulation factor in the freshwater fish pathway, Cs-134 and Cs-137 are the dominant contributors and the individual dose from ingestion of freshwater fish is a factor of 34 higher than for the drinking water pathway.

Table 6.8. Individual Whole Body Dose From Freshwater Fish Ingestion Following a Spent Fuel Cask Release to a River

Critical Nuclide	C_i (μCi/ℓ)	$\alpha_{D_{wbd_i}}$ (rem/μCi)	U_F (kg)	B_{F_i} (ℓ/kg)	RF_{wbd_i} (rem)
Sr-89	1.45×10^{-4}	8.7×10^{-3}	.57	3.0×10^{1}	2.16×10^{-5}
Sr-90	1.06×10^{-4}	1.7×10^{-1}	.57	3.0×10^{1}	3.08×10^{-4}
Ru-106	1.62×10^{-3}	3.2×10^{-4}	.57	1.0×10^{1}	2.95×10^{-6}
Cs-134	2.53×10^{-3}	7.5×10^{-2}	.57	2.0×10^{3}	2.16×10^{-1}
Cs-137	1.51×10^{-3}	4.3×10^{-2}	.57	2.0×10^{3}	7.4×10^{-2}

$RF_{wbd} = 2.9 \times 10^{-1}$ rem

6.2.5.4 Shoreline Deposits

The individual dose from exposure to shoreline deposits is calculated using the following equation from RG 1.109,

$$RS_{wbd} = U_S \cdot \sum_{i=1}^{N} S_i \cdot \alpha_{S_{wbd_i}} \tag{10}$$

where

S_i = the effective surface contamination of the shoreline ($\mu Ci/m^2$)

$\alpha_{S_{wbd_i}}$ = the dose accumulation factor for exposure to shoreline contamination ($\frac{rem}{hr}/\frac{\mu Ci}{m^2}$)

U_S = the length of time in which an average adult is exposed to shoreline contamination as a result of the release (hr)

The effective shoreline contamination by a nuclide (S_i) is estimated using the relation

$$S_i = 1.0 \times 10^2 \cdot C_i \cdot T_i \cdot W \cdot (1 - e^{-\lambda_i \tau_b}) \tag{11}$$

where

T_i = the half-life of the nuclide (days)

W = a shoreline width factor for a river shoreline (dimensionless)

τ_b = the length of time in which sediment is exposed to contaminated water (hr)

1.0×10^2 = a conversion factor (ℓ/m^2 - day)

The value of the shoreline width factor is given in RG 1.109 as 0.2. The value of τ_b used is 720 hours corresponding to a one month release. Values for the dose accumulation factors due to shoreline deposits are also given in RG 1.109. The length of time in which an adult is exposed to shoreline deposits is taken from RG 1.109 as 8.3 hrs, a yearly exposure, since it is unclear how persistent the presence of radionuclides on the shore sediment would be.

The individual dose due to shoreline deposits from dominant nuclide contributors is shown in Table 6.9. Dominant contributors to the shoreline dose are cesium and ruthenium. Notably the individual dose due to exposure to shoreline deposits is a factor of 300 smaller than the dose from the drinking water pathway.

6.2.5.5 Irrigated Foods

To determine the dose to an individual as a result of ingesting food which is irrigated with nuclide contaminated water following a liquid release, the following set of equations from RG 1.109 are used. The whole body dose equation is

$$RI_{wbd} = U_{Iv} \cdot \sum_{i=1}^{N} C_{Iv_i} \cdot \alpha_{D_{wbd_i}} + U_{Ia(Me)} \cdot \sum_{i=1}^{N} C_{Ia(Me)_i} \cdot \alpha_{D_{wbd_i}} + U_{Ia(Mi)} \cdot \sum_{i=1}^{N} C_{Ia(Mi)_i} \cdot \alpha_{D_{wbd_i}} \qquad (12)$$

where

U_{Iv} = the quantity of nuclide contaminated vegetable matter ingested by an individual of the population exposed to the irrigated food pathway after a liquid release accident (kg).

$U_{Ia(Me)}$ = the quantity of nuclide contaminated meat ingested by an individual of the population exposed to the irrigated food pathway after a liquid release accident (kg)

Table 6.9. Individual Whole Body Dose From Exposure to Shoreline Contamination Following a Spent Fuel Cask Release to a River

Critical Nuclide	C_i ($\mu Ci/\ell$)	$\alpha_{S_{wbd_i}}$ $\left(\frac{rem}{hr}/\frac{\mu Ci}{m^2}\right)$	U_S (hr)	W	T_i (days)	RS_{wbd_i} (rem)
Sr-89	1.45×10^{-4}	5.6×10^{-10}	8.3	.2	5.05×10^{1}	2.3×10^{-10}
Ru-106	1.62×10^{-3}	1.5×10^{-6}	8.3	.2	3.7×10^{2}	8.1×10^{-6}
Cs-134	2.53×10^{-3}	1.2×10^{-5}	8.3	.2	8.4×10^{2}	1.0×10^{-4}
Cs-137	1.51×10^{-3}	4.2×10^{-6}	8.3	.2	1.1×10^{4}	2.2×10^{-5}

$RS_{wbd} = 1.3 \times 10^{-4}$

$U_{Ia(Mi)}$ = the quantity of nuclide contaminated milk ingested by an individual of the population exposed to the irrigated food pathway after a liquid release accident (ℓ)

C_{Iv_i} = the concentration of nuclide in vegetable matter which has been irrigated with nuclide contaminated water (μCi/kg)

$C_{Ia(Me)_i}$ = the concentration of nuclide in beef cattle which are fed with nuclide contaminated water and forage irrigated with nuclide contaminated water (μCi/kg)

$C_{Ia(Mi)_i}$ = the concentration of nuclide in milk from cattle which are fed with nuclide contaminated water and forage irrigated with nuclide contaminated water (μCi/ℓ)

$\alpha_{D_{wbd_i}}$ = the whole body dose accumulation factor for an ingested nuclide (rem/μCi)

RI_{wbd} = the whole body dose to an individual due to ingestion of food irrigated with nuclide contaminated water after a liquid release

The concentration of a nuclide in vegetable matter (C_{Iv_i}), is determined from the equation

$$C_{Iv_i} = C_i \cdot I \cdot \left[\frac{r \cdot (1-e^{-\lambda_{Ei} \cdot t_e})}{Y_v \cdot \lambda_{Ei}} + \frac{f_I \cdot B_{Iv_i} \cdot (1-e^{-\lambda_i \cdot t_b})}{p \cdot \lambda_i} \right] \cdot e^{-\lambda_i \cdot t_h} \qquad (13)$$

where

I = the average irrigation rate for irrigated land (ℓ/m^2-hr)

r = the fraction of deposited activity retained in crops, leafy vegetables or pasture grass (dimensionless)

f_I = the fraction of time yearly in which crops are irrigated (dimensionless)

B_{Iv_i} = the stable element transfer coefficient for nuclide uptake by soil (dimensionless)

t_b = the time period during which soil is exposed to nuclide contaminated water (hr)

t_e = the time period in which crops are exposed to contamination during the growing season (hr)

λ_{Ei} = the effective rate at which nuclides are removed from crops (hr^{-1})

$= \lambda_i + \lambda_w$

λ_w = the nuclide removal rate constant for physical loss through weathering (hr^{-1})

Y_v = the agricultural productivity per unit area (kg/m^2)

t_h = the time delay between crop harvest and ingestion by man (hr)

p = the effective surface density of soil (kg/m^2)

The concentration of nuclide in animal meat products ($C_{Ia(Me)_i}$) is determined using the equation

$$C_{Ia(Me)_i} = F_{Ia(Me)_i} \cdot \left[C_{If_i} \cdot Q_f + C_{Iaw_i} \cdot Q_{aw(Me)} \right] \quad (14)$$

where

$F_{Ia(Me)_i}$ = the nuclide accumulation factor for meat (day/kg)

C_{If_i} = the concentration of nuclide in animal forage or feed which has been irrigated with nuclide contaminated water (μCi/kg)

Q_f = the forage or feed consumption rate for range cattle (kg/day)

C_{Iaw_i} = the concentration of nuclide in animal drinking water taken from a nuclide contaminated source (μCi/ℓ)

$Q_{aw(Me)}$ = the drinking water consumption rate for range cattle (ℓ/day)

The concentration of nuclide in milk from animals drinking contaminated water and eating forage or feed irrigated with contaminated water ($C_{Ia(Mi)_i}$) is determined from the equation

$$C_{Ia(Mi)_i} = F_{Ia(Mi)_i} \cdot \left[C_{If_i} \cdot Q_f + C_{Iaw_i} \cdot Q_{aw(Mi)} \right] \quad (15)$$

where

$F_{Ia(Mi)_i}$ = the nuclide accumulation factor for milk (day/ℓ)

$Q_{aw(Mi)}$ = the drinking water consumption rate for dairy cattle (ℓ/day)

Input parameters used in equation 13 to determine the concentration of nuclides in ingested vegetable matter (C_{Iv_i}) which are scenario specific but do not vary for individual nuclides are given in the first column of Table 6.10. All values except t_b and I are taken directly from RG 1.109. The value of t_b used in the analysis is smaller than the value recommended in RG 1.109 because the nuclide source is not chronic. The value of I is an upper bound on irrigation rate requirements for irrigated land nationally.*

*An average irrigation rate for irrigated land in the Ohio river region is calculated to be approximately 2 x 10^{-2} ℓ/m^2-hr, while the average irrigation rate in the Columbia Northern Pacific Region, where irrigation is more intensive, is approximately 6 x 10^{-2} ℓ/m^2-hr.(6-17)

Table 6.10. Input Parameters For Evaluating Irrigated Vegetable Nuclide Concentrations

Irrigated Vegetable Matter Parameters *	Value Used to Calculate C_{Iv_i}	Value Used to Calculate C_{If_i}
r	.25	.25
λ_w (hr^{-1})	2.1×10^{-3}	2.1×10^{-3}
t_e (hr)	1.44×10^3	7.2×10^2
Y_v (kg/m^2)	2.0	2.0
f_I	.5	.5
t_b(hr)	7.2×10^2	7.2×10^2
p (kg/m^2)	2.4×10^2	2.4×10^2
t_h (hr)	3.36×10^2	0
I (ℓ/m^2-hr)	.1	.1

*All parameter values except t_b and I were taken directly from Regulatory Guide 1.109.

Values of C_{Iv_i} for major contributing nuclides are shown in Table 6.11. Values of the bio-accumulation factor B_{Iv_i} for individual nuclides are taken from RG 1.109. Notably, the transfer of nuclides from irrigation water to vegetable matter is dominated by direct deposition on foliage.

To determine the concentration of a nuclide in animal forage or feed which results from using irrigated water (C_{If_i}), equation 13 is used with values for the input parameters given in the second column of Table 6.10. Only t_e and t_h differ in value - principally because of the shorter times to induction into the animal feed pathway. Values of C_{If_i} are also given in Table 6.11.

It is conservatively assumed in this study that animals which ingest forage irrigated with contaminated water also drink contaminated water. Therefore

$$C_{Iaw_i} = C_i \qquad (16)$$

To determine nuclide concentrations in meat and milk, equations (14) and (15) are evaluated using a forage consumption rate of 50 kg/day for beef and milk cattle and water consumption rates of 50 ℓ/day and 60 ℓ/day for beef and milk cattle, respectively from RG 1.109. The results of the evaluation of equations (14) and (15) are presented in Table 6.12. Bio-accumulation factors in meat, ($F_{Ia(Me)_i}$), and milk, ($F_{Ia(Mi)_i}$), are taken from RG 1.109.

Table 6.11. Nuclide Concentrations in Vegetable Matter For Human Consumption (C_{Iv_i}) and Animal Forage (C_{If_i}) Resulting From Irrigation With Nuclide Contaminated Water*

Critical Nuclides	C_i (μCi/ℓ)	λ_{Ei} (hr^{-1})	B_{Iv_i}	C_{Iv_i} (μCi/kg)	C_{If_i} (μCi/kg)
Sr-89	1.45×10^{-4}	2.67×10^{-3}	1.7×10^{-2}	5.49×10^{-4}	5.80×10^{-4}
Sr-90	1.06×10^{-4}	2.10×10^{-3}	1.7×10^{-2}	6.00×10^{-4}	4.92×10^{-4}
Ru-106	1.62×10^{-3}	2.18×10^{-3}	5.0×10^{-2}	8.67×10^{-3}	7.37×10^{-3}
Cs-134	2.53×10^{-3}	2.13×10^{-3}	1.0×10^{-2}	1.40×10^{-2}	1.16×10^{-2}
Cs-137	1.51×10^{-3}	2.10×10^{-3}	1.0×10^{-2}	8.55×10^{-3}	7.01×10^{-3}

* All terms are defined under equation 13 in the text

The dose to an individual from each major nuclide in the irrigated food pathway and the total dose, is shown in the last column of Table 6.13. The dominant contributors are the cesiums with Sr-90 and Ru-106 accounting for an additional 6%. The individual dose from the irrigated food pathway is a factor of four greater than the dose from the drinking water pathway.

Table 6.12. Nuclide Concentrations in Meat and Milk as a Result of Cattle Ingesting Contaminated Water or Feed Grown by Irrigation With Contaminated Water*

Critical Nuclide	C_i (μCi/ℓ)	C_{If_i} (μCi/kg)	$F_{Ia(Me)_i}$ (day/kg)	$C_{Ia(Me)_i}$ (μCi/kg)	$F_{Ia(Mi)_i}$ (day/ℓ)	$C_{Ia(Mi)_i}$ (μCi/ℓ)
Sr-89	1.45×10^{-4}	5.80×10^{-4}	6.0×10^{-4}	2.18×10^{-5}	8.0×10^{-4}	3.02×10^{-5}
Sr-90	1.06×10^{-4}	4.92×10^{-4}	6.0×10^{-4}	1.79×10^{-5}	8.0×10^{-4}	2.48×10^{-5}
Ru-106	1.62×10^{-3}	7.37×10^{-3}	4.0×10^{-1}	1.80×10^{-1}	1.0×10^{-6}	4.66×10^{-7}
Cs-134	2.53×10^{-3}	1.16×10^{-2}	4.0×10^{-3}	2.83×10^{-3}	1.2×10^{-2}	8.78×10^{-3}
Cs-137	1.51×10^{-3}	7.01×10^{-3}	4.0×10^{-3}	1.70×10^{-3}	1.2×10^{-2}	5.29×10^{-3}

* all terms are defined under equations 13, 14, and 15 in text

Table 6.13. Individual Dose From Critical Nuclides Ingested Through the Irrigated Food Pathway Following a Spent Fuel Cask Release to a River

Critical Nuclide	U_{Iv} (kg)	C_{Iv_i} (μCi/kg)	$U_{Ia(Me)}$ (kg)	$C_{Ia(Me)_i}$ (μCi/kg)	$U_{Ia(Mi)}$ (ℓ)	$C_{Ia(Mi)_i}$ (μCi/ℓ)	$^aD_{wbd_i}$ (rem/μCi)	RI_{wbd_i} (rem)
Sr-89	15.6	5.49×10^{-4}	7.8	2.18×10^{-5}	9.0	3.02×10^{-5}	8.7×10^{-3}	7.84×10^{-5}
Sr-90	15.6	6.00×10^{-4}	7.8	1.79×10^{-5}	9.0	2.48×10^{-5}	1.7×10^{-1}	1.65×10^{-3}
Ru-106	15.6	8.67×10^{-3}	7.8	1.80×10^{-1}	9.0	4.66×10^{-7}	3.2×10^{-4}	4.93×10^{-4}
Cs-134	15.6	1.40×10^{-2}	7.8	2.83×10^{-3}	9.0	8.78×10^{-3}	7.5×10^{-2}	2.4×10^{-2}
Cs-137	15.6	8.55×10^{-3}	7.8	1.70×10^{-3}	9.0	5.29×10^{-3}	4.3×10^{-2}	8.35×10^{-3}

*all terms defined under equation 12 in the text

$RI_{wbd} = 3.46 \times 10^{-2}$

6.5.3 Consequences to a Population of a Cask Immersion Accident

Consequences to a population from a hypothesized release to water are estimated in this section for the purpose of evaluating risk to the public from a liquid release accident involving spent fuel.

As stated in Section 6.5.2 the total population potentially exposed to consequences from a release to a medium flow rate river is 6×10^5 persons[(6-14)]. Thus, since the river is assumed to be the major water supply, the population exposed to the drinking water pathway is estimated to be 6×10^5 persons.

The population exposed to the freshwater fish ingestion pathway is estimated as a portion of those exposed to contaminated drinking water.

Given the quantity of fish consumed yearly by an adult (RG 1.109) the percent of this fish which is freshwater caught can be determined using Appendix C of the NRC generic report on liquid pathways[(6-13)]. Table 6.14, reproduced from Reference 6-13, shows that if only commercial fishing is considered, approximately 3% of the fish caught (and consumed) are freshwater. Alterntively, if recreational fishing is considered, approximately 17% of the fish consumed are freshwater caught. To account for the fact that a large amount of recreational fishing occurs on small streams, lakes, and ponds which are not part of potential barge routes, it is assumed that 10% of the fish consumed in the U.S. is freshwater caught in streams or lakes large enough to be part of a barge route. Therefore, for a population of 6×10^5 persons potentially affected by a liquid release, 10% of their fish consumption is freshwater caught.

Table 6.14. U.S. Consumption of Aquatic Foods*(6-13)

Fish Product Source	U.S. Commercial Harvest	U.S. Recreational Harvest	Imports
Marine	1400	1600	2100
Freshwater	97	770	no estimate

* all quantities are multiples of 10^6lb.

If it is conservatively assumed that all freshwater fish consumed by a population are locally caught then 10% of the fish ingested by an affected population of 6×10^5 persons is radioactively contaminated. Equivalently, all the fish ingested by 10% of the affected population, or 6×10^4 persons, is radioactively contaminated.

For the shoreline sediment pathway, the population exposed to shoreline sediment contamination is assumed to be the same as the population exposed to drinking water contamination and is taken to be 6×10^5.

For the irrigated food pathway, an estimate of a percent of the population which consumes animal and vegetable matter grown with radioactively contaminated irrigation water can be made by estimating the percent of crop and pasture land in an average watershed which is under irrigation.

For watershed regions east of the Rocky Mountains, where barge transport of spent fuel is feasible, a national

Table 6.15. Fraction of Land Under Irrigation In Water Sheds East of the Rocky Mountains(6-17)

Watershed Region	Total Crop and Pasture Land*	Fraction Irrigated
North Atlantic Region	23357	1.33×10^{-2}
South Atlantic-Gulf Region	40963	3.66×10^{-2}
Great Lakes Region	27324	5.13×10^{-3}
Ohio Region	47260	1.16×10^{-3}
Tennessee Region	8141	2.46×10^{-3}
Upper Mississippi Region	73907	1.89×10^{-3}
Lower Mississippi Region	16685	5.39×10^{-2}
Souris-Red-Rainy Region	19057	7.87×10^{-4}
Northern Missouri Region	254850	2.90×10^{-2}
Arkansas-White-Red Region	98190	3.87×10^{-2}
Texas-Gulf Region	79713	6.90×10^{-2}
	689447**	3.06×10^{-2}***

* 10^3 acres
** total arable land
*** weighted average using % of total arable land in water-shed region

assessment of water resources(6-17) indicates that approximately 3% of the land is irrigated. Thus, if the assumption is made that the bulk of farm products grown locally are consumed locally, then 3% of the vegetable matter and animal tissue consumed by a population of 6×10^5 persons will be irrigated with contaminated water. Equivalently, 3% of the population or 1.8×10^4 persons consume the entire irrigated portion of the crop.

