Technical Memorandum

ANL/ER-TM--85-2

DE86 010244

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
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ANL/ER-TM-85-2

PRELIMINARY ASSESSMENT OF COSTS AND RISKS OF TRANSPORTING SPENT FUEL BY BARGE

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Prepared for

Office of Civilian Radioactive Waste Management
U.S. Department of Energy
Washington, D.C.

December 1985

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DISCLAIMER

PREFACE

Transporting spent fuel and nuclear waste using barges in conjunction with trains is a viable option, and in several instances, barges may be preferred for shipping spent fuel from reactors that may not be served by railroads or that are served by railroads but near good ports. The intent of this study is to assess the cost and risk of barge transport from selected reactors that would be most likely to use the mode, using currently available data.

This study was commissioned to support the environmental assessment of potential candidate nuclear waste repository sites. In this analysis, many conservative assumptions have been made where operational data are not available that tend to make risk values greater than would actually be expected. Even though (1) only the three repository sites that were recommended for characterization in the draft environmental assessments for repository site selection are evaluated and (2) several specific ports are identified by name, their selection for use in this analysis represents no Department of Energy policy decision regarding either the final repository locations or port selection, if barges were to be used on a large scale to support commercial nuclear waste management. This study will serve as a basis for future ones that will attempt to eliminate the conservative assumptions necessitated by the lack of data. Future efforts to characterize barge transport will be actively pursued to allow more knowledgable selection among modes for transporting spent fuel and high-level nuclear waste within the commercial nuclear waste management system.

ACKNOWLEDGMENTS

Edwin L. Wilmot provided overall guidance and helpful comments. Yu Chien Yuan reviewed the final version of the document, and editing was done by Shari K. Zussman.

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EXECUTIVE SUMMARY

The purpose of this study is to analyze the costs and risks associated with transporting spent fuel by barge. The barge movements would be made in combination with rail movements to transport spent fuel from plants to a repository. For the purposes of this analysis, three candidate repository sites are analyzed: Yucca Mountain, Nevada, Deaf Smith, Texas, and Hanford, Washington. This report complements a report prepared by Sandia National Laboratories in 1984 that analyzes the costs and risks of transporting spent fuel by rail and by truck to nine candidate repository sites.

In this analysis, shipments are considered for which a large portion of the shipping distance can be by barge or for which direct access to water makes barge convenient. For these shipments, an integrated railcar/cask would be used with roll-on/roll-off (RORO) loading to transfer between rail and barge. The differences in costs and risks brought about by using lift-on/lift-off (LOLO) instead of RORO are also analyzed. The plants considered in this analysis are restricted to those on-line at the beginning of 1985. Of these on-line plants, those east of the Mississippi River having direct access to navigable water and those having rail access that are within 300 miles of an Atlantic port are considered. Shipments from the plants with water access would travel by barge to a transshipment location on the Gulf or on the Mississippi River where they would be transferred to rail for delivery to the candidate repository. Shipments from plants with rail access only would travel by rail to an Atlantic port and from there by barge to the transshipment location on the Gulf, where they would be transferred to rail for delivery to the repository. Analysis of routes showed that the ports of Baltimore, Norfolk, and Charleston were convenient for most of the shipments originating on rail. The transshipment location assumed on the Gulf is Houston and on the Mississippi it is Memphis. In general, shipments from plants on the Atlantic coast or on the Gulf coast or shipments that travel by rail to an Atlantic port are assumed to travel by water to Houston. Shipments from plants on inland waterways or on the Great Lakes are assumed to travel by water to Memphis.

It is assumed that the rail cask used will hold 14 pressurized water reactor (PWR) assemblies or 36 boiling water reactor (BWR) assemblies. Two configurations are considered--an integrated railcar/cask used for RORO transfer and a palletized rail cask used for LOLO transfer. A loaded cask/railcar system would weigh 131 tons and a loaded palletized cask would weigh 125 tons loaded. Casks are assumed to be available in numbers sufficient to meet the shipping schedule. It is assumed that the shielding and the age of the spent fuel is such that external radiation meets regulatory requirements. The barge would be 150 ft long by 43 ft wide and would carry four casks.

The number of shipments from each plant is based on a run of the WASTES model, obtained from Pacific Northwest Laboratory, for a maximum rail scenario using a 14/36 (14 PWR assemblies or 36 BWR assemblies) rail shipping cask.

Distances for both rail and water and travel times for water were determined using Shortest Path Analysis and Display (SPAD), a routing model that is part of the Freight Network Modeling System developed by Argonne National Laboratory. The travel times for rail were calculated using the values of average speed as a function of distance developed by Pacific Northwest Laboratory. Analyses of barge loading and unloading operations for both RORO and LOLO are given in Appendix A.