The weighted average method of estimating the population affected by irrigated crops excludes several important influences such as the use of well water for irrigation, and the use of irrigation for growing large non-food crops such as cotton, and national distribution of locally grown beef and irrigated food. All these factors, however, indicate that the estimate of the exposed population is conservative.

The consequences of a cask immersion accident are given in Table 6.16. These consequences are calculated using the individual doses calculated in Section 6.5.2 and the populations exposed to each dose pathway. Notably, the freshwater fish ingestion pathway dominates the population dose due to the high accumulation factors for cesium in freshwater fish.

It should be emphasized that the estimates of population dose for the cask immersion accident do not take into consideration a number of factors which would mitigate the results. These factors include the following:

Table 6.16. Consequences to An Exposed Population From a Cask Immersion Accident

Dose Pathway	Average Individual Dose (rem)	At Risk Population	Population Dose (man-rem)	Whole Body Dose Risk to Public man-rem/reactor year
drinking water	8.43×10^{-3}	6.0×10^{5}	5058	2.6×10^{-7}
freshwater fish	2.90×10^{-1}	6.0×10^{4}	17400	8.9×10^{-7}
shoreline deposits	1.30×10^{-4}	6.0×10^{5}	78	4.0×10^{-9}
irrigated foods	3.46×10^{-2}	1.8×10^{4}	623	3.2×10^{-8}
	Total All Pathways		23159*	1.2×10^{-6}*

* The probability of this consequence is estimated at 5.1×10^{-11} per reactor year.

a) Immersion of the cask in a river from which drinking water is drawn is a worst case condition. Estimates of generic barge route mileage in Section 1.0 weighted by the number of potential utility sites along the route indicate that a maximum of 44% of all barge mileage would occur in rivers used as water supplies. In addition, population consequences are estimated based on a cask immersion time of 30 days, even though a cask would probably be retrieved much faster.

b) Calculations of radioactive source strength are based on free flow of water through the cask and complete mixing with river water. The flow area used in the consequence evaluation is equivalent to an extremely large break not likely to exist even if the cask integrity were compromised. Since the cask is also likely to be buried deep in sediment, exchange of water in the cask would be severely limited, significantly reducing the expected source strength.

c) The amount of time necessary for reaction by local authorities and water supply districts is small compared to the amount of time needed for a spill to spread downstream. A release in the river model used in this study would required 12.4 days to travel 300 km. In the event that a release were to occur, it can reasonably be assumed that most local water supplies would have switched to emergency sources after a short time and that there would be a limited uptake of radioactively contaminated drinking water thereafter. In addition restrictions on fishing and the use of river water for irrigation would further mitigate the consequences of these pathways.

6.6 Risk to the Public From Intermodal Transport of Spent Nuclear Fuel

In Section 5.0 the probability of a significant release to water as a result of a spent fuel shipping accident was given as 5.1×10^{-11}/R-yr. Using the estimate of water release consequences from Table 6.16 the risk to the public is 1.18×10^{-6} man-rem/R-yr from water release accidents. From Table 6.4, risk to the public from air release accidents during intermodal transport is 1.4×10^{-8} man-rem/R-yr. Therefore the total risk to the public* from intermodal transport of spent fuel is 1.19×10^{-6} man-rem/R-yr.

Total risk to the public from air release accidents during rail transport is 3.7×10^{-7} man-rem/R-yr, which is a factor of 26 greater than the risk from air releases during intermodal transport. However, because risk from barge transport is dominated by the water release accident the total risk from intermodal transport is a factor of three larger than the risk from transport by rail alone.

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* Whole body doses only

The difference in the risk numbers calculated for intermodal and strictly rail transport is not significant since all probability estimates used in the study are order-of-magnitude estimates only. Furthermore, the risk due to spent fuel transport by either mode is negligible when it is compared with the average risk due to light water reactor operation (24.8 man-rem/R-yr for a PWR and 20 man-rem/R-yr for a BWR from reference 6-1).

Table 6.17 shows the risk to the public for a 1985 population of LWRs as a result of spent fuel transportation in three transport mix scenarios described in Section 1.0. Total risk for the estimated 1985 population of 191 reactors ranges from 7.9×10^{-5} man-rem/yr for the scenario in which 5% of the spent fuel generated annually is transported intermodally to 1.3×10^{-4} man-rem/yr for a scenario involving heavy use of intermodal transport (40% of all spent fuel transported).

Figure 6.1 shows the predicted variation in risk to the public for light and heavy use of intermodal transport. Also shown for comparison, are the results of Hodge and Jarrett[(6-3)] who modeled air releases from the wet cask and assumed light use of intermodal transport. The differences in risk predicted by these two studies for the light use scenario is less than 2×10^{-5} man-rem/yr. This difference in predicted risk is not the result of analysis of the wet cask design in Reference 6-3 since the air release risk from a wet cask estimated in this study is identical to that of a dry cask and liquid release risk can be shown to be nearly identical for wet and dry casks.

Table 6.17. Public Risk From Spent Fuel Transport Accidents for a 1985 Population of LWRs*

Transport Mix	Risk From Rail Transport (man-rem/yr)	Risk From Intermodal Transport (man-rem/yr)	Total Risk to the Public (man-rem/yr)
5% Intermodal-light use scenario (10 units of a possible 191 in 1985 serviced intermodally)†	6.7×10^{-5}	1.2×10^{-5}	7.9×10^{-5}
40% Intermodal-heavy use scenario (76 units of a possible 191 in 1985 serviced intermodally)	4.3×10^{-5}	9.0×10^{-5}	1.3×10^{-4}
80% Intermodal-upper bound (153 units of a possible 191 in 1985 serviced intermodally)	1.4×10^{-5}	1.8×10^{-4}	1.9×10^{-4}

* Assuming dry casks are used for all transport operations.

† 1985 population of U.S. reactors is assumed to be 191 (Section 1.0)

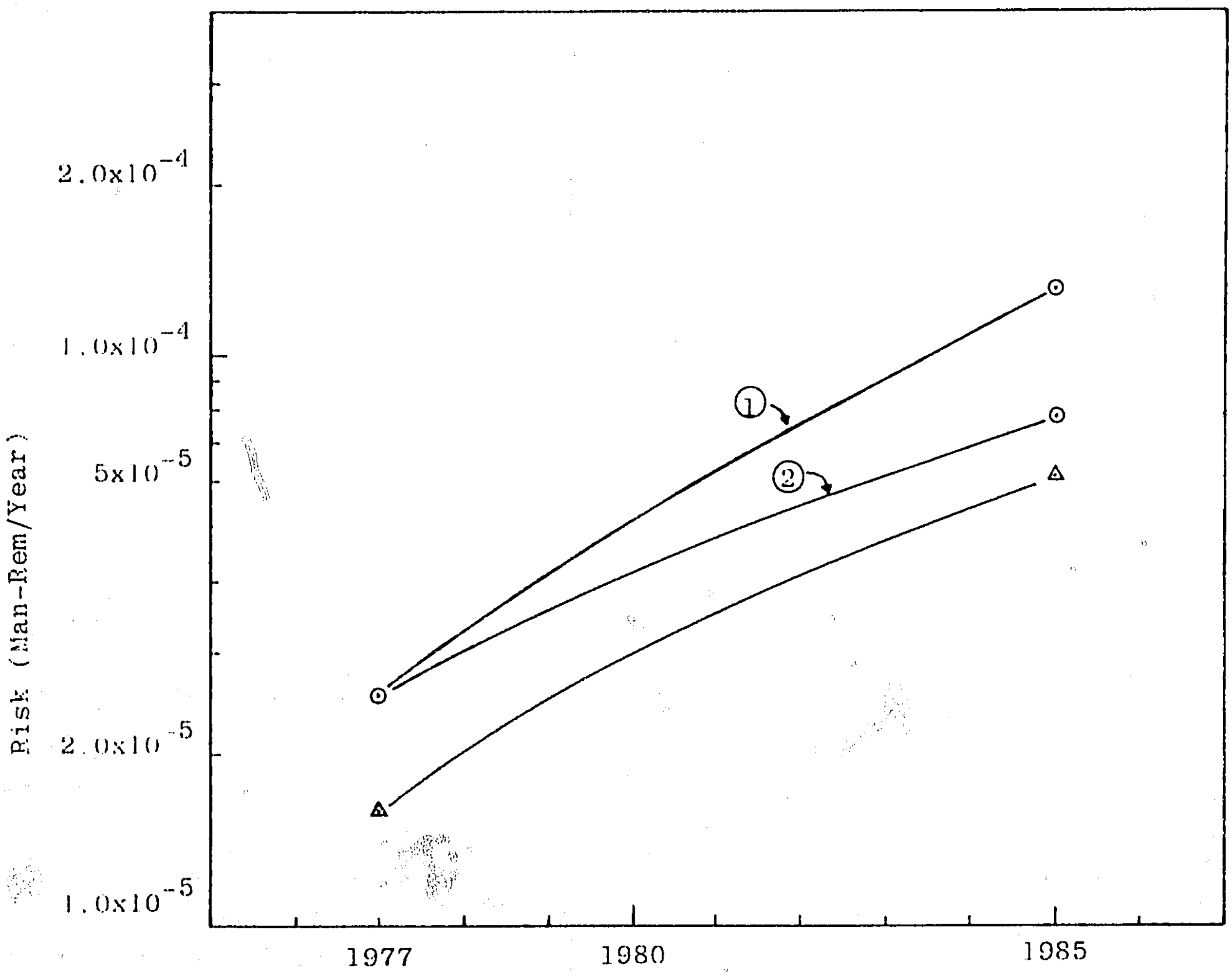

Figure 6.1. Risk to the Public From Whole Body Doses Due to Spent Fuel Shipping Accidents

⊙ Intermodal Transport (1978)
① 40% intermodal
② 5% intermodal

△ Hodge & Jarrett (1975) - 5% intermodal

The results of this study are compared with the results of other risk studies of spent fuel transport in Table 6.18. With the exception of Hodge and Jarrett the results are smaller than estimates of risk taken from other studies.[6-18, 6-19]

Table 6.18. Comparison of Estimates of Public Risk From Spent Fuel Transport Accidents From Several Sources

Source	Scenario	Whole Body Dose Risk to Public (man-rem/yr)
AIF/NESP-014 *† September 1978	Light Use of IMSFT Scenario (5% Mix)	7.9×10^{-5}
	Heavy Use of IMSFT Scenario (40% Mix)	1.3×10^{-4}
Hodge & Jarrett[(6-3)†] (April 1975)	Air release only	6.2×10^{-5}
Cohen & Dance[(6-18)‡] (November 1975)	Air release only	14.5
NUREG 0170[(6-19)**] (March 1976)	The use of air transport is considered	2.2×10^{-3}

* Calculations were made for a dry cask.

† Population of reactors expected to be operational by 1985 as estimated in Reference 6-3 was used for normalization

‡ Based on the data provided in Table 5-8 of Reference 6-18 for population doses per 1000 MWe Yr normalized to the estimated 191 reactors in the 1985 reactor population.

** Incremental risk in study is given for all spent fuel transportation at 1976 level. Risk was normalized to a 1985 level by using a factor of 191/62 to account for the larger number of reactors expected to be in operation.

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7.0 ECONOMIC EVALUATION OF WATERBORNE TRANSPORT OF SPENT FUEL

7.1 Purpose and Summary

Waterborne transport of spent nuclear fuel has been shown to be a safe method of shipment. This section explores the utility of this mode of transportation by considering its economic ramifications.

This study concludes that waterborne transportation is more costly than land transportation in all cases evaluated. This is due mainly to the high cost of cask rental which results from the extended trip and turnaround time. The conclusions of this study would be modified if:

a) industry experience with intermodal transport increases, thereby increasing the efficiency of the transport process and reducing transport costs

b) the cost of rail transport increases with respect to waterborne transport

c) special equipment and procedures are developed to facilitate transfer between land and waterborne modes

7.2 Use of Generic Routes

The comparative mileage of three generic spent fuel transport routes are shown in Table 7.1. Two of the routes

Table 7.1. Generic Spent Fuel Transport Routes Considered in Economic Evaluation

Generic Route	Description	One Way Intermodal Route Distance			Equivalent Rail Distance[a] (mi)
		Waterborne (mi)	Rail or HHT[b] (mi)	Total (mi)	
1	Utility site on or near Great Lakes to Oak Ridge, Tenn.	1,647	11	1,658	1,161
2	Utility site on Chesapeake Bay to Hampton Roads, Va., rail to Barnwell, S.C.	110	450	560	560[c]
3	Utility site on N.E. Atlantic Coast to Barnwell, S.C.	1,469	15	1,484	1,039

[a] Equivalent rail distance is the distance by rail between two endpoints of a cask trip for which a waterborne route has been defined.

[b] Heavy haul truck.

[c] Rail or truck mileage is assumed to be the same as the waterborne distance due to the short distance and directness of the waterborne link.

are representative of long distance routes between reactor units and receiving facilities. Both of these are nearly totally navigable by water. The third route consists of a short waterborne segment from a reactor to a rail head at a major port and completion of the trip by rail. The third route represents a near term need contemplated for waterborne transport; i.e., to provide a means of using rail size casks for spent fuel transport when no rail access to the utility site exists.

Table 7.1 shows equivalent distances for transporting spent fuel strictly by rail or legal weight truck (LWT). In order to account for the fact that waterborne routes are less direct and longer than overland routes, the equivalent rail mileage for a long waterborne route is determined by using a factor of 0.7. This factor was established by comparing point-to-point rail and water distances between given map points. Waterborne distances were evaluated as part of this analysis (see Appendix A) and rail route distances were obtained from commercial carriers. The 0.7 equivalence factor is also used to determine truck route distances.*

7.3 General Definitions and Modeling Assumptions

For purposes of modeling uniformity, a "trip" is defined as transporting two empty casks from the receiving facility to the utility, loading them and returning with the loaded casks to the receiving facility. A trip has three main cost accruing phases:

* A comparison with truck route distance schedules made after this work was completed resulted in a factor of 0.65, in reasonable agreement with the initial assumption.

a) conveyance - the phase of the trip in which the casks are carried from one point to another by a primary carrier

b) turnaround - the phase of the trip at either end of the journey in which the casks are removed from the primary carrier, moved to the site, loaded or unloaded, and returned to the primary carrier.* In this study, a trip will be assumed to have two turnarounds, one at the utility and one at the receiving facility.

c) intermodal transfer - the phase of the trip in which the casks are transferred from one primary mode of conveyance to another at some intermediate point in the journey. The term "intermodal transfer" is inexplicit since it implies transfer from any mode to any other mode. However, as defined in Section 1.0, intermodal transport involves the use of barge and rail or truck so an intermodal transfer here applies to a mid-trip barge/rail or rail/barge transfer. Generic intermodal route 4 requires an intermodal transfer.

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* For transport by barge, turnaround at the utility consists of removal of the casks from the barge, transporting them to the spent fuel building of the facility, filling the casks, returning to the barge and securing. Comparable transport by rail, when no rail access to the site turnaround exists, consists of taking casks from the rail head, transporting them to the fuel load out area access, filling and the returning of the loaded casks to the rail head.

Several sources of cost were identified for the comparative cost study of the various transport modes. Some of these sources of cost affect all modes of transport and some affect only one mode. The total cost of spent fuel shipping service for one reactor was calculated on a yearly basis.

A spent fuel shipment requirements for a 1000 MWe PWR consist of the transport of 65 assemblies per year between the utility and receiving facility. The reference rail cask used in this evaluation is a dry cask which holds 10 PWR assemblies or 4.5 metric tons of uranium (MTU), thus a spent fuel shipment campaign would require transport of 6.5 cask loads yearly.* It was assumed that two casks would be conveyed by a single barge per trip and two casks would be conveyed per train per trip. Therefore, a full campaign by either mode using dry casks involves 3.25 trips per reactor-year.

The wet cask holds seven assemblies, or 3.1 MTU. Thus a campaign to service one reactor using wet casks would require 4.7 trips per year.

An LWT size cask holds one PWR fuel assembly†. Therefore a spent fuel shipment campaign by LWT would require 65 trips per reactor-year.

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* The cost calculations in this section, in the interest of simplicity, consider only shipment of dry casks.

† For example, the NLI-1/2 dry cask and the NFS-4 wet cask.

7.4 Elements of Cost for Various Spent Fuel Transport Modes

The elements of cost for each trip phase for several different modes of shipment are shown in Table 7.2. These cost elements are discussed individually in the following sections. All costs are given in 1977 dollars.

7.4.1 Sources of Costs for Intermodal Transport

7.4.1.1 Waterborne Conveyance Costs

Spent fuel transport costs for the barge conveyance phase of intermodal transport are largely a function of equipment rental costs. These costs include rental fees for the casks and barge. The rail conveyance (freight) charges are added to the rental fees for the casks and barge to compute total conveyance costs.

Rental of a wet cask was quoted by commercial sources as \$3.0K/day*(7-1). Rental of a dry cask was quoted as \$3.5K/day(7-2). In both cases, the vendor used a sliding cost scale to provide a discounting capability for long term commitments. In this study, a dry cask rental fee (R_c) of \$3.5K/day was used for calculations of cost.

Costs for barge conveyance (R_b) were calculated based on a \$1.5K/day service charge for the barge, tug, and crew.(7-3)

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* The notation used here is \$3.0K/day = \$3,000/day; similarly \$1M = \$1,000,000.

Table 7.2. Elements of Cost by Trip Phase for Three Spent Fuel Transport Modes

Trip Phase	General Cost Sources	Special Elements of Cost		
		Barge-Intermodal	Rail Exclusively	LWT Exclusively
conveyance	• spent fuel containment	• cask (rail size) rental	• cask (rail size) rental	• cask (truck size) rental
	• freighting	• barge rental • rail charges	• train shipment charges	• truck freight charges
intermodal transfer	• spent fuel containment	• cask rental	-	-
	• transfer charges	• transfer equipment rental • transfer personnel charges	-	-
	• stationary equipment costs	• barge rental	-	-
turnaround	• spent fuel containment	• cask rental	• cask rental	• cask rental
	• transfer charges	• transfer equipment rental • transfer personnel charges	• transfer equipment rental • transfer personnel charges	-
	• stationary equipment costs	• transfer equipment during cask loading and unloading	• transfer equipment during cask loading and unloading	• truck detention charges during cask loading and unloading
	• capital equipment costs	• loading and unloading equipment construction cost	• installed rail access construction cost	-

Since the charges quoted above accrue by the day, it was of major importance to determine elapsed times for a trip. This, in turn, required a reasonable estimate of average barge speed.

Several conflicting estimates of average barge speed exist. WASH-1238[7-4] assumes an average speed of 4 mph for barge trips. Barge carriers[7-3] indicate an average barge speed of 9-11 mph for trips along the eastern seaboard and on the lower Mississippi. Barge speeds quoted by the commercial source[7-3] may be optimistic for a national average since barge traffic on much of the east coast and lower Mississippi involves comparatively open water. Therefore, an average barge speed of 7 mph (an average of the two estimates) is used in this study to calculate barge and cask costs for the transport portion of each trip.

Since a barge can travel 24 hours per day, the cost per mile was based on a daily covered distance of 168 mi. The total cost per mile for barge conveyance was calculated as $(2\ R_c + R_b) \cdot (\frac{1\ \text{day}}{168\ \text{mi}})$ or \$50.6/mi.

7.4.1.2 Intermodal Transfer Costs Using Roll-On/Roll-Off by HHT

Transfer costs for equipment rental and manpower (R_{it}) for intermodal transfer using HHT were based on estimates of labor, time, and equipment requirements quoted by commercial sources.[7-3,7-5] Table 7.3 presents a breakdown of costs for the labor and equipment needed to transfer two casks from railcars to a barge using HHT and equipment rigged for roll-on/roll-off.

Table 7.3. Intermodal Transfer Cost Breakdown for Roll-On/Roll-Off of Two Dry Casks by HHT

Cost Category	Source	Hourly Rate ($/hr)	Daily Rate ($/day)	Cost of Transfer Two Casks ($/transfer)
transfer personnel costs	rigger(4)	16.		
	driver(1)	16.		
	supervisor(1)	20.		
	operations engineer(2)	25.	1.44K*	7.2K
transfer equipment rental	hauler, including tractor and dollies	150.		
	rigging equipment and radiation monitoring equipment	50.	1.92K*	9.6K
stationary barge rental			1.5K	7.5K
cask rental			7.0K	35.0K
total transfer cost				59.3K

* Including a 20% markup.

The intermodal transfer time (τ_{it}) required to transfer two rail casks in either direction, given in Reference 7-3, was the sum of 4.5 days for transfer time and 0.5 day for equipment assembly.

Assuming a 20% markup on equipment rental and personnel fees and considering that stationary charges accrue on the barge and cask, the total cost for intermodal transfer of 2 rail casks is: $(2R_c + R_b + 1.2\ R_{it}) \cdot \tau_{it}$ or \$59.3K.

7.4.1.3 Turnaround Costs

7.4.1.3.1 Turnaround Costs Using HHT

A heavy haul truck system is one option for transporting spent fuel casks over the short distances (<20 miles one way) which characterize the turnaround portion of intermodal routes. Since turnaround is required for any barge shipment campaign, we assume that an efficient HHT transport system similar to the gooseneck unit discussed in Section 2.0 would be used.

The time needed during turnaround to remove a cask from the barge using HHT is less than the time required for barge/rail transfer since railcar assemblies are not required. However, since the utility site may be some distance from navigable water there may be up to one day of travel time between the barge slip and the loading and unloading site.(7-6)

Total HHT turnaround time was estimated by assessing the amount of time involved in each operation, with operations running concurrently whenever possible. The total turnaround time for a two cask shipment at the utility was estimated to be 7.5 days, assuming a 0.5 day time to pickup or drop off a cask with HHT equipment and a 0.5 day travel time to the site (Figure 7.1). Cask pickup time estimates were quoted by commercial haulers(7-6) who assumed that specially designed gooseneck hauling equipment and quick release tiedowns were used. If a less efficient transfer process were used, it could add as much as 2 days to the overall turnaround operation. Also, a longer travel time (one day to the site) could add as much as two days to the total turnaround time. Using these figures; the most pessimistic prediction of turnaround time was found to be 11.5 days.*

Two estimates of the rental cost of HHT equipment needed for a turnaround operation were obtained. One estimate of $150/hr was supplied by an east coast contractor(7-3). Another estimate of $100/hr was supplied by a west coast crane operator(7-6), who assumed that a specially designed pickup arrangement would be used and no extras, such as escort vehicles, would be required. An average estimate of $125/hr was used for this study. The crew size and cost estimates were taken from Reference 7-6. A crew is assumed to consist of one driver, one helper, one or two riggers and one foreman. Turnaround costs for equipment and personnel (R_t) was $1.67K/day. Total turnaround costs were estimated to be $(2R_c + R_b + R_t) \cdot \tau_t$ or $76.3K per turnaround. The annual operational costs for turnaround using HHT, assuming

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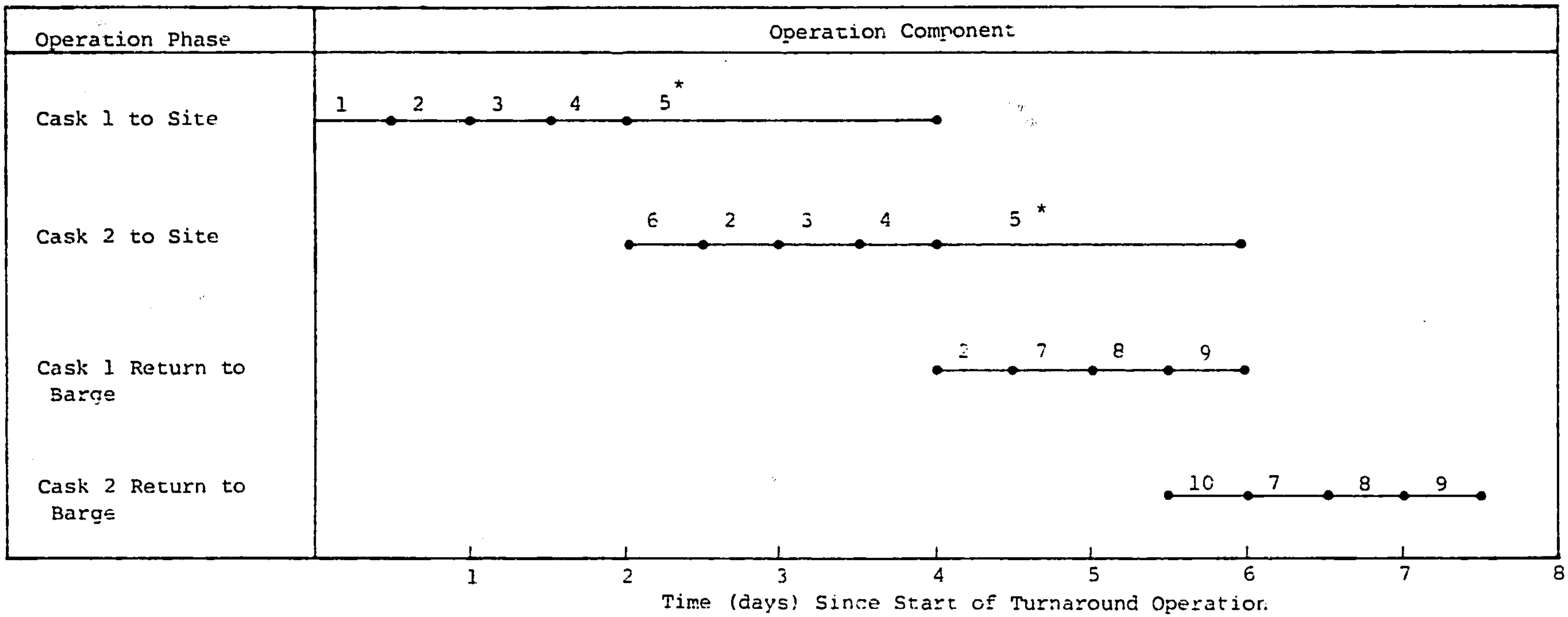
* An estimate of the time needed to transfer three rail casks from a rail head to a utility site 17 miles away and return with full casks was quoted by a commercial cask rental source(7-2) as approximately 9 days(7-12 days) Therefore, the 7.5 day turnaround for two casks is reasonable but shorter times are possible.



Operational Components

1. HHT Assembly
2. HHT Pickup of Cask
3. HHT Transport Cask to Site
4. HHT Dropoff of Cask
5. Cask Loaded/Unloaded
6. HHT Return to Barge
7. HHT Transport of Cask to Barge
8. HHT Dropoff of Cask @ Barge
9. Securing of Cask to Barge
10. HHT Return to Site

*Corresponds to time needed to load rail sized cask with spent fuel at a utility as quoted by a commercial cask rental source[7-2]. The time needed to effect unloading of the cask at the receiving facility is estimated by the same source to be approximately half the loading time, or 1 day.

Figure 7.1 Turnaround Operation Times at Utility Site Within 20 Miles of Dockside for Roll-On/Roll-Off of Two Dry Casks by HHT.

3.25 trips per year, would be approximately $250K. A detailed breakdown of HHT operational costs per turnaround are given in Table 7.4.

A significant savings in operational costs for HHT turnaround can be achieved if HHT vehicles are committed to the barge, since they could be left assembled on the barge during the trip and rolled off at the facility, thus shortening the turnaround operation by one to three days. Availability of HHT vehicles will determine whether commitment of vehicles will be possible.

If HHT access to a utility site is to be used, it was assumed that several capital improvements would be made, including construction of a docking facility and permanent road. Construction of a concrete docking facility was estimated to cost $500K and secondary construction was estimated to cost $22K/mi.(7-5) Thus, use of HHT roll-on/roll-off access for a reactor located 5 mi. from a suitable dockside would require a capital expenditure of $610K.

7.4.1.3.2 Turnaround Costs Using a Floating Bridge

Turnaround of rail casks can be accomplished in an efficient manner at sites which have floating bridge and rail access. With this mode of turnaround transport, casks or rail cars may be directly transferred on and off of barges with no disassembly operations. The equipment involved and the procedure used for loading and unloading are discussed in Section 2.0.

Table 7.4. Intermodal Turnaround Cost Breakdown for HHT Turnaround of Two Dry Casks at a Utility Site*

Cost Category	Cost Source	Hourly Rate ($/hr)	Daily Rate ($/day)	Cost to Turnaround Two Casks ($/turnaround)
turnaround transfer personnel	•driver (1) •helper (1) •rigger (2) •supervisor (1)	16 16 16 20	672	5.04K
turnaround transfer equipment rental	•HHT gooseneck equipment & quick release tiedown	125	1.0K	7.5K
stationary barge rental			1.5K	11.25K
cask rental			7.0K	52.5K
total turnaround cost				76.3K

* Assuming a turnaround time of 7.5 days.

Crew requirements for operating a floating bridge would include a train crew of two men and a rail/barge facility crew of two men in addition to the barge crew. It was estimated that the total manpower requirement for the turnaround of a single cask would be 32 hours.(7-7) At $16 per man-hour, total personnel cost per cask turnaround (R_t) would be $512. Total time required to transport two casks to the utility site would be one day, and it was assumed that both casks could be returned and secured on the barge in one day. If two days per cask are needed to load the casks in the spent fuel area and some overlap in operation is assumed, a total of five days would be involved in the turnaround of two casks.

Considering stationary charges of $1.5K/day for the barge and $3.5K/day for the cask, the total operational turnaround cost using a floating bridge would be $2R_t + (2R_c + R_b) \cdot \tau_t$ or about $43.5K/turnaround.* The yearly operational cost of turnaround at the utility using direct roll-on/roll-off rail cars and floating bridge access to the utility assuming 3.25 trips per year would be about $142K.

In some cases, a floating bridge may be installed for another purpose.† Cost of construction of a floating bridge itself was estimated to be $1.5M‡(7-8). Cost of constructing rail access to the site was based on an estimate of $750K/mi., including leveling and bridges**(7-9).

* Expressions for HHT access cost differ from those for FB access cost, since FB turnaround does not require a bridge or train crew throughout the turnaround operation.

† Several proposed utility sites have floating bridge access to provide for shipment of heavy reactor components during construction since adequate rail links do not exist.

‡ For sites with less navigational and access constraints, the cost of a bridge could be as low as $1M.

** Cost per mile of rail construction assumed the rail access must traverse fairly rough terrain.

Comparison of Costs for HHT vs. FB Turnaround

Table 7.5 presents a comparison of the estimated operational and capital costs for turnaround using HHT access and FB access to a facility for two cases; i.e., a facility five miles from dockside, and a facility one mile from dockside. Clearly, the use of a floating bridge may have an economic advantage over using HHT for turnaround for short distances to the utility site from dockside. If a waterborne trip is part of an intermodal journey dominated by the rail portion, another advantage may be gained since transfer to rail may be made at a major port where carfloat loading facilities already exist. This would significantly reduce the intermodal transfer cost.

7.4.2 Sources of Costs for Rail Transport

7.4.2.1 Rail Conveyance Costs

Charges and rates for transportation of spent fuel by rail have been made assuming that irradiated nuclear material can be shipped via regular train.* Since a national

* The Association of American Railroads has recommended that their carriers require spent nuclear fuel to be carried on "special trains", which carry no other freight and travel at speeds of less than 35 mph.(7-10) A special train rate is quoted on a per mile basis by carriers individually and is additive to the regular train shipment charge. A commercial carrier source(7-11) quotes the special train charge at $19.72/mi. A second source(7-12) quotes an average special train charge of $20/mi. As an example, the total charge per mile for a 1,000 mile shipment of a fully loaded dry cask including the special train charges, would be $29.86/mi. The case for the railroads is still under review, but the commercial railroads appear to have lost their right to charge differently for special trains by a recent court decision.

Table 7.5. Comparison of Costs for Intermodal Turnaround Using HHT vs. Using FB for Two Cases

Cost Breakdown	For a Utility Site 5 Miles Distant from Dockside		For a Utility Site 1 Mile Distant From Dockside	
	HHT Access	FB Access	HHT Access	FB Access
C_c - Capital Cost($K)	610	5,250	522	2,250
C_o - Annual Operating Cost ($K/R-yr)	250	142	250	142
C_t - Total annual cost of turnaround* ($K/R-yr)	270	317	268	217
Turnaround cost per trip† ($K/trip)	83.2	97.4	82.3	66.6

* Calculated on a simple basis assuming an operating life of 30 years, i.e.,

$$C_t(\$K/R\text{-}yr) = C_o(\$K/R\text{-}yr) + \frac{C_c(\$K)}{30\ R\text{-}yr}$$

† Assuming 3.25 trips per reactor year are made between utility and receiving facility using dry casks.

standard set of tariffs exist for regular train shipments of spent nuclear fuel, the rates may be assumed not to vary radically from carrier to carrier.

Figure 7.2 shows a plot of average tariff charges per 100 lb. of shipment weight as a function of mileage, taken from rail shipment data for eastern railroads(7-12). The top plot is for casks with irradiated fuel, and the bottom plot is for empty casks. The broken lines are extrapolated from the data and are perhaps high since tariff charges will probably level off over longer distances. Table 7.6 details a charge per mile for dry casks based on rates taken from Figure 7.2. An attempt to verify these figures by direct contact with a commercial rail carrier(7-11) produced tariff quotations of $6.54/100 lb. for casks with irradiated fuel between San Onofre, Ca. and Hanford, Wash. Assuming the rail mileage between points to be approximately 1100 mi., these costs are nearly $16/mi. for a loaded dry cask. Hence, the estimates in Table 7.6 may be somewhat low for current use.

Cost of cask rental during the conveyance phase of rail transport was calculated using the daily cask rental charge of $3.5K/day and an average train speed that includes all stops and yard operations between the end points of the trip. Two estimates from commercial sources were used to establish the estimate of average train speed used in this evaluation. One source, a commercial cask supplier with experience in transporting nuclear material by rail, estimated average train speed at 7 mph.(7-2) A second commercial

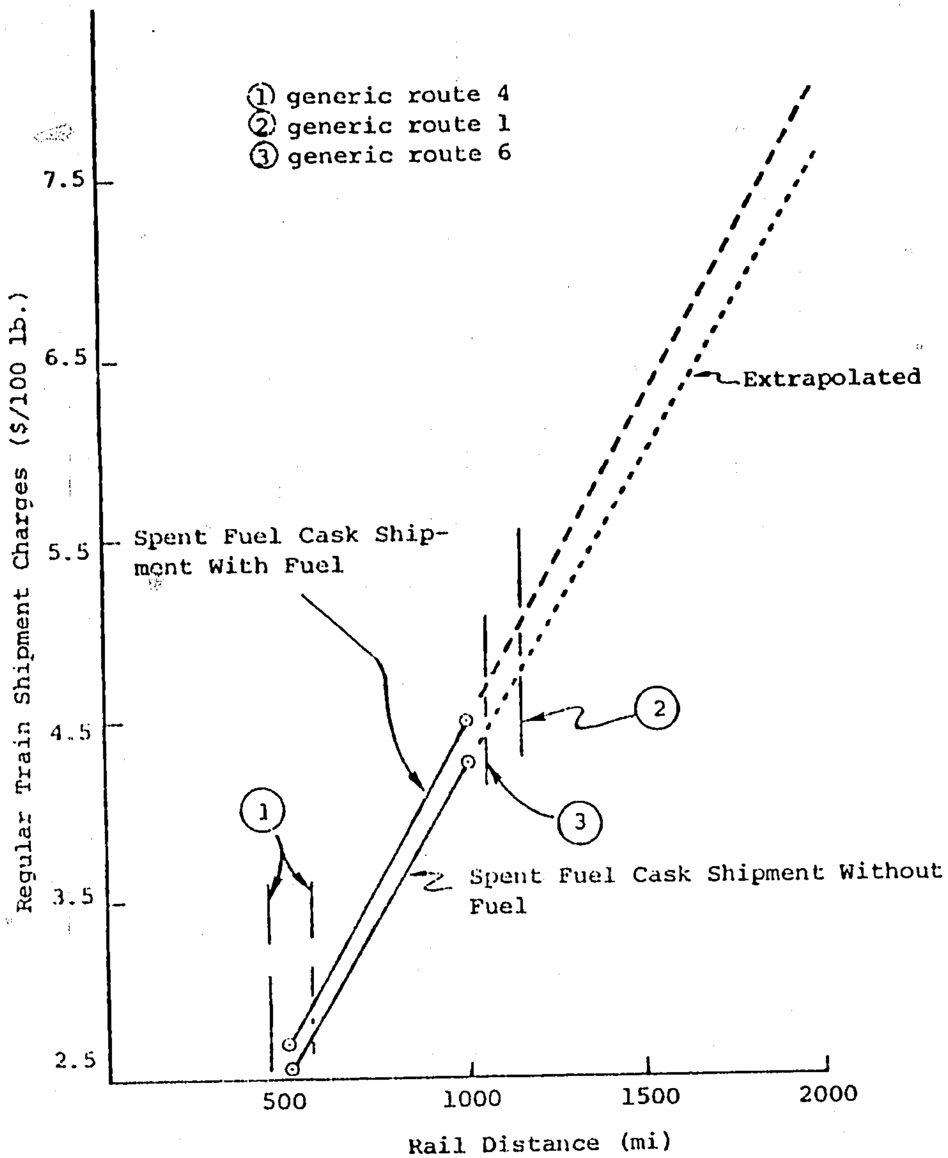


Figure 7.2. Regular Train Shipping Charges ($/100 lb Weight) For Loaded and Empty Spent Fuel Casks

Table 7.6. Cost per Mile for Various Distances of Spent Fuel Cask Shipment by Regular Train

Cask Type and Load Status	Shipping Weight (lbs.)	Regular Train Freighting Charge ($/mi)			
		500 (mi.)	1000 (mi.)	1500 (mi.)	2000 (mi.)
Dry Cask Loaded	2.19×10^5*	11.16	9.86	9.21	8.70
Dry Cask Empty	2.01×10^5	9.85	8.44	7.91	7.54

* Reference proposed weight agreement between National Lead Industries (NLI) and railroads.

source[7-13] used transportation data between Oak Ridge, Tennessee and Hanford, Washington to estimate an average regular train speed of between 4.5 mph and 7.5 mph. An average regular train speed of 6 mph was used in this assessment.

7.4.2.2 Rail Transport Turnaround Costs

Turnaround times are difficult to estimate for rail shipments at the utility end of the route since some reactor sites have rail service into the spent fuel loading area while other sites are located a considerable distance from suitable rail heads. Waterborne shipment of spent fuel would be competitive for utilities that do not presently have suitable rail connections to their site. Turnaround options are possible for sites without existing rail access. The first option would be to use HHT transfer from a suitable railyard, employing essentially the same technique described for barge turnaround. The turnaround costs per trip for this option were assumed similar to those incurred for barge transport. A second option would be to build rail access to the plant. As stated above, the average cost of rail construction including leveling and bridge building is estimated to be $0.75M/mi or $3.75M to connect a utility site to a railhead 5 mi. distant.

The cost of a turnaround operation using HHT access with a railhead is approximately $270K/reactor-year. For those facilities where terrain permits, construction of rail access for distances up to 7 miles would be competitive with HHT turnaround if it is assumed that the minimum turnaround time possible is four days.

It was assumed rail turnaround can be achieved directly at the receiving facility end of the route.