The transportation costs developed are subdivided into capital and maintenance costs for the railcar/cask system and shipping costs, for both rail and water. The costs for moving the spent fuel from the plants to the transshipment locations of Houston and Memphis total $738 million--$54 million for maintenance, $375 million for capital, and $309 million for shipping. This is an average cost of $146,000 per shipment, or $22 per kilogram of spent fuel. Depending on repository site, the total costs for moving the spent fuel from Houston and Memphis to the repository range between $42 and $57 million for maintenance, $299 and $410 million for capital, and $193 and $356 million for shipping--a total between $533 and $825 million. The average cost would be between $105,000 and $163,000 per shipment, or $16-$25 per kilogram of spent fuel. If LOLO were used instead of RORO, approximately $3000 per shipment in crane charges would be required for loading and unloading the casks, or an additional cost of $15 million. This amounts to $0.47 per kilogram of spent fuel, which is a cost increase of 2.1%.

The nonradiological risks for the water portion of the shipments considered in this analysis amount to 1.7 deaths and 4.4 injuries. For rail transport between plants and ports the figures are 0.056 deaths and 2.1 injuries. For rail transport from Houston and Memphis to the repository site the risks are between 1.1 and 3.5 deaths and between 43 and 130 injuries, depending on repository site.

Radiological risks are calculated assuming that external radiation is at the limit allowed by regulations. The calculations are conservative and the risk estimates can be considered maximal. These risks are for normal transportation only and include both occupational and non-occupational exposure. Only gamma radiation is considered for this assessment. No accident scenarios are considered.

The total radiation dose due to all shipments from plants to the transshipment locations at Houston and Memphis is 1000 person-rem for workers involved in the transport and 490 person-rem for the general population. This translates to an estimated 0.10 latent cancer fatalities for workers and 0.049 latent cancer fatalities for the general population. The total radiation dose due to all shipments from Houston and Memphis to the candidate repository sites ranges between 390 and 560 person-rem for transportation workers and between 100 and 180 person-rem for the general population. The resulting latent cancer fatality estimates range between 0.039 and 0.056 for workers and 0.010 and 0.018 for the general population. Using LOLO instead of RORO decreases both the worker and general population risk during loading and

1. INTRODUCTION

1.1 PURPOSE

The purpose of this study is to analyze the costs and risks associated with transporting spent fuel by barge. The barge movements would be made in combination with rail movements to transport spent fuel from plants located on navigable waterways or located a short distance by rail from a port facility. The shipments would be to a repository site. For purposes of this analysis, only three candidate repository sites are analyzed. They are Yucca Mountain, Nevada; Deaf Smith, Texas; and Hanford, Washington. Because all three of these sites are inland, the final delivery to the sites would be by rail. The radiation risks analyzed in this study are for normal transportation (no accidents) only.

This report complements a report prepared by Sandia National Laboratories that analyzes the costs and risks of transporting spent fuel by rail and by truck to nine potential candidate repository sites (Neuhauser et al. 1984). The Sandia analysis includes accident risks. It uses shipment schedules and cost and risk calculations that are based on new reference-design casks. Two scenarios were analyzed, one in which 100% of all shipments are made completely by truck and one in which 100% of all shipments are made completely by rail.

In the study presented here, only three of the nine candidate repository sites have been selected for analysis. Also, future-generation cask designs have been assumed. Since the future-generation casks have larger capacities, the major impact of their use is fewer shipments. Because the repository sites considered in this analysis are inland, with no access to navigable water, and because many plants are not located on navigable waterways, a 100% water scenario for comparison with the 100% rail and 100% truck scenarios is not possible. Multimodal moves are required for many of the plants.

1.2 BACKGROUND

In general, the potential use of water transport for spent fuel has been neglected, and there has been little analysis of this mode in environmental assessments. A generic assessment of barge transportation of spent fuel was prepared for the Atomic Industrial Forum in 1978 by Science Applications, Inc. (Unione et al. 1978). This study concluded that approximately 80% of the reactors presently operating have definable intermodal routes in which more than 90% of the mileage is by water. However, the repository locations considered in that study were in the eastern United States, whereas several currently being considered are in the west. The study concluded that water transport of spent fuel was generally viable, with the risks small and comparable to rail, but with costs higher than rail or truck.

In 1980, Allied General Nuclear Services studied transportation of radioactive material by water (Anderson and Jones 1980). This report presented an overview of possible applications and problems, and means of solving these problems for transportation of radioactive materials by water. Also, a detailed case study of a particular nuclear plant site located on navigable water was presented. The study concludes that there are real advantages in using water transport, particularly for sites not served by rail and for sites whose primary transport route passes through heavily populated areas. The study recommends continued examination of water transport of radioactive materials, and the development of standards for possible future operations.