7.4.3 Sources of Costs for Legal Weight Truck (LWT) Transport

7.4.3.1 LWT Conveyance Costs

Cost of spent fuel shipment by truck was based on the cost of the truck and driver and of a legal weight truck (LWT) cask. The LWT casks which are available weigh approximately 22 tons and carry one PWR assembly or two BWR assemblies. A recently quoted rental fee for an LWT cask is \$0.85K/day.[7-2] The cask rental rate includes the services of a technical representative who is responsible for the coordination of cask loading and who insures the safety and efficiency of the process.

The cost of freighting by LWT, as quoted by commercial carriers, includes the cost of the truck and driver and is expressed as a rate per mile of round trip distance.[7-14] The rate is \$1.60/mi for round trips of less than 200 miles; \$1.10/mi for round trips of 500-1000 miles; and \$0.95/mi. for trips over 1200 miles. An additive charge of \$0.15/mi. for a second driver is used in cost calculations.

Speeds for LWT shipment of spent fuel casks are quoted as 30 mph.[7-14] However, a derating factor of 25% was used by the industry to estimate transit times through urban routes and through the northeast in general. An overall speed of 25 mph was used in this study to avoid segregating routes into urban and non-urban portions.

7.4.3.2 LWT Transport Turnaround Costs

A LWT cask and its trailer can be delivered to the fuel receiving bay at a utility. Likewise, at the receiving facilities, the cask can be delivered directly to an unloading crane. Thus, the only turnaround costs incurred using LWT shipment are the rental charges on the cask during turnaround and the detention charge on the truck. A detention charge of up to $150/day is paid by the utility for keeping equipment longer than 10 hours.[7-14] Normal turnaround time for LWT transported casks is one day at the utility and 0.5 day at the receiving facility. The difference in time results from the receiving facility's higher level of handling experience.[7-2]

7.4.4 Other Sources of Costs for Transport

Other cost sources affecting all modes of spent fuel transport include insurance premiums carried on the cask contents. Insurance covering damage or injury to personnel or hauling equipment resulting from shipment of spent fuel is covered by the Price-Anderson law and was not considered in this study. Damage to any transport equipment as a result of carrier negligence or accident is not considered as a cost source to the utility or receiving facility. Damage to the cask and contents can be covered with property insurance on a yearly basis and the cost is dependent on the value of the cask.

Directly quoted premiums and insurance coverage on the cask were not available; however, a reasonable premium estimate of $6K for a one-way waterborne trip for one cask may be made[7-14] based on an individual rail cask value of

$3M. For casks carried by rail or by truck, only the contents of the cask are insurable - at the following rates:

a) $0.05/$100 of the value of LWT cask contents at 50K/assembly

b) $0.10/$100 of the value of rail cask contents at $500K

A final cost source peculiar to the waterborne mode stems from the emergency response required for an accident involving the loss of a cask* or damage to a cask. Cask damage or loss are low probability events by any mode of shipment and recovery costs have not been evaluated. However, recovery of a lost cask is a potential requirement for waterborne shippers. This study did not add the cost of recovery to the total cost of waterborne transit for several reasons:

a) The probability of such an accident per reactor year is sufficiently low that it would be unreasonable to expect individual utilities, carriers and receiving facilities to keep equipment committed to potential recovery operations.

b) This study assumed that, in the event of loss of a cask, the cost of recovery would be borne partially through insurance.

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* Not leakage or violation of cask integrity, but simply the sinking of the cask with the barge.

7.5 Annual Cost Estimates for Several Generic Routes

Results of the economic cost assessment for each of the three generic routes in Table 7.1 are shown in Tables 7.7 - 7.9. In all cases, the cost source criteria discussed in Section 7.2 was used. The three major carrier modes considered were waterborne transportation, rail shipment and shipment by LWT. Intermodal transport was considered for three generic routes, including the relatively short generic route 4.* The floating bridge access was considered in cases where it represented a potential cost saving alternative.

7.6 Discussion of Results

The range of cost per reactor year of spent fuel shipment by various transit modes for medium and long distance routes between utility and receiving facility is summarized in Table 7.10. In all cases, waterborne transit is the most expensive mode of transportation considered.

The largest contributor to overall campaign cost for the intermodal and rail modes of transport is turnaround cost, as shown in Tables 7.7 - 7.9. Turnaround costs are greater for waterborne transport than for rail transport by a factor of 1.5 to 2.0. Hence, while conveyance costs for waterborne transport are competitive with other transport modes, the turnaround costs and intermodal costs render waterborne shipments more expensive than transportation by rail or LWT.

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* It was assumed that the casks were waterborne for a short distance and that the trip was completed by rail for generic route 4.

Table 7.7. Economic Assessment Summary - Comparison of Spent Fuel Transport Costs by Barge, Rail and Truck for Generic Route 1.

Trip Route	Cost Component		Transport Costs (1)					Legal Weight Truck Route
			Intermodal Route (waterborne > 90%)		Rail Route			
			HHT Access (2)	FB Access (2)	HHT Access (2) at Utility	Rail Access (2) to Utility built	Rail Access (3) to Utility Exists	
Conveyance	Freight Cost	Barge	30					
		Train			20.8			
		Truck						2.5
	Cask Rental		70		56			3.4
Turnaround	Total Turnaround Cost		166.6 (4)	201.5 (4)	92.5 (5)	81.6 (6)	28 (7)	1.9
Non Phase Related Costs	Insurance		24		.3			.2
Total Cost Per Trip			290.6	325.5	169.6	158.7	105.1	8.0
Total Cost Per Reactor Year ($M/R-yr)			.94 (8)	1.06 (8)	.55 (8)	.52 (8)	.34 (8)	.52 (9)
Option Costs ($M/R-yr)			.94 - 1.06		.34 - .55			.52

(1) all costs in $K/trip unless noted.
(2) utility is assumed to be located 7 mi. from navigable water and 7 mi. from a railhead, receiving facility is located 4 mi. from navigable water and has rail service.
(3) assumes rail service is available to the facility into the spent fuel area.
(4) cask rental, operational costs and capital costs for turnaround at both ends.
(5) HHT access at both ends used.
(6) includes cask rental during turnaround and cost of rail construction to utility.
(7) includes cask rental during turnaround only.
(8) costs predicated on 6.5 cask loads per year or 3.25 trips between the utility site and the receiving facility.
(9) costs predicated on 65 cask loads per year or 65 trips between the utility site and the receiving facility.

Table 7.8. Economic Assessment Summary - Comparison of Spent Fuel Transport Costs by Barge, Rail and Truck for Generic Route 4

Trip Phase	Cost Component		Transport Costs[1]: Intermodal Route (short waterborne leg) (2): HHT Access at Utility	Intermodal Route (short waterborne leg) (2): FB Access at Utility	Intermodal Route (waterborne > 90%) (2): HHT Access Both Ends	Intermodal Route (waterborne > 90%) (2): FB Access Both Ends	Rail Route (2): HHT Access at Utility	Rail Route (2): Rail Access to Utility (built)	Rail Route (2): Rail Access to Utility Exists	Truck Route
Conveyance	Freight Cost	Barge	3.0		10.5					
		Train	9.9				11.9			
		Truck								1.2
	Cask Rental		35		26		28			1.7
Midtrip Intermodal Transfer	Total Transfer Costs		118.6[3]	16[4]						
Turnaround	Total Turnaround Costs		82.7[5]	81.5[5]	165.4[6]	163[6]	78.5[7]	79.8[8]	28[9]	1.9[10]
Non-Phase Related Costs	Insurance		24		24		3			.2
Total Trip Cost			273.2	169.4	227.9	225.5	118.7	120.0	68.2	5.0
Total Yearly Cost ($M/R-yr)			.89[11]	.55[11]	.74[11]	.73[11]	.39[11]	.39[11]	.22	.33[12]
Cost Range for Mode ($M/R-yr)			.55 - .89				.22 - .39			.33

(1) all costs in $K/trip unless noted.
(2) utility is assumed to be 3 mi. from nearest navigable water and 7 mi. from rail head with a major port at 110 mi. distance by water.
(3) includes cask rental and transfer costs for 2 transfers one on the trip the utility and one for the return trip.
(4) if floating bridge access at the utility is used, intermodal transfer at a major port can utilize carfloat unloading facilities with a total transfer time for two casks assumed to be less than or equal to 1 day
(5) includes cask rental, transfer operation cost and capital costs for transfer at one end.
(6) includes cask rental, transfer operation cost and capital costs for transfer at both ends.
(7) includes cask rental, transfer operation cost and cost of road improvement at utility.
(8) includes cask rental and cost of rail construction to utility.
(9) includes cask rental charges during turnaround only
(10) includes detention charges for truck.
(11) costs predicated on 6.5 cask loads per year of 3.25 trips between the utility site and the receiving facility.
(12) costs predicated on 65 cask loads per year of 65 trips between the utility site and the receiving facility.

Table 7.9. Economic Assessment Summary - Comparison of Spent Fuel Transport Costs by Barge, Rail and Truck for Generic Route 6

Trip Phase	Cost Component		Transport Costs [1]					
			Intermodal Route (waterborne > 90%)		Rail Route			Legal Weight Truck Route
			HHT Access [2]	FB Access [3]	No Rail Service to Utility HHT Access Used [2]	Rail Access to Utility Built [2]	Rail Access to Utility Exists [3]	
Conveyance	Freight Cost	Barge	27					
		Train			19.1			
		Truck						2.3
	Cask Rental		62		56			3.4
Turnaround	Total Turnaround Cost		167.5 [4]	155.4 [5]	158.9 [4]	67.8 [6]	14. [7]	1.9
Non Phase Related Costs	Insurance		24		.3			.2
Total Cost Per Trip			281.5	269.4	234.3	143.2	89.4	7.8
Total Cost Yearly ($M/R-yr)			.91 (8)	.88(8)	.76(8)	.47(8)	.29(8)	.51(9)
Option Cost Range ($M/R-yr)			.88 - .91		.29 - .76			.51

(1) all costs in $K/trip unless noted.
(2) utility is assumed to be on navigable water and 7 mi. from a rail head while receiving facility is assumed to be 15 mi. from navigable water with rail service.
(3) rail service to utility is assumed to exist into the spent fuel area.
(4) cost includes cost of road construction and HHT access at both ends of trip.
(5) cost includes cost of FB construction and operation at both ends of trip.
(6) includes task rental during turnaround and cost of construction.
(7) costs predicated on 6.5 cask loads per year or 3.25 trips between the utility site and the receiving facility.
(8) costs predicated on 65 cask loads per year or 65 trips between the utility site and the receiving facility.

Table 7.10 Cost Ranges for Transport of Spent Fuel by Various Modes

Transport Mode		Cost of Shipment Per Reactor Year ($M/R-yr)[1]	
		Medium Distance Route[2] (400-600 mi.)	Long Distance Route[2] (>1000 mi.)
Rail	Rail access to utility initially exists	.22	.29 - .34
	No rail access to utility initially exists	.39	.52 - .76
Legal Weight Truck		.33	.51 - .52
Inter-modal	Barge < 50% + Rail	.59 - .89	-
	Barge > 90%	.73 - .74	.88 - 1.06

(1) Costs predicated on $3.5K/day cost of dry cask rental.
(2) One-way distance from utility to receiving facility.

The single largest source of cost of spent fuel shipment by any mode of transport is cask rental. Cask rental charges comprise 60-70% of the cost of spent fuel shipment by intermodal transport. Since cask rental charges accrue as a function of conveyance and turnaround time, the slowest modes of shipment will suffer the highest cask rental costs. Waterborne conveyance is slow, and the water routes are somewhat tortuous. However, rail conveyance is also slow; and since both incur a high cask rental cost, they are competitive.

The greatest contribution of cask rental charges to intermodal transport cost occurs during the turnaround and intermodal transfer phases of the trip. Use of HHT equipment in turnaround produces turnaround times of approximately eight days and intermodal transfer times of five days for two casks. Intermodal transport with HHT requires transfer at both ends of the trip. Rail transit, even with no rail access at the utility, requires transfer by HHT only at the utility site. Therefore, the cost of turnaround for waterborne modes is more expensive than for rail.

Use of direct railcar loading equipment can eliminate some of the turnaround cost by reducing turnaround time. In addition, the capital cost may be spread over the life of the reactor. However, the utilities must be reasonably near water for a floating bridge to be cost effective for turnaround. This is evidenced by the high cost of access for generic route 1 with an average distance of 7 miles between the utility and navigable water.

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APPENDIX A. Reactor Location and Intermodal Access Data

Figure A.1. Generic Route 1
Great Lakes Route

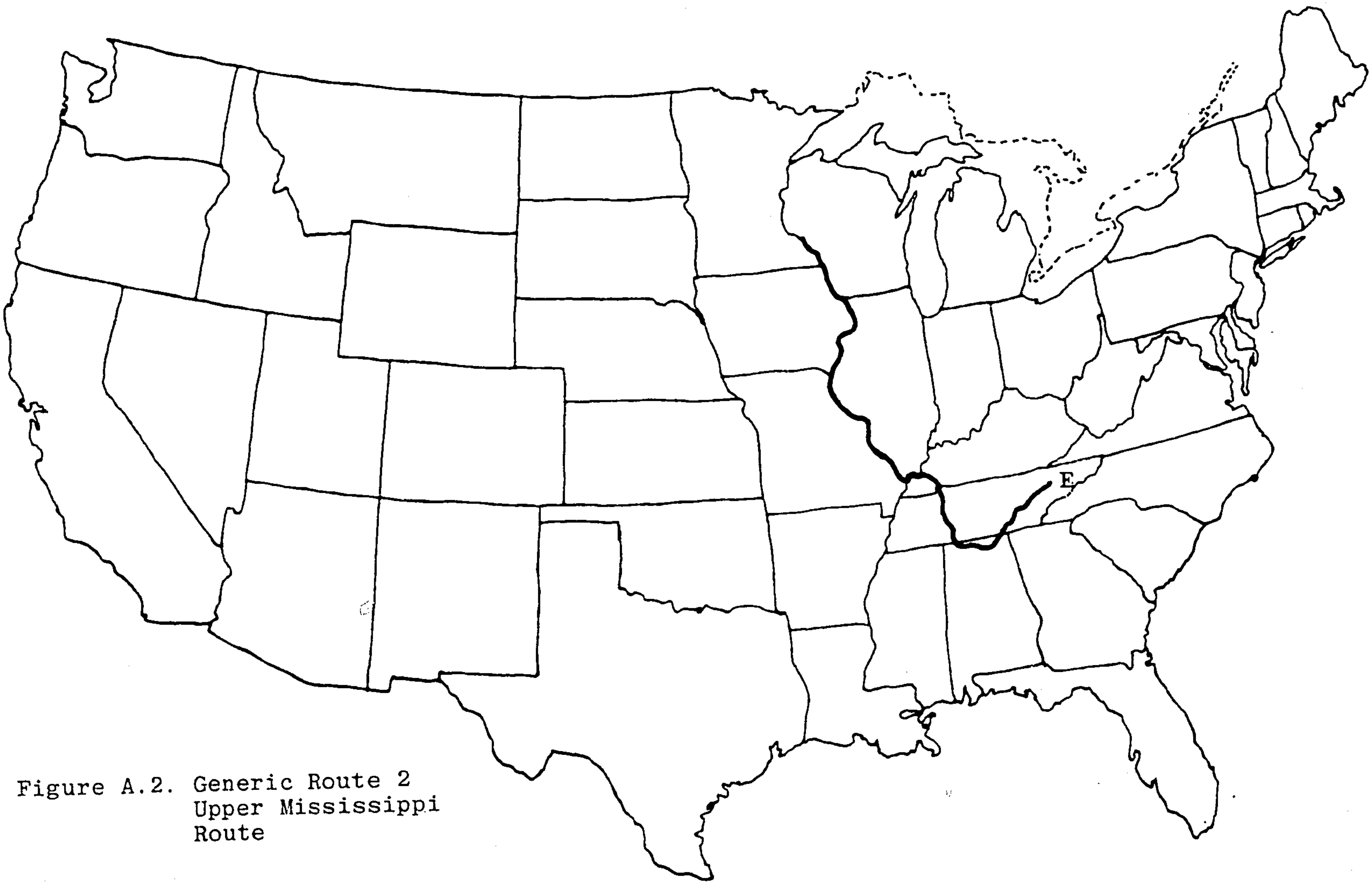

Figure A.2. Generic Route 2
Upper Mississippi
Route

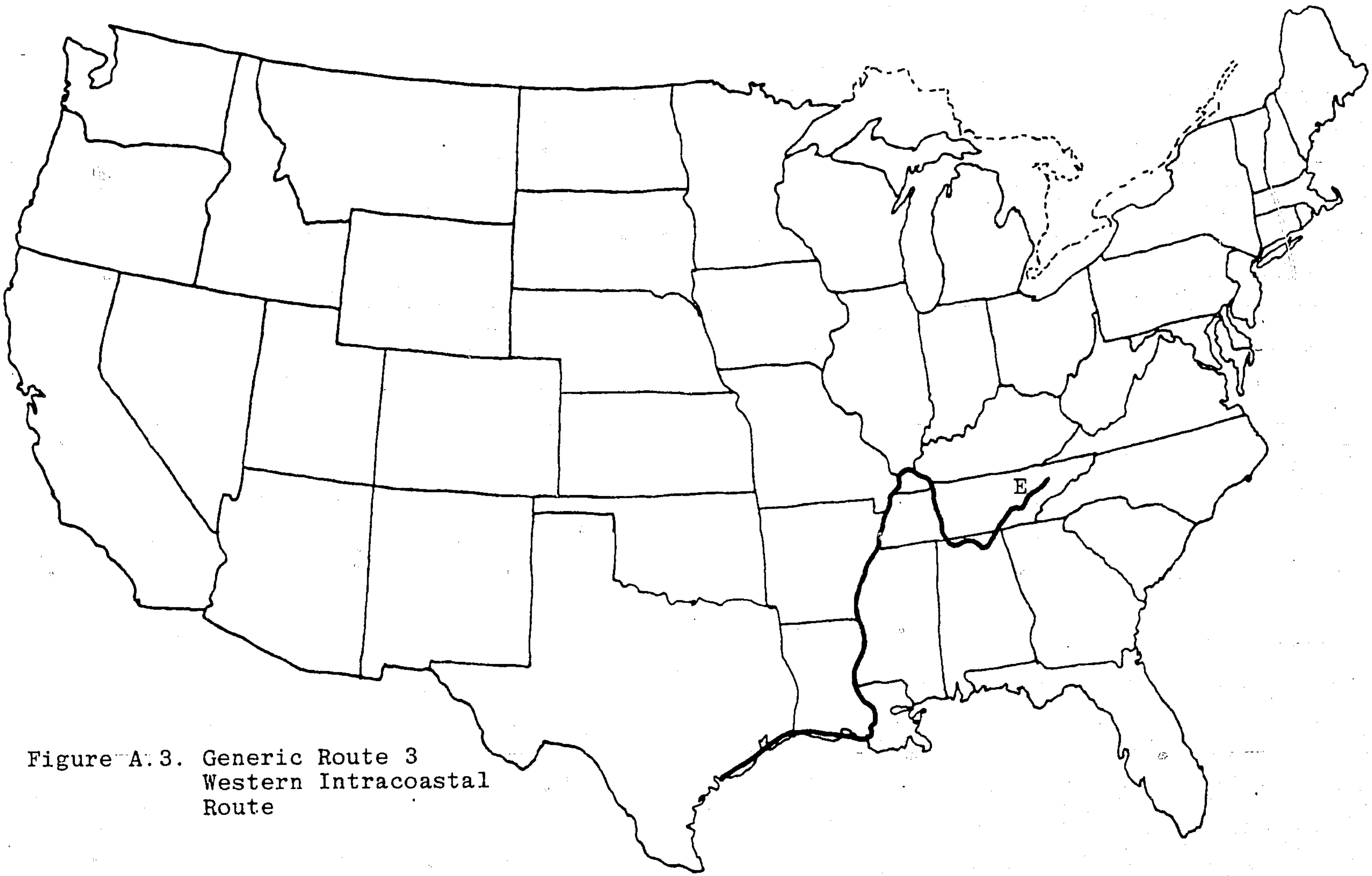

Figure A.3. Generic Route 3
Western Intracoastal
Route

Figure A.4. Generic Route 4
Short Waterborne Hop

Figure A.5. Generic Route 5
Inland Northeast
Route

Figure A.6. Generic Route 6
Coastal Northeast
Route

Figure A.7. Generic Route 7
Chesapeake Bay Route

Figure A.8. Generic Route 8
Eastern Intracoastal
Route

Table A.1. Inland Waterway Link Descriptions[A-1,A-2]

	System	Lower Terminus	Upper Terminus	Distance mi.	Controlling Depth ft.	Navigable Season months
1	Upper Mississippi	Cairo, Illinois (confluence with Ohio River)	Minneapolis, Minnesota	858	9	9
2	Lower Mississippi	Gulf of Mexico	Confluence with Ohio River	954	9 to 40	12
3	Illinois River	Grafton, Illinois (confluence with Mississippi)	Chicago, Ill. (at Lake Michigan)	327	9	10
4	Missouri River	Confluence with Mississippi (Just north of St. Louis)	Sioux City, Iowa	732	9	7.5
5	Ohio River	Cairo, Illinois (confluence with Mississippi)	Pittsburgh, Pa.	981	9	12
6	Allegheny River	Pittsburgh, Pa.	East Brady, Pa.	72	9	12
7	Monongahela River	Pittsburgh, Pa.	Fairmont, West Virginia	129	9	12
8	Kanawha River	Point Pleasant, W. Va. (confluence with Ohio River)	Deepwator, West Virginia	91	9	12
9	Green River	Confluence with Ohio River (near Evansville, Ind.)	Dam 3	108	9	12
10	Cumberland River	Confluence with Ohio River (near Smithland, Ky.)	Celina, Tenn.	381	9	12
11	Tennessee River	Paducah, Ky. (confluence with Ohio River)	Knoxville, Tenn.	652	9	12
12	Arkansas River	Confluence with Mississippi River (near Rosedale, Miss.)	Catoosa, Okla.	448	9	12

Table A.1. (Continued)

	System	Lower Terminus	Upper Terminus	Distance mi.	Controlling Depth ft.	Navigable Season
13	Barkley Canal	Tennessee River	Cumberland River	2	9	12
14	New York State Barge Canal (NYSBC)	Hudson River	Niagra River (Tonawanda NY)	552	12	8
15	Hudson River	Atlantic Ocean	NYSBC	155	14-32	8-12
16	Black Warrior River	Gulf of Mexico	Birmingham, Ala	466	9	12
17	Chattahoochee River	Gulf of Mexico	Columbus Ga/ Bainbridge, Ga	297	9	12
18	Coloosahatchee River System	Gulf of Mexico	Atlantic Intra-coastal Water-way	90	10	12

Table A.2. Intracoastal Waterway Link Descriptions

	System	Lower Terminus	Upper Terminus	Distance mi.	Controlling Depth ft.	Navigable Season
1	Gulf Intracoastal Waterway (west)	Brownsville, Texas	New Orleans, La.	690	10	12
2	Gulf Intracoastal Waterway (east)	New Orleans, La.	Apalachee Bay, Fla. (Near St. Marks, Fla.)	407	10	12
3	Port Allen-Morgan City cut-off	Morgan City, La. (On Gulf Intracoastal Waterway, west)	Port Allen, La. (Near Baton Route, La.)	64	10	12
4	Atlantic Intracoastal Waterway	Miami, Fla.	Chesapeake Bay	1129	12	12
5	Chesapeake Bay	Atlantic Ocean (Norfolk, Va.)	Chesapeake & Delaware Canal	200	42	12
6	Delaware River & Bay	Atlantic Ocean	Trenton, N.J.	129	12-40	12
7	Chesapeake & Delaware Canal	Chesapeake Bay	Delaware River	40	40	12
8	Atlantic Intracoastal Waterway* (Ocean Coastal)	N.Y. City	Bangor, Maine	495	$\geq$40	12
9	Atlantic Ocean Segment†	Delaware River	New York City, N.Y.	180	$\geq$40	12
10	Gulf of Mexico Segment†	St. Marks, Fla.	Fort Myers, Fla.	220	$\geq$40	12

* Signifies a semi-protected route still classifiable as intracoastal.

† Signifies an unprotected open ocean route usable by properly outfitted ocean-going equipment.

Table A.3. Utility Locations and Intermodal Access Constraints(A-3,A-4)

REACTOR	LOCATION	NEAREST WATERWAY	STATUS	NAVIGABLE	R.R.
1. Arkansas N.S. 1,2	Pope Co. Ark.	Dardanelle Reservoir Arkansas River	O,B	YES	YES Missouri Pacific (MP)
2. Duane Arnold E.C.	Linn Co. Iowa	Cedar River	O	NO	YES Rock Island (RI)
3. Bailly G.S.	Porter Co. Indiana	Lake Michigan	B	YES	YES Chicago South Shore
4. Beaver Valley P.S. 1,2	Beaver Co. Penn. (25 mi. NW of Pittsburgh)	Ohio River	O,B	YES	YES New Cumb. & Pittsburg, Conrail (CON)
5. Browns Ferry N.P.S. 1,2,3	Limestone, Ala.	Wheeler Lake (Tennessee River)	O,O,O	YES	NO
6. Brunswick Stm. Elec. Plant 1, 2	Brunswick Co. N.C. (Southport, N.C.)	Cape Fear River (1.75 mi. to Atlanta Ocean)	B,O	POSS	YES Seaboard Coast Line (SCL)
7. Calvert Cliffs N.P.D. 1, 2	Calvert Co. Md. (Wash., D.C. 45 mi)	Chesapeake Bay	O,O	YES	NO

STATUS LEGEND

O = operational

B = under construction

A = construction permit applied for

P = planned

Table A.3. (Continued)

REACTOR	LOCATION	NEAREST WATERWAY	STATUS	NAVIGABLE	R.R.
8.Donald C. Cook P. 1,2	Baroda, Mich. (Benton HBR 11 Mi. N.)	Lake Michigan	O,B,	YES	YES Ches. and Ohio
9.Cooper, N.S.	Nemaha Co. Nebr. (Lincoln Nebr. 60 Mi.)	Missouri River	O	NO	YES Burlington Northern (BN)
10.Crystal River N.G.P. 3 (1,2 are coal fired)	Citrus Co. Fla. (70 mi. N of Tampa)	Gulf of Mexico	B	YES	YES SCL
11.Davis-Besse N.P.S. 1,2,3	Ottawa Co. Ohio (21 mi. E. of Toledo)	Lake Erie	B,A,A	YES	YES N and W
12.Diablo Canyon N.P.D. 1,2	San Luis Obispo Co. (150 mi. NW of L.A.)	Pacific Ocean	B,B	YES (Breakway exists)	NO
13.Enrico Fermi A.P.P. 2	Lagoona Beach, Monroe Co. Michigan	Lake Erie	B	YES	YES DT & SL
14. Joseph Farley N.P. 1,2	Houston Co. Ala (16.5 mi. E. of Dothan)	Chattahoochee River 1 Mi. away	B,B	YES	YES SOU Line (SOU)
15. J.A. Fitzpatrick N.P.P.	Scriba, Oswego Co. N.Y.	Lake Ontario	O	YES	YES CON
16.Forked River N.G.S. 1	Ocean Co. New Jersey (same site as Oyster Creek)	Barnegat Bay (Atlantic Ocean)	B	YES	YES CON
17.Edwin I. Hatch N.P.P. 1,2	Baxley, GA. (Savannah Co. 67 mi.)	Altamaha River	O,B,	NO	YES SOU

Table A.3. (Continued)

REACTOR	LOCATION	NEAREST WATERWAY	STATUS	NAVIGABLE	R.R.
18. Hutchinson Island P. 1,2 (St. Lucie)	Fort Pierce, Fla.	Indian River (AIW)	O,B	YES	NO
19. Indian Point, N.U. 2,3	Buchanan, N.Y. (Nr. Peckskill)	Hudson River	O,O	YES	NO
20. Kewaunee, N.P.P.	Kewaunee Co., Michigan (Green Bay 27 mi.)	Lake Michigan	O	YES	NO
21. Limerick G.S. 1,2	Montgomery Co. Pa. (20 mi. NW of Philadelphia	Schuykill, R.	B,B	NO	YES CON
22. LaSalle Cty S. Units 1,2	Brookfield TWP (60 mi. SW Chicago)	Illinois River (~1 Mi.)	B,B	YES	YES Santa Fe (SF)
23. Maine Yankee A.P.P.	Wiscasset Me. (Portland Me. 34 Mi.)	Montsweag Bay Back River	O	YES	YES Boston & Maine (B&M)
24. McGuire N.S. 1,2	Lake Norman N.C. Mechlenburg Co.	Lake Norman	B,B	NO	YES SCL
25. Midland N.P.P. 1,2	Midland Co. Mich.	Tittabawasse River	B,B	NO	YES Chesapeake & Ohio (C&O)
26. Millstone N.P.S. 1,2,3	Waterford, Conn.	Long Island Sound	O,O,B	YES	YES CON

Table A.3. (Continued)

REACTOR	LOCATION	NEAREST WATERWAY	STATUS	NAVIGABLE	R.R.
27. North Anna P.S. 1,2,3,4	Louisa Co., Va. (40 mi. NW of Richmond)	North Anna, Reserv.	B,B,B,B	NO	YES C&O
28. Point Beach, N.P. 1,2	W. Shore Lake Michigan (30 mi. Southeast G. Bay)	Lake Michigan	O,O	YES	NO
29. Prairie Island, N.G.P. 1,2	Goodhue Co., Minn. (6 mi. NW of Redwing)	Mississippi	O,O	YES	YES Chicago, Mil. St. Paul (CMSP)
30. Rancho Seco, N.G.S. 1,2	S.E. Sacramento Co. (25 mi. SE of Sacro, CA.)	Folsom Canal Reservoir	O,O	NO	YES Southern Pacific (SP)
31. Salem, N.G.S. 1,2	Salem Co., N.J. (20 mi. from Wilm. Del.)	Delaware River (Bay)	O,B,	YES	NO
32. San Onofre, N.G.S. 1,2,3	San Diego, Ca. (17 mi. from Oceanside)	Pacific Ocean	O,B,B	YES	YES SF
33. Seabrook, N.S. 1,2	Hampton, N.Y. (40 mi. NE of Boston)	Hampton Harbor (Atlantic)	B,B	YES	NO
34. Sequoyah, N.P.P.1,2	Hamilton Co., Tenn. (12 mi. NE of Chattanooga)	Chickamonga Lake	B,B	YES	YES SOU
35. Shoreham, N.P.S.	Northshore Long Island	Long Island Sound	B	YES	NO
36. Susquehanna Steam E.S. 1,2	Luzerne Co., PA (16 mi from Wilkes-Barre, PA)	Susquehanna River	B,B	POSS.	YES CON

Table A.3. (Continued)

REACTOR	LOCATION	NEAREST WATERWAY	STATUS	NAVIGABLE	R.R.
37. Three Mile Island S. 1,2	Goldsboro, PA (Daupin Co., 10 mil from Harrisburg, PA.)	Susquehanna River	O,B,	POSS.	YES CON
38. Trojan, N.P.	Columbia Co., Oregon (30 mi. N of Portland, Or)	Columbia River	O	YES	YES BN
39. Virgil C. Summer N.S. 1	Fairfield Co., S.C. (26 mi. N of Columbia, SC)	Lake Monticello	B	NO	YES SOU
40. Waterford Steam E.S. 7	Taft Louisiana 22 mi. West of New Orleans	Mississippi River	B	YES	YES Texas & Pacific (TP)
41. Watts Bar, N.P. 1,2	Rheu Co. Tenn. (45 mi. NE of Chattanooga, Tenn.)	Tennessee River	B,B	YES	YES SOU
42. Zimmer N.P.S. 1,2	Clarmont Co., Ohio (25 mi. SE of Cinn. Ohio)	Ohio River	B,B	YES	NO
43. Zion S. 1,2	NE Illinois, (40 mi. of Chicago)	Lake Michigan	O,O	YES	YES Chicago & N.Western (C&NW)
44. Big Rock Pt. N.P.	Charlevoid, Mich.	Lake Michigan	O	YES	YES C&O
45. Connecticut Yankee A.P.P.	Haddam Conn (22 mi. SE of Hartford)	Connecticut River	O	YES	NO
46. Dresden N.P.S. 1,2,3	Morris Illinois	Des Plaines River	O,O,O	YES	YES East Joliet & Eastern

Table A.3. (Continued)

REACTOR	LOCATION	NEAREST WATERWAY	STATUS	NAVIGABLE	R.R.
47. Fort Calhoun S. 1,2	Washington Co., Nebraska	Missouri River	O,A,	YES	YES C & NW
48. Robert Emmett Ginna N.P.P.	Ontario, N.Y.	Lake Ontario	O	YES	NO
49. Humboldt Bay N.P.P.3	Humboldt, Ca.	Humboldt Bay	O	YES	YES S.P.
50. Monticello, N.G.P.	Monticello,Minn (33 Mi. NW of Minn-SP.)	Mississippi	O	NO	YES BN
51. Nine Mile Point N.S. 1,2	Scriba, N.Y. (35 mi. N of Syracuse)	Lake Ontario	O,B	YES	YES CON
52. Oconee N.S. 1,2,3	Oconee Co., S.C. (26 mi. W of Greenville, S.C.)	Lake Keowee (Keowee River)	O,O,O	NO	NO
53. Oyster Creek, N.G.S	Lacey Twnshp, N.5 (Same site as Forked River NP no. 17)	Barnegat Bay	O	YES	YES CON
54. Palisades N.P.S.	Van Buren Co., Mich. (35 mi. W of Kalamazoo, Mich.)	Lake Michigan	O	YES	YES C&O
55. Peach Bottom P.S. 2,3	York Co. Penna.	Susquehanna River (Conowingo Pond)	O,O	NO	YES CON
56. Pilgrim N.P.S. 1,2	Plymouth Twp. Mass (5 mi. E. of Plymouth)	Cape Cod Bay	O,A,	YES	NO
57. Quad Cities N.P.S. 1,2	Cordova Ill. (20 mil NE of Davenport,IA	Mississippi River	O,O	YES	YES CMSP

Table A.3. (Continued)

REACTOR	LOCATION	NEAREST WATERWAY	STATUS	NAVIGABLE	R.R.
58. H.B. Robinson Steam E.P. 2	Darlington Co., S.C. (56 mi. NE of Columbia)	Lake Robinson S.C.	O	NO	YES SCL
59. Surry P.S. 1,2	Surrey Co., VA. (17 mi. from Newport News VA. NW)	James River	O,O	YES	NO
60. Turkey Point P. 3,4	Dade Co., Fla.	Biscayne Bay	O,O	YES	NO
61. Vermont Yankee G.S.	Windham Co., Vt. (39 mi. N. Holyoke Mass.)	Connecticut River (Vernon Pond)	O	NO	YES Central Vermont
62. Yankee Atomic Electric	Rowe Mass (24 mi. NE of Pittsfield, Mass.)	Sherman Pond (Deerfield River)	O	NO	NO
63 Bellefonte N.P. 1,2	Jackson Co., Ala. (7 mi. ENE of Scottsboro, Ala.)	Guntersville Res. (Tennessee River)	B,B	YES	YES SOU
64. Catawba N.S. 1,2	York Co., S.C. (17 mi. SE of Charlotte NC)	Lake Wylie	B,B	NO	YES SOU
65. Commanche Peak Steam E.S. 1,2	Somervell Co., Texas (65 mi. SW of Dallas - Ft. Worth)	Squaw Creek Res.	B,B	NO	YES SF
66 Douglas Point N.P.S. 1,2	Charles Co., Md. (30 mi. SSW of Wash, D.C.)	Potomac River	A,A	YES	NO
67. Grand Gulf, N.S. 1,2	Clairborne Co., Miss. (55 mi WSW of Jackson Miss.)	Mississippi River	B,B	YES	YES ICG

Table A.3. (Continued)

REACTOR	LOCATION	NEAREST WATERWAY	STATUS	NAVIGABLE	R.R.
68. Hanford No. 2 (W.P.P.S.S. 1,2)	Erda Reser. Richland, Wash.	Columbia River (3 mi.)	B,B	YES	YES
69. LaCrosse River	Genoa Wisc. (20 mil S. of LaCrosse)	Mississippi	O	YES	YES BN
70. Perry N.P.S. 1,2	Lake Co., Ohio (35 mi. NE of Cleveland Ohio)	Lake Erie	A,A	YES	YES CON
71. Shearon Harris N.P.P. 1-4	20 Mi. of Raleigh, N.C.	Cape Fear River (Reservoir of Buckhorn Creek)	A,A,A,A	NO	YES SOU
72. Vogtle N.P. 1,2	Burke Co., GA (26 mi. SSE of Augusta)	Savannah River	B,B	POSS.	YES SOU
73. Allens Creek N.G.S. 1,2	Austin Co., Texas (45 mi. W. of Houston)	Brazos River	A,A,	NO	YES SF
74. Braidwood S. 1,2	Will Co., Ill. (20 mi. SSW of Joliet,Ill)	Kanakee River (3 mi. E.)	B,B	NO	YES ICG
75 Byron Station	Ogle Co. Ill. (2 mi. from Byron, Ill.)	Rock River (2 mi. W.)	B,B	NO	YES CMSP
76. River Bend S. 1,2	W. Feliciana Parrish	Mississippi River	A,A	YES	YES ICG
77. Callaway N.P.S. 1,2	Callaway Co., MO. (80 mi.W. St. Louis,MO.)	Missouri River (5 mi. S.)	B,B	YES	YES MP

Table A.3. (Continued)

REACTOR	LOCATION	NEAREST WATERWAY	STATUS	NAVIGABLE	R.R.
78. Cherokee, NA. 1,2,3	Cherokee Co., S.C. (21 mi. ENE of Spartanburg S.C.)	Broad River (Ninety Nine Island Res.)	A,A,A,	NO	YES SOU
79. Clinton P.S. 1,2	DeWitt Co. 6 mi. E. of Clinton	Salt Creek Reservoir	B,B,	NO	YES ICG
80. Greenwood E.C. 2,3	St. Clair Co., Mich. (55 mi. NNE of Detroit Mich.)	Lake Huron (10 mi. N)	A,A,	NO	YES C&O
81. Koshkonong, N.P. 1,2	SW Jefferson Co., Wisc. (52 mi. SW of Milw)	Rock River Lake Koshkonong	A,A,	NO	YES C&NW
82. Montague, N.P.S. 1,2	Franklin Co. NW Mass 35 mi ESE of Greenfield Mass.	Connecticut River (1.5 mil)	A,A,	NO	YES B&M
83. Perkins N.S. 1,2,3	Davis Co. N.C., 20 mi. 55 W. of Winston-Salem	Yadkin River	A,A,A	NO	YES SOU
84. Quanicassee P. 1,2	Bay County, Mich. 6 mi E of Bay City	Saginaw Bay	A,A	YES	YES
85. South Texas Project 1,2	S.C. Matagona Co. 90 Mi. SW of Houston	Gulf of Mexico (10 mi.)	B,B	POSS.	YES MP
86. Sterling P.P.N.U. 1	Cayuga Co. N.Y. 50 Mi. E. of Rochester	Lake Ontario	A	YES	YES CON
87 Wolf Creek G.S. 1	Coffey Co. Kansas (28 mi. ESE of Emporia, Kansas)	Neosho River Cooling Lake	A	NO	YES MP