In 1973, Subcommittee N552 of the American National Standards Institute (ANSI) was chartered and subsequently prepared a draft proposed guide for water transportation of irradiated nuclear fuel. Recently this subcommittee, now the ANSI N14.24 Subcommittee, rewrote the original draft proposed standard and produced the current ANSI N14.24 Standard titled "Domestic Barge Transport of Highway Route Controlled Quantities of Radioactive Materials" (ANSI 1985). This standard is designed to be useful to shippers of radioactive materials in the preparation, initiation, and completion of shipments of radioactive materials by barge. This recent activity is indicative of renewed interest in barge as a means of transporting radioactive materials.

1.3 ORGANIZATION OF REPORT

Section 2 of this report discusses the scenarios and assumptions used in this study, including plant sites considered, routing strategy, equipment used and shipment schedule. Section 3 presents the routes used, along with distances and travel times. Section 4 explains the development of transportation costs and summarizes them (for maintenance, capital, and shipping). The nonradiological transportation risks are discussed in Section 5, and Section 6 discusses the radiological transportation risks. Detailed derivations and calculations are relegated to appendices.

2. ASSUMPTIONS AND SCENARIO DESCRIPTIONS

The following is a summary of the assumptions made and a description of the scenarios used in the cost and risk assessment of transportation of spent fuel by barge. In general, shipments considered are those for which a large portion of the distance can be made by barge or for which direct access to water makes barge convenient. For these shipments, an integrated railcar/cask would be used, with roll-on/roll-off (RORO) loading to transship between rail and barge. The effects on costs and risks of using a palletized cask with lift-on/lift-off (LOLO) loading for transshipment between rail and water are calculated to provide a cost and risk comparison.

2.1 PLANT SITES INCLUDED IN STUDY

The plants considered in this assessment are restricted to those on-line at the beginning of 1985 (American Nuclear Society 1985). All the on-line plants east of the Mississippi River having direct access to navigable water are considered except those on the Mississippi River that also have rail access. The on-line plants with rail connections but with no water access that are within 300 miles of an Atlantic port are also considered. No other plants are considered. The plants considered in this analysis are shown in Table 2.1. The data on rail and water access were provided by Sandia National Laboratory and Oak Ridge National Laboratory, respectively.

2.2 ROUTING STRATEGY

Those shipments originating by rail would be transferred to barge at an Atlantic port. The port chosen would depend on rail connections and distance from the plant. Where distances are reasonable, the ports of Baltimore, Norfolk, and Charleston are assumed because of facilities available at these ports, including cranes of sufficient capacity for LOLO. All shipments, both those originating on rail and those originating on water, would be transferred to rail for final delivery to the candidate repository site. These transfers would take place either on the Gulf Coast or on the Mississippi River. For this study, the Gulf Coast transfer site assumed is Houston, Texas, and the Mississippi River transfer site is Memphis, Tennessee. These sites are assumed based on their port facilities (which include cranes suitable for LOLO), their rail connections to the repository sites (Yucca Mountain, Nevada; Deaf Smith, Texas; and Hanford, Washington), and their locations relative to the required water routes.

Shipments originating from plants on water are routed on the most direct water route to the transshipment location (Houston or Memphis) that provides the most direct overall route to the repository. Those shipments originating on rail would move to the Atlantic port for transshipment. From there, they would travel to Houston or Memphis to be transshipped to rail. Analysis of the rail move from the transshipment locations at Houston or Memphis to each

Table 2.1. Plants Included in Analysis

Plant	State	Plant	State
Big Rock Point	MI	North Anna	VA
Browns Ferry	AL	Oyster Creek	NJ
Brunswick	NC	Palisades	MI
Calvert Cliffs	MD	Peach Bottom	PA
Cook	MI	Pilgrim	MA
Crystal River	FL	Point Beach	WI
Davis-Besse	OH	Robinson	SC
Dresden	IL	Salem	NJ
Farley	AL	Sequoyah	TN
Fitzpatrick	NY	St. Lucie	FL
Ginna	NY	Summer	SC
Hatch	GA	Surry	VA
Indian Point	NY	Susquehanna	PA
Kewaunee	WI	Three Mile Island	PA
Maine Yankee	ME	Turkey Point	FL
McGuire	NC	Vermont Yankee	VT
Millstone	CT	Zion	IL
Nine Mile Point	NY		

of the candidate repositories is also included in this study. Details of the routings used in this study and tables summarizing routes, distances, and round-trip times are presented in Section 3.

2.3 EQUIPMENT

It is assumed that the rail cask used will hold 14 PWR assemblies or 36 BWR assemblies (a 14/36 shipping cask). Two configurations are considered: an integrated railcar/cask used for RORO transfer and a palletized rail cask used for LOLO transfer. A loaded cask/railcar system would weigh 131 tons and a loaded palletized cask would weigh 125 tons loaded. Casks are assumed to be available in numbers sufficient to meet the shipping schedule. It is assumed that the shielding and the age of the spent fuel is such that external radiation meets regulatory requirements. The barge used would be 150 ft long by 43 ft wide and would carry four casks. Details of the RORO and LOLO transfer facilities are contained in Appendix A.