Table A.3. (Continued)

REACTOR	LOCATION	NEAREST WATERWAY	STATUS	NAVIGABLE	R.R.
88. Blue Hills N.P.P. 1,2	Newton Co., Texas	Sabine River	A,A	NO	YES SF
89.Hope Creek, 1,2	Burlington Co., N.J.	Delaware River	B,B	YES	NO
90.Tyrone Energy Park	Dunn Co. Wisc (20 mi. SW of Eau Clair, Wisc.)	Chippewa River	A	NO	YES CMSP
91 Hartsville, 1,2,3,4	Smith Co., Tenn. (Hatesville, Tenn.)	Cumberland River	A,A,A,A	YES	NO
92 Phipps Bend 1,2	Hawkins Co., Tenn. (Surgeonsville, Tenn.)	Holston River	A,A	NO	YES SOU
93 Skagit, 1,2	Skagit Co. Wash. (Sedro Wooley, Wash.)	Puget Sound	A,A	YES	YES BN
94 Alan R. Barton 1,2	Chilton and Elmore Cos., Ala. (Clanton, Ala.)	Coosa River Res.	A,A	NO	YES L&N
95 Palo Verde 1,2,3	Wintersburg, Az.	Salt River Verde River Roosevelt Lake	B,B,B	NO	YES SP
96 Jamesport 1,2	Suffolk Co., N.Y. (Jamesport, N.Y.)	Long Island Sound Bay Inlet	A,A	YES	YES Long Island Rail Road
97 Pebble Springs 1,2	Gilliam Co., Oregon (Arlington, Oregon)	Columbia River	A,A	YES	YES Union Pacific (UP)
98 New England 1,2	Washington Co. R.I. (Charlestown R.I.)	Rhode Island Sound (Providence Bay)	A,A	YES	Unknown (U)

Table A.3. (Continued)

REACTOR	LOCATION	NEAREST WATERWAY	STATUS	NAVIGABLE	R.R.
99. Green County	Green County N.Y. (Cementon N.Y.)	Hudson River	A	YES	U
100. Black Fox 1,2	Rogers Co., Oakla. (Inola Okla.)	Oalogah Res.	A,A	NO	YES MP
101. Atlantic 1,2	New Jersey Coast (Atlantic City)	Atlantic Ocean (Breakwater)	A,A	YES	NO
102 Marble Hill, 1,2	Jefferson Co., Indiana (Jeffersonville, Ind.)	Ohio River	A,A	YES	YES B&O
103. Yellow Creek 1,2	Tishomungo Co., Miss.	Tennessee River	A,A	YES	YES SOU
104. W.P.P.S.S. 3,5	Grays Harbor Co., Wash. (Satsop, Wash.)	Grays Harbor Bay	A,A	YES	YES BN
105. Sears Island Project	Searsport, Me.	Atlantic Ocean	P	YES	YES B&M
106. Portland 5	(Undesignated), Pa.	Delaware River	P	NO	YES CON
107. Atlantic 3,4	New Jersey Coast (undesignated)	Atlantic Ocean	P,P	YES	NO
108. Central Iowa	Vandalia Ia.	DeMoines River	P	NO	U
109 Eire 1,2	Berlin Hts. Ohio	Lake Erie	P,P	YES	U
110. SR 1,2 (Undesignated)	Undesignated S.C.	Santee River	P,P	NO	U
111. Sundesert, U.P.P. 1,2	Blythe, Ca.	Colorado River	A,A	NO	YES SF

Table A.4.
Key

AI	-	Atlantic Intracoastal Waterway
Ark	-	Arkansas River
CB	-	Chesapeake Bay
CU	-	Cumberland River
DE	-	Delaware River
FS	-	Flint System
GI	-	Gulf Intracoastal Waterway
GL	-	Great Lakes
HS	-	Houston Ship Canal
HU	-	Hudson River
Ill	-	Illinois River
JA	-	James River
LM	-	Lower Mississippi River
MI	-	Missouri River
NYCDB	-	New York City to Delaware Bay
NYSC	-	New York State Barge Canal
OC	-	Ocean Coastal, Maine to Boston Bay
Ohio	-	Ohio River
PO	-	Potomac River
RMFL	-	Rail Mileage Final Link
RMPW	-	Rail Mileage Plant to Water
SA	-	Savannah River
Tenn	-	Tennessee River
UM	-	Upper Mississippi River
B	-	Barnwell, S.C.
O	-	Oak Ridge, Tenn.

Table A.4. Intermodal Route Descriptions

No.	Plant	Route Description and Mileage per Link	Receiving Facility	Total Miles By Barge	Notes...
1	Arkansas 1,2	L.M./383; Ohio/45; Ark/200; Tenn./652; RMFL/4	O	1310	Barge loading at Rx site
2	Duane Arnold	RMPW/85; UM/484; Ohio/45; Tenn./652; RMFL/4	O	1296	
3	Bailly G.S.	UM/220; Ill/354; Ohio/45; Tenn./652; GL/55; RMFL/4	O	1356	
4	Beaver Valley 1,2	Ohio/900; Tenn./652; RMFL/4	O	1582	
5	Browns Ferry 1,2,3	Tenn/343; RMFL/4	O	373	
6	Brunswick 1,2	RMPW/2; SA/150; AI/275; RMFL/15	B	537	
7	Calvert Cliffs 1,2	SA/150; AI/585; CB/138; RMFL/15	B	983	
8	Cook 1,2	UM/220; Ill/354; Ohio/45; Tenn./652; GL/75; RMFL/4	O	1376	
9	Cooper Station	UM/182; MI/556; Ohio/45; Tenn./652; RMFL/4	O	1465	
10	Crystal River	SA/150; AI/700; RMFL/15	B	960	
11	Davis Besse	UM/220; Ill/354; Ohio/45; Tenn./652; GL/750; RMFL/4	O	2051	

Table A.4. (Continued)

No.	Plant	Route Description and Mileage per Link	Receiving Facility	Total Miles	Notes...
12	Diablo Canyon				*Rail accross country
13	Fermi	UM/220; Ill./354; Ohio/45; Tenn./542; NYSC/700; RMFL/4	O	2001	
14	Farley 1,2	SA/150; GI/500; FS/125; AI/350; RMFL/15	B	1235	
15	Fitz-Patrick	NYCDB/180; SA/150; AI/585; DE/80; CB/246; HU/155; NYSC/200; GL/30; RMFL/15	B	1736	
16	Forked River	NYCDB/110; SA/150; SI/585; DE/80; CB/246; RMFL/15	B	1281	
17	Hatch	RMPW/95; SA/150; RMFL/15	B	355	
18	Hutchin-son Island	SA/150; AI/350; RMFL/15	B	610	
19	Indian Point	NYCDB/180; SA/150; AI/585; DE/80; CB/246; HU/60; RMFL/15	B	1411	
20	Kewannee	UM/220; Ill/354; Ohio/45; Tenn./652; GL/185; RMFL/4	O	1486	
21	Limerick 1,2	RMPW/20; SA/150; AI/585; DE/272; CB/Comb; RMFL/15	B	1137	
22	Lasalle	UM/220; Ill/258; Ohio/45; Tenn./652; RMFL/4	O	1205	
23	Maine Yankee	OC/400; NYCDB/180; SA/150; AI/585; DE/80; CB/246; RMFL/15	B	1751	
24	McGuire	RMFL/180	B	180	Direct Rail
25	Midland	RMPW/30; UM/220; Ill/354; Ohio/45; Tenn./652; GL/550; RMFL/4	O	1881	
26	Millstone	OC/125; NYCDB/180; SA/150; AI/585; DE/80; CB/246; RMFL/15	B	1476	
27	North Anna	RMPW/45; SA/150; AI/585; CB/103; RMFL/15	B	993	

Table A.4. (Continued)

No.	Plant	Route Description and Mileage per Link	Receiving Facility	Total Miles	Notes...
28	Point Beach	UM/220; Ill/354; Ohio/45; Tenn./652; GL/175; RMFL/4	O	1476	
29	Prarie Island	UM/820; Ohio/45; Tenn./652; RMFL/4	O	1520	
30	Rancho Seco		O		*Rail Across country
31	Salem	SA/150; AI/226; CB/Comb; RMFL/15	B	1071	
32	San Onofre	LM/805; Ohio/45; PO/80; Tenn./652; GI/250; HS/50; RMFL/1540*,4	O	3461	*Rail across country
33	Seabrook	OC/300; NYCDB/180; SA/150; FS/585; DE/80; CB/246; RMFL/15	B	1651	
34	Sequoyah	Tenn./150; RMFL/4	O	180	
35	Shoreham	OC/75; NYCDB/180; SA/150; AI/585; DE/80; CB/246; RMFL/15	B	1426	
36	Susquah-Hanna	RMPW/110; SA/150; AI/585; DE/272; CB/Comb; RMFL/15	B	1227	
37	Three Mile Island	RMPW/80; SA/150; AI/585; CB/188; RMFL/15	B	1113	
38	Trojan		O		Rail across country
39	Summer	RMFL/90	B	90	Rail Direct
40	Water-ford Steam	LM/830; Ohio/45; Tenn./652; RMFL/4	O	1557	
41	Watts BAR	Tenn./120; RMFL/4	O	150	
42	Zimmer	Ohio/485; Tenn./652; RMFL/4	O	1167	
43	Zion	UM/220; Ill/354; Ohio/45; Tenn./652; GL/50; RMFL/4	O	1351	

Table A.4. (Continued)

No.	Plant	Route Description and Mileage per LInk	Receiving Facility	Total Miles	Notes...
44	Big Rock Point	UM/220; Il1/354; Ohio/45; Tenn/652; GL/300; RMFL/4	O	1601	
45	Conn. Yankee	OC/130; NYCDB/180; SA/150; AI/585; DE/80; CB/246; RMFL/15	B	1481	
46	Dresden	UM/220; Il1/270; Ohio/45; Tenn/652; RMFL/4	O	1217	
47	Ft. Calhoun	UM/220; MI/665; Ohio/45; Tenn/652; RMFL/4	O	1612	
48	R.E. Ginna	NYCDB/180; SA/150; AI/585; DE/80; CB/246; HU/155; N&SC/200; GL/50; RMFL/15	B	1756	
49	Humbolt Bay		O		Rail across country
50	Monti-cello	RMPW/70; UM/855; Ohio/45; Tenn/652; RMFL/4	O	1652	
51	Nine Mile Point	NYCDB/180; SA/150; AI/585; DE/80; CB/246; HU/155; NYSC/200; GL/20; RFML/15	B	1726	
52	Oconee	RMFL/4	B	30	Rail Direct
53	Oyster Creek	NYCDB/110; SA/150; AI/585; DE/80; CB/246; RMFL/15	B	1281	
54	Palisades	UM/220; Il1/354; Ohio/45; Tenn/652; GL/100; RMFL/4	O	1401	
55	Peach Bottom	RMPW/30; SA/150; AI/585; CB/208; RMFL/15	B	1083	
56	Pilgrim	OC/250; NYCDB/180; SA/150; AI/585; DE/80; CB/246; RMFL/15	B	1601	
57	Quad Cities	UM/504; Ohio/45; Tenn/652; RMFL/4	O	1231	

Table A.4. (Continued)

No.	Plant	Route Description and Mileage per Link	Receiving Facility	Total Miles	Notes...
58	Robinson	RMFL/165	B	165	Direct Rail
59	Surry	SA/150; AI/585; JA/50; RMFL/15	B	895	
60	Turkey Point	SA/150; AI/485; RMFL/15	B	745	
61	Vermont Yankee	RMPW/75; NYCDB/180; SA/150; AI/585; DE/80; CB/246; HU/155; RMFL/15	B	1581	
62	Yankee Rowe	RMPW/50; NYCDB/180; SA/150; AI/585; DE/80; CB/246; HU/155; RMFL/15	B	1556	
63	Bell Fonte	Tenn/240; RMFL/4	O	270	
64	Catawba	RMFL/130	B	130	Direct Rail
65	Commanche Peak	RMPW/275; LM/805; Ohio/45; Tenn/652; GI/259; HS/50; RMFL/4	O	2089	
66	Douglas Point	SA/150; AI/585; CB/175; RMFL/15	B	1020	
67	Grand Gulf	LM/570; Ohio/45; Tenn/652; RMFL/4	O	1297	
68	Hanford #2		O		Rail across country
69	Lacross	UM/675; Ohio/45; Tenn/652; RMFL/4	O	1402	
70	Perry	UM/220; Ill/354; Ohio/45; Tenn/652; GL/750; RMFL/4	O	2051	
71	Harris	RMPW/50; SA/150; AI/425; RMFL/15	B	735	
72	Vogtle	RMFL/130	B	130	Direct Rail
73	Allens Creek	RMPW/80; LM/805; Ohio/45; Tenn/652; GI/259; HS/50; RMFL/4	O	1921	

Table A.4. (Continued)

No.	Plant	Route Description and Mileage per Link	Receiving Facility	Total Miles	Notes....
75	Braidwood	RMPW/25; UM/220; Ill/288; Ohio/45; Tenn/652; RMFL/4	O	1260	
76	Byron Station	RMPW/75; UM/484; Ohio/45; Tenn/652; RMFL/4	O	1286	
77	River Bend	LM/700; Ohio/45; Tenn/652; RMFL/4	O	1427	
78	Callaway	UM/182; MI/159; Ohio/45; Tenn/652; RMFL/4	O	1068	
79	Cherokee	RMFL/100	B	100	Direct Rail
80	Clinton	RMPW/75; UM/220; Ill/163; Ohio/45; Tenn/652; RMFL/4	O	1185	
81	Greenwood	RMPW/25; UM/220; Ill/354; Ohio/45; Tenn/652; GL/600; RMFL/4	O	1926	
82	Kosh-Konong	RMPW/50; UM/220; Ill/354; Ohio/45; Tenn/652; GL/80; RMFL/4	O	1431	
83	Montague	RMPW/80; PO/160; NYCDB/180; SA/150; AI/585; DE/80; CB/246; RMFL/15	B	1591	
84	Perkins	RMFL/180	B	180	Direct Rail
85	Quani-cassee	UM/220; Ill/354; Ohio/45; Tenn/652; GL/550; RMFL/4	O	1851	
86	So. Texas	LM/805; Ohio/45; Tenn/652; GI/384; RMFL/4	O	1916	Dredge canal for barge loading
87	Sterling	NYCDB/180; SA/150; AI/585; DE/80; CB/246; HU/155; NYSC/200; GL/30; RMFL/15	B	1736	
88	Wolf Creek	RMPW/100; UM/182; MI/382; Ohio/45; Tenn/652; RMFL/4	O	1391	
89	Blues Hills	RMPW/60; LM/805; Ohio/45; Tenn/652; GI/253; RMFL/4	O	1845	
90	Hope Creek	RMPW/50; SA/150; AI/585; DE/246; CB/Comb; RMFL/15	B	1141	
91	Tyrone	RMPW/35; UM/820; Ohio/45; Tenn/652; RMFL/4	O	1555	

Table A.4. (Continued)

No.	Plant	Route Description and Mileage per Link	Receiving Facility	Total Miles	Notes...
92	Harts-ville	Tenn/652; CU/204; RMFL/4	O	886	
93	Phipps Bend	RMFL/100	O	100	Direct Rail
94	Skagit		O		Rail across country
95	Barton	RMPW/150; Tenn/343; RMFL/4	O	523	
96	Palo Verde		O		Rail across country
97	James Port	OC/100; NYCDB/180; SA/150; AI/585; DE/80; CB/246; RMFL/15	B	1451	
98	Pebble Springs		O		Rail across country
99	New England	OC/200; NYCDB/180; SA/150; AI/585; DE/80; CB/246; RMFL/15	B	1551	
100	Green County	NYCDB/180; SA/150; AI/585; DE/80; CB/246; NYSC/120; RMFL/15	B	1471	
101	Black Fox	RMPW/125; LM/383; Ohio/45; ARK/350; Tenn/652; RMFL/4	O	1585	
102	Atlantic 1,2	NYCDB/75; SA/150; AI/585; DE/80; CB/246; RMFL/15	B	1246	
103	Marble Hill	Ohio/337; Tenn/652; RMFL/4	O	1019	
104	Yellow Creek	Tenn/450; RMFL/4	O	480	
105	WPPSS 3,5		O		Rail across country

Table A.4. (Continued)

No.	Plant	Route Description and Mileage per Link	Receiving Facility	Total Miles	Notes...
106	Sea Island	OC/475; NYCDB/180; SA/150; AI/585; DE/80; CB/246; RMFL/15	B	1676	
107	Portland	RMPW/75; SA/150; AI/585; CB/305; RMFL/15	B	1225	
107	Atlantic 3,4	NYCDB/25; SA/150; AI/585; DE/80; CB/246; RMFL/15	B	1196	
108	Central Iowa	RMPW/250; LM/484; Ohio/45; Tenn/652; RMFL/4	O	1461	Distance to navigable water > 10% of trip length
109	Erie	UM/220; Ill/354; Ohio/45; Tenn/652; GL/725; RMFL/4	O	2026	
110	SR 1,2	RMFL/100	B	100	Direct Rail
111	Sun Desert		O		Rail across country

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A-3. USNRC, "Facilities Licensing Application Record," OMIPC: NLO, December 1976.

A-4. F.A. Heddleson, "Design Data and Safety Features of Commercial Nuclear Power Plants," Volumes 1-5, ORNL NSIC-55.

APPENDIX B. Probabilities of Sustained Thermal Environments and Penetration of a Cask by Stubs or Missiles

B.1 Thermal Environments and Severe Accident Frequencies

The probability of penetration of a spent fuel cask can be evaluated as the product of the probability of a serious accident in which a missile or a stub may be generated and the conditional probability of a penetration given a stub or missile impact.

The probability of a serious accident potentially involving stub or missile impacts can be determined from Coast Guard records. In particular, the Coast Guard data file system(B-1) contains filed data on waterborne accidents reported through the following:

a) Marine Board of Inquiry Reports
b) USCG Narrative Documents
c) US Port Authority Commander Letters of Transmittal
d) Other written sources

This data base inquiry encompassed the entire network of western rivers for cargo barge and tank barge accidents occurring over a six year period from 1970-1975. It also included data from a large area of the southern Mississippi River, an area that is very similar to the Chesapeake Bay Area. A suitable filtering of data was performed for barge accidents reported in this file in order to separate accidents fitting a relatively general category, such as collisions, into severity levels; damage in dollars sustained by the vessel and cargo and the extent of the loss (a total or non-total loss of the vessel) were used as the scaling criteria. Other parameters of significance, such as the presence of fire, were also considered and separate listings were made in the computer output included in the appendix. The relative numbers of occurrences for ten casualty types involving cargo barges similar to the type used in spent fuel transport are shown in Table B.1 as a function of dollar amounts of damage for a six year period. Table B.2 gives a similar breakdown of data for tank barges. The categories entitled Collisions, Rammings, and Fires and/or Explosions were of particular interest to this study: these are given as casualty types 1, 2, and 4, respectively. Values for all casualty categories were normalized using barge mileage estimates taken from the Corps of Engineers National Summary literature(B-2) of 9.8×10^7 cargo barge miles/year and 3.8×10^7 tank barge miles/year.

Two parameters were used to determine severe accident frequencies:

a) instances involving total loss of vessel and contents

b) instances resulting in cargo damage $\geq$ \$100.5K

The cargo barge accident data in Table B.1 includes the following significant occurrences over a six-year period:

a) 36 collision and ramming incidents resulting in total loss of the vessel and its contents

b) 1 fire and explosion incident resulting in total loss of the vessel and its contents

c) 3 fire and explosion incidents resulting in $\geq$ \$100.5K in cargo damage

d) 20 collision and ramming incidents resulting in $\geq$ \$100.5K in cargo damage

Key of Casualty Descriptions for Tables B.1 and B.2

NATURE OF CASUALTY	DESCRIPTION
1	Collisions
2	Rammings
3	Groundings
4	Fire and/or Explosions
5	Founderings and Capsizing
6	Structural Failures
7	Heavy Weather
8	Cargo Damage - No Damage to Vessel
9	Barge Breakaway
10	Other - Undetermined or Not Classified

Table B.1. Summary of Incidence Data on Cargo Barge Accidents on Western Rivers for the Period 1969–1970 Inclusive

VESSEL DAMAGE ($, THOUSANDS)	NATURE OF CASUALTY 1	2	3	4	5	6	7	8	9	10	TOT
0 – .5	269	252	114	3	62	18	0	1	20	226	965
+.5 – 1.5	133	74	42	0	21	13	0	0	5	28	316
+1.5 – 3.5	135	119	57	0	28	16	2	0	23	32	412
+3.5 – 10.5	190	236	87	3	67	56	2	0	17	58	716
+10.5 – 30.5	84	119	49	2	37	30	1	0	7	38	367
+30.5 – 100.5	35	59	29	2	17	11	0	0	7	3	165
+100.5 – 300.5	4	1	2	0	4	1	0	0	3	1	16
+300.5 – 1000.5	1	0	1	0	0	0	0	0	0	0	2
+1000.5 – 3000.5	0	0	0	0	0	0	0	0	0	0	0
OVER 3000.5	0	0	0	0	0	0	0	0	0	0	0

CARGO DAMAGE ($, THOUSANDS)	NATURE OF CASUALTY 1	2	3	4	5	6	7	8	9	10	TOT
0 – .5	810	740	339	7	118	81	3	0	71	358	2527
+.5 – 1.5	7	10	4	0	28	13	0	0	0	7	69
+1.5 – 3.5	5	25	6	0	24	21	1	1	0	2	85
+3.5 – 10.5	14	37	11	0	31	19	1	0	10	9	132
+10.5 – 30.5	4	18	8	0	11	6	0	0	0	2	[illegible]
+30.5 – 100.5	5	14	11	0	15	3	0	0	1	4	53
+100.5 – 300.5	6	14	2	3	8	2	0	0	0	2	37
+300.5 – 1000.5	0	1	0	0	1	0	0	0	0	1	3
+1000.5 – 3000.5	0	0	0	0	0	0	0	0	0	0	0
OVER 3000.5	0	1	0	0	0	0	0	0	0	1	2

	NATURE OF CASUALTY 1	2	3	4	5	6	7	8	9	10	TOT
VESSEL TOTAL LOSS	10	26	12	1	26	25	0	0	2	2	104

Table B.2. Summary of Incidence Data on Tank Barge Accidents on Western Rivers for the Period 1969-1970 Inclusive.

VESSEL DAMAGE ($, THOUSANDS)	NATURE OF CASUALTY 1	2	3	4	5	6	7	8	9	10	TOT
0 - .5	173	172	38	8	0	5	0	0	3	123	522
+.5 - 1.5	72	33	13	2	0	2	0	0	1	3	126
+1.5 - 3.5	131	75	35	0	2	3	0	0	2	4	252
+3.5 - 10.5	146	157	47	5	2	4	1	0	2	8	372
+10.5 - 30.5	61	86	46	8	3	6	0	0	0	3	213
+30.5 - 100.5	35	23	18	7	2	2	0	0	1	0	88
+100.5 - 300.5	4	2	3	1	1	0	0	0	0	0	11
+300.5 - 1000.5	0	2	0	0	0	0	0	0	0	0	2
+1000.5 - 3000.5	0	0	0	0	0	0	0	0	0	0	0
OVER 3000.5	0	0	0	0	0	0	0	0	0	0	0

CARGO DAMAGE ($, THOUSANDS)	NATURE OF CASUALTY 1	2	3	4	5	6	7	8	9	10	TOT
0 - .5	585	513	168	29	7	17	1	0	9	140	1469
+.5 - 1.5	7	6	11	0	0	0	0	0	0	0	24
+1.5 - 3.5	9	3	7	0	0	1	0	0	0	0	20
+3.5 - 10.5	12	13	12	0	1	0	0	0	0	1	39
+10.5 - 30.5	4	8	0	2	1	2	0	0	0	0	17
+30.5 - 100.5	4	6	2	0	1	2	0	0	0	0	15
+100.5 - 300.5	1	1	0	0	0	0	0	0	0	0	2
+300.5 - 1000.5	0	0	0	0	0	0	0	0	0	0	0
+1000.5 - 3000.5	0	0	0	0	0	0	0	0	0	0	0
OVER 3000.5	0	0	0	0	0	0	0	0	0	0	0

	NATURE OF CASUALTY 1	2	3	4	5	6	7	8	9	10	TOT
Vessel Total Loss	1	[illegible]	3	3	1	1	[illegible]				[illegible]

The range of probability for evaluating the likelihood of severe impact used in this report is

$$P_{SI} = 3.4 \times 10^{-8} \text{ to } 6.1 \times 10^{-8}\text{/b-mi}$$

The range of probability for a fire or explosion is

$$P_E = 1.7 \times 10^{-9} \text{ to } 5.1 \times 10^{-9}\text{/b-mi}$$

B.2 Penetration Equations for Defining Massive Cask Boundary Failure Phenomena

A number of equations exist for modeling the pentration of one dimensional steel plates by missiles. One formula for penetration of steel plates by missiles taken from Ballistic Research Laboratory (BRL) data(B-3) is

$$T = [(MV^2/2)/(49200\ R^{3/2})]^{2/3} = (MV^2/2)^{2/3}/(1343\ R)$$

where

T = thickness of steel to be just perforated (in.)
$MV^2/2$ = normal kinetic energy of missile (ft.-lb.)
R = missile radius (in.)
V = normal velocity (ft./sec.)

Another formula, given in a Sandia Laboratory report(B-4) based on earlier ballistic results, is

$$T = 12(MV^2/2)/(\frac{\pi}{2}YR^2)$$

where Y = yield stress of the plate (psi) and the other parameters are the same as above. Because both of these relationships were developed to characterize the penetration of missiles through infinite plates, their application in a one dimensional analysis is limited to plates whose dimensions are much greater than the length of the missile. However, the basic idea behind them, that of energy dissipation, is relatively insensitive to the missile length. This basic idea permits the application of these models to probabilistic models of the penetration of plates by stubs.

For missile penetration, MV^2 is the kinetic energy of the missile if the object being struck is immovable. For cask penetration by a stub, the relevant energy is the kinetic energy of the cask. Both of these limits could be obtained by considering M to be the reduced mass M, $M_2/(M_1 + M_2)$ and V the relative velocity. Furthermore, both of these relations neglect the effect of material behind the plate. A steel plate backed by a lead plate is more resistant to penetration since there would be increased energy dissipation due to the deformation of both the lead and the steel.

Figure B.1 shows the relation for T and $MV^2/2$ for both models. The point $V/R = 58\ sec^{-1}$ corresponds to the standard 40 in. drop on a 6 in. diameter post for a 200,000 lb. cask (the nominal weight of NLI 10/24 cask assembly). See Section 3 for details.

In this report, a penetration to the cask interior which involves penetration of 3½" of stainless steel and 6" of lead is of particular interest. (This is equivalent to $3.5 + 6.0 \times 3000/90000 = 3.7$" stainless steel in the "Sandia" relation due to the low yield stress for lead.)

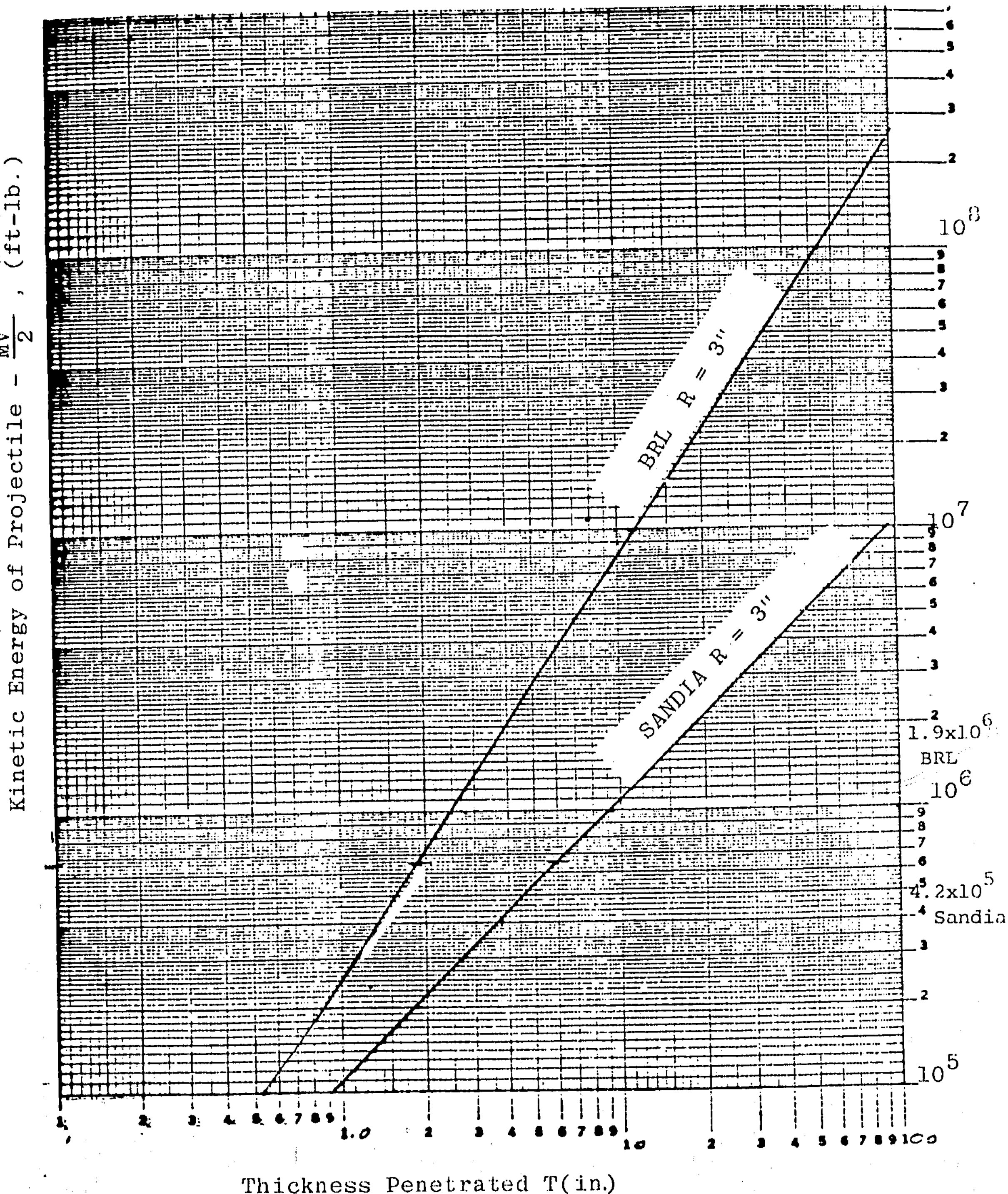

Figure B.1. Plots of BRL and Sandia Relations for 3" Radius Projectiles

B.3 Penetration of the Cask Boundary by Missile Impacts

Full penetration of the protective layers of the NLI 10/24 cask, using BRL and Sandia data, requires that:

$$\text{(BRL)} \quad \left(\frac{MV^2}{2}\right)^{2/3} \left(\frac{1}{R}\right) > 4.97 \times 10^3 \tag{1}$$

$$\text{(Sandia)} \quad \left(\frac{MV^2}{2}\right) \left(\frac{1}{R^2}\right) > 4.36 \times 10^4 \tag{2}$$

Characterizing the missile in terms of the missile density, ρ, the length to width ratio, λ, and the impact area radius, R, yields

$$M = (3.545 \times 10^{-3})\rho\lambda R^3 \tag{3}$$

The kinetic energy of the missile is

$$\begin{aligned} KE &= \left(\frac{3.545 \times 10^{-3}}{2}\right) \rho\lambda R^3 \; V^2 \\ &= (1.77 \times 10^{-3})\rho\lambda R^3 \; V^2 \end{aligned} \tag{4}$$

Thus, the two penetration criteria become

$$\text{(BRL)} \quad \left[(1.78 \times 10^{-3})\rho\lambda R^3 \; V^2\right]^{2/3} \left(\frac{1}{R}\right) > 4.97 \times 10^3 \tag{5}$$

$$\text{(Sandia)} \quad \left[(1.78 \times 10^{-3})\rho\lambda R^3 \; V^2\right] \left(\frac{1}{R^2}\right) > 4.36 \times 10^4 \tag{6}$$

which yields a required impact velocity of

$$\text{(BRL)} \quad V > \frac{1.41 \times 10^4}{(\rho\lambda)^{1/2} R^{3/4}} \tag{7}$$

$$\text{(Sandia)} \quad V > \frac{4.96 \times 10^3}{(\rho\lambda)^{1/2} R^{1/2}} \tag{8}$$

The cumulative probability of an impact speed greater than or equal to any given speed ν is represented as

$$P(V \geq \nu \mid \nu \leq a) = (1 - \nu/a)^4 \tag{9}$$

where a is the maximum collision velocity considered possible. A maximum collision velocity of 20 mph ≈30 ft/s (for two barges moving at 10 mph) is given by Shappert et al.[B-5] This yields

$$P(V > \nu \mid \nu \leq a) = (1 - \nu/30)^4 \tag{9a}$$

$$\text{(BRL)} \quad V > (1.41 \times 10^4) \frac{1}{(\rho\lambda)^{1/2} R^{3/4}} \tag{10}$$

$$\text{(Sandia)} \quad V > (4.96 \times 10^3) \frac{1}{(\rho\lambda)^{1/2} R^{1/2}} \tag{11}$$

If we allow V_o to be the threshold criteria and we assume the probability of the missile not buckling during impact to be $1/\lambda$, the probability of penetration given by Fullwood et al.[B-6] is

$$P(V > V_o, \lambda < \lambda_c) = \frac{1}{\lambda}(1 - k\lambda^{-1/2})^4 \tag{12}$$

where

$$\text{(BRL)} \qquad k = \frac{4.7 \times 10^2}{R^{3/4}\ \rho^{1/2}} \qquad (13)$$

and

$$\text{(Sandia)} \qquad k = \frac{1.69 \times 10^2}{R^{1/2}\ \rho^{1/2}} \qquad (14)$$

for the two analytic methods.

Noting that the penetration probability is maximized at $\lambda^{(\frac{1}{2})} = 3k$, a maximum penetration probability may be written by differentiating eq. 12 as

$$P(\lambda,V)_m = \left(\frac{1}{9k^2}\right)\left(1 - \frac{k}{3k}\right)^4 = \frac{2.195 \times 10^{-2}}{k^2} \qquad (15)$$

which, when evaluated for the respective k factors, yields

$$\text{(BRL)} \qquad P(\lambda,V)_m = (9.94 \times 10^{-8})R^{3/2}\ \rho \qquad (16)$$

$$\text{(Sandia)} \qquad P(\lambda,V)_m = (7.69 \times 10^{-7})R\rho \qquad (17)$$

Averaging over a uniform distribution of missile radii from 3" to 18" and using a maximum material specific gravity ρ=10, we found the probability of penetration due to missile impact to be

$$\text{(BRL)} \qquad P_{MI} = 3.38 \times 10^{-5}/\text{impact} \qquad (18)$$

$$\text{(Sandia)} \qquad P_{MI} = 8.07 \times 10^{-5}/\text{impact} \qquad (19)$$

The above may be regarded as the conditional probability of a cask penetration given an impact by a missile generated in the collision of two vessels. The choice of large missile surface areas is based on engineering judgment, with due consideration of the likelihood of extremely large dense items being present on the impacting vessel.

For the purposes of this study the BRL criteria is considered more accurate; therefore, the probability of missile penetration given an impact is taken to be

$$P_{MI} = 3.4 \times 10^{-5}/\text{impact} \qquad (19a)$$

The probability of an explosion severe enough to generate the missile described previously on page B-7 is

$$P_E = 1.7 \times 10^{-9}/\text{b-mi to } 5.1 \times 10^{-9}/\text{b-mi} \qquad (19b)$$

with a probability of 0.01[B-6, B-7] used to assess the conditional likelihood that large missiles will be generated. Thus,

$$P_{ME} = 1.7 \times 10^{-11}/\text{b-mi to } 5.1 \times 10^{-11}/\text{b-mi} \qquad (19c)$$

The probability of cask puncture by the impact of a detonation-produced missile, using a safety factor of 10 for the higher velocity missiles involved, is

$$P_{M1} = P_{MI} \cdot P_{ME}$$

$$= 5.8 \times 10^{-15}/\text{b-mi to } 1.7 \times 10^{-14}/\text{b-mi} \qquad (19d)$$

Again using a factor of 0.01 as the conditional probability that large missiles are produced in a collision, the probability of large missiles impacting the casks as a result of a barge collision is

$$P_{MSC} = 3.4 \times 10^{-10}/\text{b-mi to } 6.1 \times 10^{-10}/\text{b-mi} \quad (19e)$$

Thus, the corresponding probability of a cask puncture by collision-produced missiles is

$$P_{M2} = 1.2 \times 10^{-14}/\text{b-mi to } 2.1 \times 10^{-14}/\text{b-mi} \quad (19f)$$

Both P_{M1} and P_{M2} are exceedingly small probabilities when compared to other probabilistic sources of cask failures modeled in section 5.0.

B.4 Stub Penetration of the Cask Boundary

Stubs encountered in an accident may vary in size, but it is assumed that a stub less than 3" in radius will probably buckle under impact; a stub 18" in radius represents the maximum size of stub likely to be found on a transport vessel (e.g. barge). The probability of a stub penetration of a cask is a function of

a) the probability of encountering a stub in an accident (P_{SE})

b) the probability that the encountered stub is small enough in radius (but $\geq$ 3") to penetrate the cask body (P_R)

c) the probability of the impact velocity being sufficiently high to produce penetration (P_V)

The intersection of these three events is

$$P_S = P_{SE} \cdot P_R \cdot P_V \qquad (20)$$

which defines the probability of cask puncture by a moving stub.