2.4 SHIPMENTS

The number of shipments from each plant is based on a run of the WASTES model, obtained from Pacific Northwest Laboratory, for a maximum rail scenario using a 14/36 rail shipping cask. The numbers of shipments are detailed in Section 3.

3. POTENTIAL TRANSPORTATION ROUTES

3.1 ROUTES AND TRANSFER LOCATIONS

Analysis of the potential routes from the plant sites to both assumed transshipment locations, Houston and Memphis, led to the assignment of transshipment locations to plant sites shown in Table 3.1. In general, shipments originating on the Atlantic Coast, on the Gulf, or shipped by rail to an Atlantic port travel by water to Houston. Shipments originating on the Great Lakes or on the inland river system travel by water to Memphis. Figure 3.1 shows the potential routings to Houston for plants with direct water access to the Atlantic or the Gulf. Figure 3.2 shows the potential routings to Memphis from plants on the Great Lakes and inland river systems. Figure 3.3 shows the potential routings to Houston from plants within 300 miles of Atlantic ports; the routings include a rail portion to the port and a water portion from the port to Houston. The ports of Baltimore, Norfolk, and Charleston handle all these shipments except for those from Vermont Yankee, which are routed through Albany. Figure 3.4 shows the rail routings from the the transshipment locations (Houston and Memphis) to the candidate repository locations (Deaf Smith, Texas; Yucca Mountain, Nevada; and Hanford, Washington).

3.2 DISTANCES AND TRANSIT TIMES

The distances, numbers of shipments, and round-trip travel times for the routings are summarized in Tables 3.2 through 3.5. The distances are based on output from SPAD, a routing model that is part of the Argonne National Laboratory (ANL) Freight Network Modeling System (ANL 1985). SPAD was used to find minimum cost routings. For the direct water shipments, the minimum-cost water routes from the plants to the transshipment locations were used. For plants shipping by rail, minimum-cost rail routes were found to the assumed Atlantic ports and minimum-cost water routes were found from the ports to the transshipment locations. Then the minimum-cost combined route was used. This two-step procedure was used to force the shipment to go by water. The actual minimum-cost route may be direct rail. Minimum-cost rail routes from the transshipment locations to the repository sites were found using SPAD to complete the routings from plant to repository.

The travel times for the waterways were based on output from SPAD. For open water, both ocean and Great Lakes, the SPAD travel times were modified since the travel time models used in SPAD assume self-propelled vehicles. For ocean travel, average speeds were restricted to 9 mph or less, and for the Great Lakes, 7 mph or less. Average rail speeds were based on rail distance traveled, using the relationship between distance and average speed given by Pacific Northwest Laboratory (1984).

Barge loading and unloading times are based on estimates described in Appendix A. The time required for barge loading at the plant is estimated to be 26 hours and at a port, 50 hours. The extra time at the port is allowed for early delivery of the railcars to facilitate coordination of the various work forces required at the port. Unloading the barge at the transshipment location requires 26 hours. A total 2-1/2 days are allowed to turn the cask around at the plant and 2-1/2 days are allowed at the repository.

Table 3.1. Potential Routings Through the Assumed Transshipment Locations

Direct Water				Rail to Water	
Transfer at Houston		Transfer at Memphis		Transfer at Houston	
Plant	State	Plant	State	Plant	State
Brunswick	NC	Big Rock Point	MI	Hatch	GA
Calvert Cliffs	MD	Browns Ferry	AL	McGuire	NC
Crystal River	FL	Cook	MI	North Anna	VA
Farley	AL	Davis-Besse	OH	Peach Bottom	PA
Indian Point	NY	Dresden	IL	Robinson	SC
Maine Yankee	ME	Fitzpatrick	NY	Summer	SC
Millstone	CT	Ginna	NY	Susquehanna	PA
Oyster Creek	NJ	Kewaunee	WI	Three Mile Island	PA
Pilgrim	MA	Nine Mile Point	NY	Vermont Yankee	VT
Salem	NJ	Palisades	MI		
St. Lucie	FL	Point Beach	WI		
Surry	VA	Sequoyah	TN		
Turkey Point	FL	Zion	IL		