The probability of the existence of a moving stub is taken as 0.01 of the probability of a serious collision in order to allow for the fact that it is unlikely that even a serious collision will produce a direct side impact of the cask by a stub. Thus, the probability of the cask colliding with a moving stub is

$$P_{SE} = 3.4 \times 10^{-10} \text{ to } 6.1 \times 10^{-10}/\text{b-mi} \qquad (20a)$$

In case of impact by a stub, the determining mass is that of the cask itself. Substituting the cask mass into equations 1 and 2 yields

$$\text{(BRL)} \quad V \geq 10.6\ R^{3/4} \qquad (21)$$

$$\text{(Sandia)} \quad V \geq 3.74\ R \qquad (22)$$

which maximizes the probability of entry for smaller stubs. For a 3" radius stub, the impact velocities necessary for penetration, as found by the BRL and Sandia equations are 24.2 ft/sec and 11.2 ft/sec, respectively. By noting that the maximum speed which is assumed possible for a collision or ramming is 30 ft/sec and substituting into equations 21 and 22, the corresponding maximum stub radii capable of penetration are

(BRL) $R_m = \left(\frac{30}{10.6}\right)^{4/3} = 4''$ (23)

(Sandia) $R_m = \left(\frac{30}{3.74}\right) = 8''$ (24)

The probability that the stub radius will be less than R_m for a uniform distribution of stub radii from A to B is

$$P_R = \int_A^{R_m} f(x)dx = \frac{R_m - A}{B-A} \quad (25)$$

Hence, for stubs ranging from 3" to 18" in radius,

(BRL) $P_R = 6.6 \times 10^{-2}$ (26)

(Sandia) $P_R = 0.333$ (27)

At this point we wish to know the "average" speed of a stub which will penetrate the cask wall, and the probability of occurrence of such a stub. It is already known, or has been assumed in the above calculations, that

a) stubs greater than 18" in radius are unlikely

b) stubs of <3" in radius will likely buckle on impact

c) stubs of radius greater than 4" or 8" (depending on which penetration equation is used) will not puncture

d) relative impact speeds between stub and cask greater than 30 ft/sec are unlikely

e) the lower limit of penetration velocities from penetration equations 21 and 22 are 24.2 ft/sec and 11.2 ft/sec, respectively

The expected value of penetrating velocities ("average" penetrating speed) is determined by using a modified cumulative distribution for penetration velocity. The cumulative probability of the impact velocity (V) being within the range where puncture can occur is obtained from the distribution

$$P(V \leq \nu \mid b \leq \nu \leq a) = \frac{P(V \leq \nu \cap b \leq \nu \leq a)}{P(b \leq \nu \leq a)} \quad (28)$$

where b and a represent the lower and upper puncture velocity bounds. The conditional probability of V being less than ν and within the interval $b \leq \nu \leq a$ is simply the cumulative probability of V being less than ν minus the cumulative probability of V being less than b. Thus, equation 28 becomes

$$P(V \leq \nu \cap b \leq \nu \leq a) = \left(1 - (1 - \frac{\nu}{a})^4\right) - \left|1-(1- \frac{b}{a})^4\right| \quad (29)$$

The probability of V being within the interval $b \leq \nu \leq a$ is simply the probability of V being greater than b, or

$$P(b \leq \nu \leq a) = (1 - \frac{b}{a})^4 \quad (30)$$

Hence, the cumulative probability of V being less than ν, given that it is within the interval $(b \leq \nu \leq a)$, can be expressed as

$$P(V \leq \nu \mid b \leq \nu \leq a) = 1 - \frac{1}{h} (1 - \frac{\nu}{a})^4 \quad (31)$$

where $h = (1 - \frac{b}{a})^4$

Knowing the cumulative probability function (equation 31), the probability density function is:

$$f(\nu \mid b \leq \nu \leq a) = \frac{4}{ah} (1 - \frac{\nu}{a})^3 , \tag{32}$$

and the expected value of the distribution is

$$E(\nu \mid b \leq \nu \leq a) = \int_b^a \frac{4}{ah} (1 - \frac{\nu}{a})^3 \; \nu d\nu \tag{33}$$

$$= b + \frac{a}{5} (1 - \frac{b}{a}).$$

The expected impact velocity, given the two lower puncture velocity bounds b = 24.2 ft/s (BRL) and b = 11.2 ft/s (Sandia) are determined from equation 33, using a = 30 ft/s as the upper puncture velocity bound;

$$\text{(BRL)} \quad E(\nu \mid 24.2 \leq \nu \leq 30) = 25.4 \text{ ft/s} \tag{34a}$$

$$\text{(Sandia)} \quad E(\nu \mid 11.2 \leq \nu \leq 30) = 15 \text{ ft/s} \tag{34b}$$

The corresponding probabilities of these impact collision speeds existing are given by equation 9,

$$P_V = (1 - \nu/30)^4 \tag{35}$$

$$\text{(BRL)} \quad P_V = 5.53 \times 10^{-4} \tag{35a}$$

$$\text{(Sandia)} \quad P_V = 6.25 \times 10^{-2} \tag{35b}$$

Thus, the probability of stub penetration per impact derived from both sources is

$$P_I = P_R \cdot P_V \tag{36}$$

$$(\text{BRL})\ P_I = (5.53 \times 10^{-4})(6.6 \times 10^{-2}) = 3.65 \times 10^{-5}/\text{b-mi} \quad (36a)$$

$$(\text{Sandia})\ P_I = (6.25 \times 10^{-2})(0.333) = 2.08 \times 10^{-2}/\text{b-mi} \quad (36b)$$

It is unlikely that the probability of a cask penetration per impact by a missile or stub is adequately predicted by the Sandia equations since, as shown by Fullwood,(B-6) the relation implies that the cask would not survive the stub impact test which is a prerequisite of licensing. Therefore, the BRL results are accepted and the following probability of cask penetration by a stub is used in this report:

$$P_I = 4.0 \times 10^{-5}/\text{impact}$$

Using the probability of the cask encountering a moving stub from equation 20a, the probability of a puncture of the cask wall by a moving stub is,

$$P_S = 1.4 \times 10^{-14} \text{ to } 2.4 \times 10^{-14}/\text{b-mi}$$

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APPENDIX C. Estimate of Liquid Release Source Term for a Worst Case Spent Fuel Shipping Cask Accident

C.1 Introduction

This appendix describes the technical basis used to develop source terms for radioactivity release in a postulated worst case spent-fuel shipping cask accident during its transport. It is assumed that the accident causes failure of the cask containment and rods, and the damaged cask falls into the body of water exposing the spent fuel assemblies to the natural water environment. For reference purposes, the cask is assumed to contain up to 10 PWR spent fuel assemblies which are cooled by natural convection in the normal shipping mode.

The radioactivity source term development for this case closely parallels the procedure used for a severe reactor accident case[C-1], that is, a two component source term is defined which consists of (1) an initial source and (2) a delayed source. The rationale and data involved in the definition of the sizes of these two sources are described in the following sections.

C.2 The Initial Source Term

It is expected that an accident severe enough to cause failure of the cask will also cause some damage to the fuel assemblies inside. The fracturing of fuel rod claddings would expose rod contents to incoming fresh water or seawater. Fission products present in the fuel-cladding gap, as well as fission products at accessible fuel surfaces, could be readily dissolved by the water. Subsequent flushing of the cask cavity by circulation processes could then transport these fission products to the natural environment.

The first step in defining the initial source is to obtain an estimate of the amount and type of fission product species that might be readily exposed to water in the postulated scenario. Calculations of fission product release from UO_2 fuel during irradiation under reactor operating conditions may be used to provide such an estimate. Calculations based on simple diffusion models are preferred because these indicate the fission product fractions which tend to reach grain boundaries within the fuel. After reaching grain boundaries, fission product species probably agglomerate to form separate phases which exhibit different potentials for further migration to the fuel rod gap through interconnected porosity. If the latter occurs, the inventory is in the gap and is readily exposed to water, provided the cladding is broken. If migration out of the fuel does not occur, some portion of the grain boundary inventory may still become readily exposed to water, because discharged reactor fuel pellets are usually cracked into smaller pieces and fractures in these types of materials are often found to follow intergranular paths. Although this is an oversimplified picture of the complex interactions that take place in fissioning UO_2, it is used in this study as the basis for a conservative estimate of the magnitude of the easily dissolved portion of the fission product inventory.

Results of fission product release calculations using both an empirical diffusion model and the old equivalent sphere diffusion model are reported in Appendix VII of WASH-1400 (DRAFT)[(C-2)]. The predicted releases are summarized in Table C.1. The first four fission products here have releases in the range of 5 to 20% while the strontium value is a factor of 3 to 10 lower. Diffusion coefficient data also provided in Appendix VII of WASH-1400[(C-3)] indicate ruthenium release would be similar to strontium. This would also presumably apply to elements which are chemical analogs of ruthenium such as technetium, molybdenum, cadmium, and perhaps palladium, rhodium, or silver. Diffusion data for all the other fission products (mainly rare earths, zirconium, niobium, and activation produced actinides) are very limited, but another tabulation[C-4] suggests these diffuse at somewhat slower rates in UO_2 than do strontium and ruthenium. Our esimates for the diffusion release of fission product species (based on these observations) are: 20% for the halogens, alkali, metals, tellurium group species and their chemical analogs; 2% for the alkaline earths, the transition metals, and their chemical analogs; and 1% for all other elements. This is considered to be a conservatively high estimate, but necessary in view of the lack of more precise data.

Table C.1. Fission Product Diffusion Release Predictions for Discharge Reactor Fuel.

Fission Product	Release Fraction: Empirical Model	Release Fraction: Equivalent Sphere Model
Xe	.08	.10
I	.14	.10
Cs	.21	.05
Te	.10 (est.)	.10 (est.)
Sr	.02	.02

Data taken from Table 1., Appendix VII, WASH-1400 (DRAFT).

The second step in defining the initial source is to estimate the fraction of the potentially available radioactive material that would actually be rapidly dissolved. For the purposes of this study it is assumed that only one-tenth of the diffusion release values given above would actually become readily dissolved in the initial exposure of cask contents to water. Two good reasons for this assumption are that the accident would probably not cause all fuel rods to crack or shatter, and more important, it is doubtful that the fuel itself would be cracked to the extent necessary to expose all grain boundary surfaces directly to water. Fuel grain sizes vary somewhat, but assuming a nominal value of 100 μm suggests that a fuel pellet would have to crack into about a million pieces to expose all grains. Cracking into pieces of about 1000 μm is more reasonable and photomicrographs of high burnup UO_2 fuel have been published which tend to confirm this order of subdivision[C-5, C-6]. A UO_2 particle size of 1000 μm implies that only 10% of the grain boundary surfaced would be directly exposed to water (assuming the cladding had failed) and hence only one-tenth of the diffusion release fission product would be readily dissolved (assuming soluable forms for all species). In summary, the initial source term for the cask accident is defined as follows in terms of percentages of the total activity content of the spent fuel contents:

a) 2% of the halogens, the alkali metals, the tellurium group, and their chemical analogs

b) 0.2% of the alkaline earths, the transition metals group, and their analogs

c) 0.1% of all other species

C.3 The Delayed Source Term

The delayed source term for the cask accident case is defined using the same rationale that was used to define the delayed source term for a severe reactor accident in reference.[C-1] The process is envisioned as gradual leaching of the exposed fuel with all fission products going into solution at the same rate. The leaching is assumed to take place at a temperature of about 25°C. Using a fuel particle size of 1000 μm and a fuel density of 10 g/cm^3, the following expressions for fractional leaching with time can be obtained from equations (1) and (2) of reference[C-1]:

$$f_1 = 6 \times 10^{-5} (t); \; t \leq 30 \text{ days};$$

$$f_2 = 6 \times 10^{-6} (t - 30); \; t \geq 30 \text{ days}.$$

where,

f = the cumulative fraction of fission product leached

t = time in days.

Solution of these two equations produced the cumulative fractions leached given in Table C.2.

Table C.2. Fission Product Leach Fractions Versus Time for the Cask Accident

Exposure Time (days)	Cumulative Fraction Leached
1	6×10^{-5}
10	6×10^{-4}
30	1.8×10^{-3}
180	2.7×10^{-3}
730	6.0×10^{-3}

It should be noted that the above leach expressions are believed to conservatively overestimate the actual rate of leaching because the water volume in the cask cavity is rather limited. It is estimated that this water volume would have to flush several times a day in order to prevent buildup of fission product water concentrations to levels which might inhibit the leaching process. This estimate is based on standard procedures used in making laboratory measurements of leach rates, which require frequent water changes in the first several days. Such a flushing rate implies large openings to the cask cavity and relatively rapid circulation in the natural water body. However, since accident details are not well defined, it seems appropriate to use this conservative formulation.

C.4 Combination of Source Terms

The total radioactivity release to water for the postulated shipping cask accident is the sum of the initial

APPENDIX D. Calculation of Downstream Concentrations From A Point Source For Use In Evaluating Liquid Release Consequences

D.1 General Relationships

Consider a "conservative effluent" that is dispersing in river water under conditions of steady, or only slowly varying, river flow. A conservative substance is defined here as one which undergoes no process other than dilution. It is also specified that the fluid properties of the conservative effluent are identical to those of the ambient river water. This work closely follows a review paper by Sayre(D-1) on natural mixing processes in rivers.

The general convection-diffusion equation for a dispersing substance is written for an arbitrary control volume (c.v.) as shown in equation (1).

$$\rho \int_{v} \frac{\partial c}{\partial t}\, dv = -\rho \int_{s} c\, \vec{u} \cdot \vec{n}\, ds + \rho \int_{s} E_m \nabla \cdot \vec{n}\, ds \qquad (1)$$

rate of change of mass in c.v.	rate of change of mass in c.v. due to convection across surface of c.v.	rate of change of mass in c.v. due to molecular diffusion across surface of c.v.

where

$\rho \equiv$ mass density of dispersing substance

$\vec{u}$ = fluid velocity

c = concentration by weight

$\vec{n}$ = unit normal vector directed outward from surface of c.v.

E_m = molecular diffusion coefficient

Transforming the surface integrals to volume integrals yields the familiar result:

$$\frac{\partial c}{\partial t} + \nabla \cdot C\vec{u} = E_m \nabla^2 C \qquad (2)$$

Resolving the instantaneous concentration and velocity into sums of time averaged and fluctuation components yields

$$c = \overline{c} + c' \tag{3}$$

$$u = \overline{u}_i + u_i' \tag{4}$$

where the subscript i denotes the i^{th} coordinate direction. Using equations (3) and (4), and neglecting the molecular diffusion term in equation (2), equation (2) for turbulent flows becomes

$$\frac{\partial \overline{c}}{\partial t} + \overline{u}_i \frac{\partial c_i}{\partial x_i} = \frac{\partial}{\partial x_i} \overline{c'} \, \overline{u'} \tag{5}$$

The term on the right hand side of equation (5) is due to turbulent diffusion and is usually represented as a gradient-type transfer term

$$\frac{\overline{c}_i \overline{u}_i'}{c_i u_i} = -E_i \frac{\partial \overline{c}}{\partial x_i} \tag{6}$$

Substituting of equation (6) into equation (5) and dropping bars, yields the usual form of the general convection diffusion equation for a conservative substance in a turbulent open-channel flow

$$\frac{\partial c}{\partial t} + u \frac{\partial c}{\partial x} + v \frac{\partial c}{\partial y} + v \frac{\partial c}{\partial z} = \frac{\partial}{\partial x} \left(E_x \frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y} \left(E_y \frac{\partial c}{\partial y}\right) + \frac{\partial}{\partial z} \left(E_z \frac{\partial c}{\partial z}\right) \tag{7}$$

where

$c(x,y,z,t) \equiv$ concentration of dispersing substance

$(z,y,z) \equiv$ coordinates x - longitudinal

y - vertical

z - transverse

E_x, E_y, E_z = coefficients for turbulent mass transfer in x,y,z directions.

Mixing due to the convective term is called dispersion. Mixing due to the turbulent transfer term is called turbulent diffusion or simply diffusion. The boundary conditions for equation (7) are

$$vc \frac{\partial y}{\partial n} = 0 \quad , \quad wc \frac{\partial c}{\partial n} = 0 \tag{8}$$

and

$$E_y \frac{\partial c}{\partial y}\frac{\partial y}{\partial n} = 0 \quad , \quad E_z \frac{\partial c}{\partial z}\frac{\partial z}{\partial n} = 0 \tag{9}$$

Boundary conditions (8) and (9) say that there is no transport of particles across the wetted perimeter or the water surface by either convection or diffusion.

Assuming the transfer coefficients E_x, E_y, and E_z are constant, we can replace them with mixing coefficients K_x, K_y, and K_z. Also we can replace the longitudinal velocity by cross-sectional average velocity $\bar{u}$. Equation (7) then becomes (including decaying concentration)

$$\frac{\partial c}{\partial t} + \bar{u} \frac{\partial c}{\partial x} = K_x \frac{\partial^2 c}{\partial x^2} + K_y \frac{\partial^2 c}{\partial y^2} + K_z \frac{\partial^2 c}{\partial z^2} - \lambda c \tag{10}$$

D.2 Downstream Concentration From an Instantaneous Point Source

For the case where effluent is released from a point in one slug which is convected and diluted as it travels downstream, $\frac{\partial c}{\partial y}$ and $\frac{\partial c}{\partial z}$ both equal zero, so equation (10) reduces to:

$$\frac{\partial c}{\partial t} + \bar{u} \frac{\partial c}{\partial x} = K_x \frac{\partial^2 c}{\partial x^2} - \partial c \quad (11)$$

whose solution is

$$C(x,t) = \frac{W}{A\gamma} \frac{1}{z\sqrt{\pi k_x t}} \exp \left[\frac{(x-\bar{u}t)^2}{4 k_x t} \right] \exp(-\lambda t) \quad (12)$$

where

$A \equiv$ cross sectional area
$W \equiv$ weight of conservative substance
$\gamma \equiv$ specific weight of water
$\lambda \equiv$ decay rate of concentration

Equation (12) is equivalent to the form given in appendix B of NUREG-0140 (D-2) and also to the one-dimensional version of Equation (9) in Regulatory Guide 113. (D-3)

D.3

When the source can still be characterized as eminating from a point but it is continous, the longitudinal dispersion can be neglected in equation (10) which becomes

$$\bar{u} \frac{\partial c}{\partial x} = K_z \frac{\partial^2 c}{\partial z^2} - \lambda c \quad (13)$$

whose solution is

$$C(z,x) = \frac{FC_I}{\bar{u}d} \frac{1}{2\sqrt{\pi k_z x/\bar{u}}} \exp \left[\frac{-z^2 \bar{u}}{4k_z x} - \lambda t \right] \quad (14)$$

where

F = volumetric discharge rate of effluent
C_I = concentration of effluent initially
d = depth of flow

Table D.1. Mixing Distances for Tests Run in Reference D-4.

Section #	Transverse Mixing Coefficient K_z ($ft^2/sec.$)			Downstream Distance to Total Mixing Region (ft) X
1-59	d = 1.62 u* = 0.26	0.097	B = 51.8 $\bar{u}$ = 0.69	9,543
2-59	d = 2.83 u* = 0.22	0.143	B = 154 $\bar{u}$ = 0.91	7,516
3-59	d = 1.27 u* = 0.38	0.111	B = 61 $\bar{u}$ = 0.47	7,877
4-59	d = 2.80 u* = 0.18	0.116	B = 111 $\bar{u}$ = 0.53	28,147
5-59	d = 1.91 u* = 0.16	0.070	B = 148 u = 0.99	98,462
1-60	d = 2.77 u* = 0.33	0.210	B = 6- $\bar{v}$ = 1.70	14,571
2-60	d = 6.99 u* = 0.34	0.547	B = 195 $\bar{u}$ = 2.81	97,669
4-60	d = 5.12 u* = 0.14	0.165	B = 80 $\bar{u}$ = 2.2	42,666
1-61	d = 6.87 u* = 0.35	0.553	B = 175 $\bar{u}$ = 2.58	71,439
2-61	d = 1.60 u* = 0.26	0.096	B = 53 $\bar{u}$ = 0.81	11,850

$K_z = 0.23\, du^*$

$X = .5 \cdot \bar{u} \cdot B^2/k_z$

REFERENCES

D-1. W.W. Sayre, "Natural Mixing Processes in Rivers," Environmental Impact on Rivers (River Mechanics III), Edited and Published by Hsich Wen Shen (1973).

D-2. Draft Liquid Pathway Generic Study, NUREG-0140, September 1976.

D-3. Estimating Aquatic Dispersion of Effluents from Accidental and Routine Reactor Releases for the Purpose of Implementing Appendix 1, Regulatory Guide 1.113, April 1977.

D-4. Hugo B. Fischer, "Dispersion Predictions in Natural Streams," Journal of the Sanitary Engineering Division, Proceedings of the ASCE, paper 6169, Vol. 94, no. SA 5, October, 1968.

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