Figure 3.1. Potential Routes for Direct Water Shipments to Houston

Figure 3.2. Potential Routes for Direct Water Shipments to Memphis

Figure 3.3. Potential Routes for Rail/Water Shipments to Houston

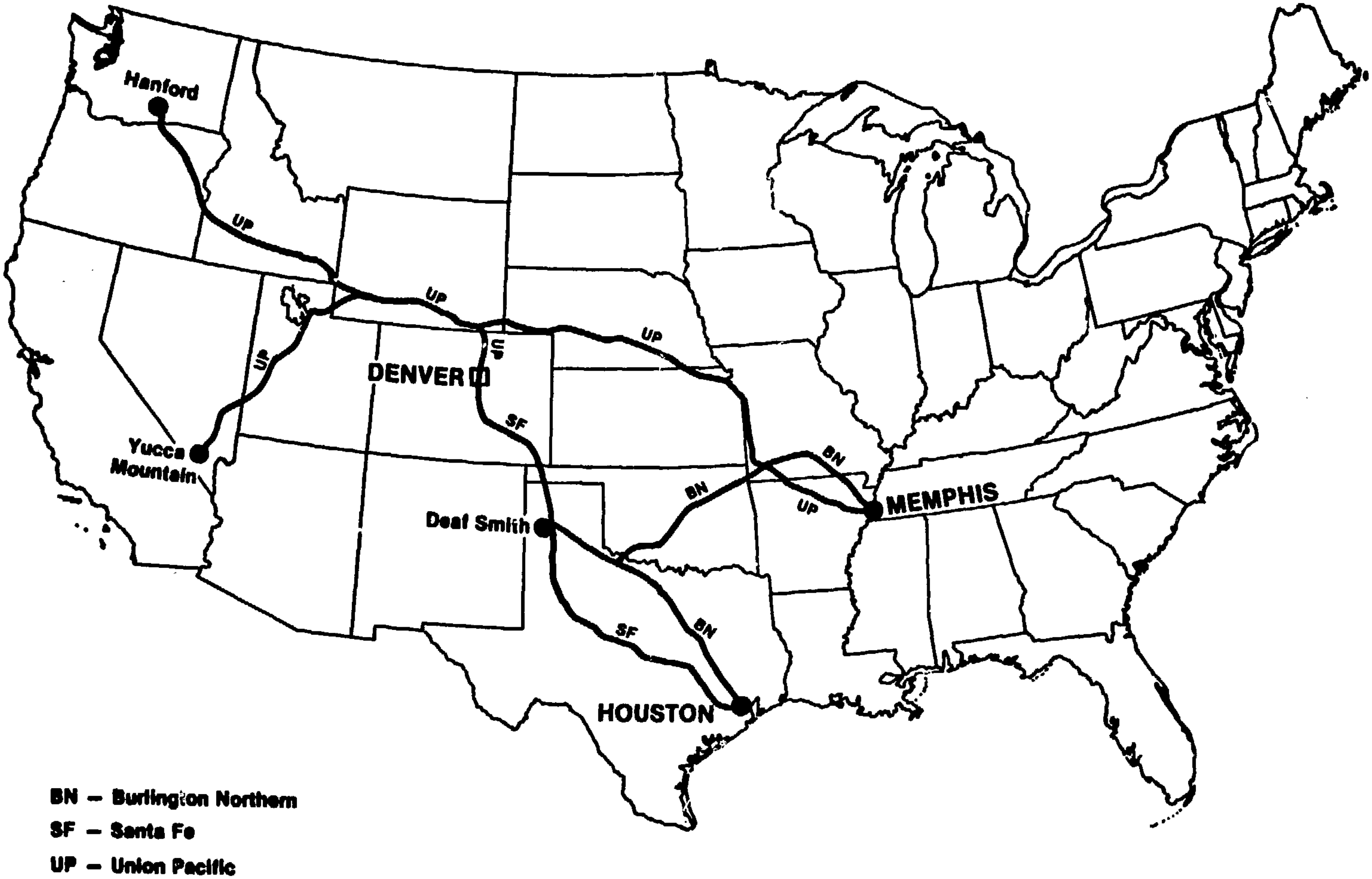

Figure 3.4. Potential Rail Routes from Barge/Rail Transfer to Assumed Candidate Repository Sites

Table 3.2. Direct Water Shipments to Houston

Plant	State	Distance, mi[‡a]	Number of Shipments[‡b]	Round-Trip Time (days)[‡c]
Brunswick	NC	1,689	241	20.8
Calvert Cliffs	MD	2,118	180	24.8
Crystal River	FL	836	97	12.9
Farley	AL	895	125	21.4
Indian Point	NY	2,263	120	29.2
Maine Yankee	ME	2,547	140	28.8
Millstone	CT	2,371	253	27.1
Oyster Creek	NJ	2,171	108	25.3
Pilgrim	MA	2,471	106	28.0
Salem	NJ	2,108	222	24.7
St. Lucie	FL	1,204	201	17.8
Surry	VA	1,979	144	23.4
Turkey Point	FL	1,042	200	14.8

[‡a] Distances based on Shortest Path Analysis and Display (SPAD).

[‡b] Total number of shipments obtained from the WASTES model--rail only for 14/36 rail cask.

[‡c] Includes loading and unloading railcars to/from the barge and 2-1/2 day turnaround time for the casks at the plant. Barge speeds based on Shortest Path Analysis and Display (SPAD) output.

Table 3.3. Direct Water Shipments to Memphis

Plant	State	Distance, mi[‡a]	Number of Shipments[‡b]	Round-Trip Time (days)[‡c]
Big Rock Point	MI	798	14	23.8
Browns Ferry	TN	256	313	14.3
Cook	MI	547	182	21.2
Davis-Besse	OH	1,308	77	30.9
Dresden	IL	405	257	18.2
Fitzpatrick	NY	1,660	127	33.3
Ginna	NY	1,604	72	32.7
Kewaunee	WI	634	91	23.6
Nine Mile Point	NY	1,660	131	33.3
Palisades	MI	587	114	22.3
Point Beach	WI	622	120	23.3
Sequoyah	TN	447	156	16.5
Zion	IL	528	168	20.7

‡a Distances based on Shortest Path Analysis and Display (SPAD).

‡b Total number of shipments obtained from the WASTES model--rail only for 14/36 rail cask.

‡c Includes loading and unloading railcars to/from the barge and 2-1/2 day turnaround time for the casks at the plant. Barge speeds based on Shortest Path Analysis and Display (SPAD) output.

Table 3.4. Shipments from Plant to Port by Rail, from Port to Houston by Barge

Plant	State	Port	State	Rail Distance (mi)[‡a]	Water Distance (mi)[‡a]	Number of Shipments[‡b]	Round-Trip Time (days)[‡c]
Hatch	GA	Charleston	SC	267	1,580	161	31.8
McGuire	NC	Charleston	SC	279	1,580	28	32.3
North Anna	VA	Norfolk	VA	230	1,966	145	33.9
Peach Bottom	PA	Baltimore	MD	78	2,108	312	28.9
Robinson	SC	Charleston	SC	195	1,580	83	28.8
Summer	SC	Charleston	SC	168	1,580	2	27.8
Susquehanna	PA	Baltimore	MD	206	2,108	175	34.3
Three Mile Island	PA	Baltimore	MD	114	2,108	103	30.4
Vermont Yankee	VT	Albany	NY	118	2,343	94	36.4

‡a Distances based on Shortest Path Analysis and Display (SPAD) output.

‡b Total number of shipments obtained from the WASTES model--rail only for 14/36 cask.

‡c Includes loading and unloading railcars to/from the barge and 2-1/2 day turnaround time for the casks at the plant. Barge speeds based on Shortest Path Analysis and Display (SPAD) output. Rail speeds based on those by Pacific Northwest Laboratory (1984).

Table 3.5. Rail Shipments from Barge/Rail Transfer Location to Candidate Repository Sites

Transfer Location	Repository Site	Distance (mi)[‡a]	Number of Shipments[‡b]	Round-Trip Time (days)[‡c]
Houston	Deaf Smith	650	3,240	18.3
Houston	Yucca Mountain	2,137	3,240	25.8
Houston	Hanford	2,312	3,240	26.3
Memphis	Deaf Smith	899	1,822	20.4
Memphis	Yucca Mountain	2,097	1,822	25.5
Memphis	Hanford	2,272	1,822	25.8

‡a Distances based on Shortest Path Analysis and Display (SPAD).

‡b Number of shipments obtained from the WASTES model--rail only for 14/36 rail cask. The number assumes that only one repository site will be selected.

‡c Includes 2-1/2 day turnaround time for the casks at the repository site. Rail speeds based on those given by Pacific Northwest Laboratory (1984).

4. TRANSPORTATION COSTS

The costs of transporting spent fuel are summarized in this section. The costs are subdivided into capital and maintenance costs for the railcar/cask system and shipping costs as was done by Neuhauser et al. (1984). Details on the development of the costs presented in this section are given in Appendix B.

4.1 MAINTENANCE COSTS

The railcar/cask system maintenance costs are based on $125,000 per year for each cask/railcar, as reported in Neuhauser et al. (1984). To obtain the maintenance cost per shipment, a daily maintenance cost of $430 was developed assuming 80% use of the cask/railcar system. This daily cost was then multiplied by the round-trip time to obtain the maintenance cost allocated to one shipment (one cask).

4.2 CAPITAL COSTS

The capital costs associated with a cask/railcar system are based on a cost of $5.3 million for the system, with a life of 15 years. This cost was amortized over 15 years at 15%. A daily capital cost of $3100 was developed assuming 80% use of the cask/railcar system. This was multiplied by the round-trip time to obtain the maintenance cost allocated to one shipment (one cask).

4.3 SHIPPING COSTS

An estimate of shipping costs by barge was developed based on representative operating costs for a barge/towboat combination. The actual type of towboat used will vary, depending on route. For example, open-water towboats would be required on the Great Lakes and ocean parts of a route. For some inland waterways shallow-draft towboats would be required. On the Chicago River special towboats with telescoping bridges are required for passage under a number of low bridges. A typical towboat is represented here by a daily cost of $8000 per day when under power and $5500 per day when idle. The barge costs are $2000 a day.

The estimated cost for loading cask/railcar units to the barge using the RORO option is $6300 per cask at the Atlantic ports and $2900 at the plants having direct access to navigable water. The cost for unloading the cask/railcar units from the barge at the transshipment locations using RORO is $6300 per cask.

The shipping costs for rail are those developed by Pacific Northwest Laboratory (1984). These costs are based on distance and weight (loaded weight for fuel transport and empty weight for returning the empty cask) and different formulas apply for each of four regions: Western, North Central, Southern, and Northeastern. Also included is an escort fee based on the loaded distance.

4.4 SUMMARY OF COSTS

Table 4.1 presents the maintenance costs, capital costs, and shipping costs per shipment (a single cask) for the 13 plants shipping directly by water to Houston. Also shown are the total costs for all shipments for each of these plants based on the number of shipments projected by the WASTES model. Table 4.2 is a similar table, showing costs for the 13 plants shipping directly by water to Memphis. Table 4.3 shows the costs, per shipment and the total for all shipments, for the plants shipping by rail to an Atlantic port and then by water to Houston. For those plants, the shipping costs are separated into barge shipping costs and rail shipping costs. Table 4.4 shows the maintenance, capital, and rail shipping costs, for single shipments and the total for all shipments, for transportation between each of the two transshipment locations (Houston and Memphis) to each of the three candidate repository sites (Deaf Smith, Yucca Mountain, and Hanford). Table 4.5 gives the total transportation costs for moving all spent fuel shipments from the plants to the transshipment locations and from the transshipment locations to each of the candidate repository sites. Also shown is the resulting average costs per kilogram of uranium.

4.5 EFFECT OF USING LOLO ON TRANSPORTATION COSTS

The costs presented above are based on loading and unloading the barge using RORO. If LOLO is used instead, approximately \$3000 per shipment in crane charges are required for loading and unloading the casks (\$1500 per lift). This additional cost amounts to \$0.47 per kilogram of spent fuel, which is an increase in total cost of 2.1%.

Table 4.1. Transportation Costs for Direct Water Shipment to Houston

Plant	Costs per Shipment (thousands of $)[a]			Number of Shipments[e]	Total Costs (thousands of $)		
	Maintenance[b]	Capital[c]	Shipping[d]		Maintenance	Capital	Shipping
Brunswick	8.94	64.48	54.76	241	2,150	15,540	13,200
Calvert Cliffs	10.66	76.88	64.76	180	1,920	13,840	11,660
Crystal River	5.55	39.99	35.15	97	540	3,880	3,410
Farley	9.20	66.34	56.40	125	1,150	8,290	7,050
Indian Point	12.56	90.52	75.79	120	1,510	10,860	9,090
Maine Yankee	12.38	89.28	74.60	140	1,730	12,500	10,440
Millstone	11.65	84.01	70.58	253	2,950	11,760	9,880
Oyster Creek	10.88	78.43	66.01	108	1,180	8,470	7,130
Pilgrim	12.04	86.80	72.86	106	1,280	9,200	7,720
Salem	10.62	76.57	64.55	222	2,360	17,000	14,330
St. Lucie	7.65	55.18	44.29	201	1,540	11,090	8,900
Surry	10.06	72.54	61.40	144	1,460	10,450	8,840
Turkey Point	6.36	45.88	39.76	200	1,270	9,180	7,950
Total				2,137	21,040	142,060	119,540

[a] A rail cask is considered to be a single shipment.

[b] Maintenance costs for cask and railcar at $125,000 per year for each cask/railcar system (Neuhauser et al. 1984).

[c] Capital costs for cask/railcar system of $5.3 million with life of 15 years. Capital investment amortized over 15 years at 15%.

[d] Shipping costs include loading and unloading railcars to/from the barge.

[e] Total number of shipments obtained from the WASTES model--rail only for 14/36 rail cask.

Table 4.2. Transportation Costs for Direct Water Shipments to Memphis

Plant	Costs per Shipment (thousands of $)[‡a]			Number of Shipments[‡e]	Total Costs (thousands of $)		
	Maintenance[‡b]	Capital[‡c]	Shipping[‡d]		Maintenance	Capital	Shipping
Big Rock Point	10.23	73.78	62.26	14	140	1,030	870
Browns Ferry	6.15	44.33	38.68	313	1,920	13,880	12,110
Cook	9.12	65.72	55.80	182	1,660	11,960	10,160
Davis-Besse	13.29	95.79	80.15	77	1,020	7,380	6,170
Dresden	7.83	56.42	48.40	257	2,010	14,500	12,440
Fitzpatrick	14.32	103.23	86.18	127	1,820	13,110	10,940
Ginna	14.06	101.37	84.55	72	1,010	7,300	6,090
Kewaunee	10.15	73.16	61.83	91	920	6,650	5,620
Nine Mile Point	14.32	103.23	86.18	131	1,880	13,520	11,290
Palisades	9.59	69.13	58.51	114	1,090	7,880	6,670
Point Beach	10.02	72.23	61.01	120	1,200	8,670	7,320
Sequoyah	7.09	51.15	44.11	156	1,110	7,980	6,880
Zion	8.90	64.17	54.55	168	1,500	10,780	9,160
Total				1,862	17,280	124,640	105,720

‡a A rail cask is considered to be a single shipment.

‡b Maintenance costs for cask and railcar at $125,000 per year for each cask/railcar system (Neuhauser et al. 1984).

‡c Capital costs for cask/railcar system of $5.3 million with life of 15 years. Capital investment amortized over 15 years at 15%.

‡d Shipping costs include loading and unloading railcars to/from the barge.

‡e Total number of shipments obtained from the WASTES model--rail only for 14/36 rail cask.

Table 4.3. Transportation Costs for Rail to Port, Barge to Houston

Plant	Costs per Shipment (thousands of $)[‡a]				Number of Shipments[‡f]	Total Costs (thousands of $)			
			Shipping					Shipping	
	Maintenance[‡b]	Capital[‡c]	Rail[‡d]	Barge[‡e]		Maintenance	Capital	Rail	Barge
Hatch	13.67	98.58	19.09	65.25	161	2,200	15,870	3,070	10,510
McGuire	13.89	100.13	19.60	65.25	28	390	2,800	550	1,830
North Anna	14.58	105.09	17.56	74.89	145	2,110	15,240	2,550	10,860
Peach Bottom	12.43	89.59	11.17	78.48	312	3,880	27,950	3,490	24,490
Robinson	12.38	89.28	16.04	65.25	83	1,030	7,410	1,330	5,420
Summer	11.95	86.18	14.62	65.25	2	20	170	30	130
Susquehanna	14.75	106.33	18.07	78.48	175	2,580	18,610	3,160	13,730
Three Mile Island	13.07	94.24	13.46	78.48	103	1,810	9,710	1,390	8,080
Vermont Yankee	15.65	112.84	13.50	94.16	94	1,470	10,610	1,270	8,850
Total					1,103	15,490	108,370	16,840	83,900

[‡a] A rail cask is considered to be a single shipment.

[‡b] Maintenance costs for cask and railcar at $125,000 per year for each cask/railcar system (Neuhauser et al. 1984).

[‡c] Capital costs for cask/railcar system of $5.3 million with life of 15 years. Capital investment amortized over 15 years at 15%.

[‡d] Rail shipping costs are based on formulas developed by Pacific Northwest Laboratory (1984).

[‡e] Shipping costs include loading and unloading railcars to/from the barge.

[‡f] Total number of shipments obtained from the WASTES model--rail only for 14/36 rail cask.

Table 4.4. Transportation Costs for Barge/Rail Transfer Location to Candidate Repository Sites by Rail

Transfer	Repository	Costs per Shipment (thousands of $)[‡a] Maintenance[‡b]	Capital[‡c]	Shipping[‡d]	Number of Shipments[‡e]	Total Costs (thousands of $) Maintenance	Capital	Shipping
Houston	Deaf Smith	7.87	56.73	34.12	3,240	25,500	183,800	110,550
Houston	Yucca Mountain	11.09	79.98	67.82	3,240	35,930	259,130	219,740
Houston	Hanford	11.31	81.53	71.21	3,240	36,640	264,160	230,720
Memphis	Deaf Smith	8.77	63.24	45.00	1,822	15,980	115,220	81,990
Memphis	Yucca Mountain	10.96	79.05	67.17	1,822	19,970	144,030	122,380
Memphis	Hanford	11.09	79.98	70.13	1,822	20,210	145,720	127,780

[‡a] A rail cask is considered to be a single shipment.

[‡b] Maintenance costs for cask and railcar at $125,000 per year for each cask/railcar system (Neuhauser et al. 1984).

[‡c] Capital costs for cask/railcar system of $5.3 million with life of 15 years. Capital investment amortized over 15 years at 15%.

[‡d] Rail shipping costs are based on formulas developed by McNair et al. (1984).

[‡e] Total number of shipments obtained from the WASTES model--rail only for 14/36 rail cask.

unloading. The reduction in worker risk is due to reduced crew and greater distances from casks. The general population dose is reduced because of the slightly shorter time required for LOLO. The total reduction in worker dose for all shipments is 100 person-rem, or a decrease of 10%. The total reduction for the general population for all shipments is 10 person-rem, or a decrease of 2%. A maximally exposed individual would receive a dose on the order of 10 millirem, which translates to a cancer death risk of 10^{-6}.

Table 4.5. Transportation Cost Summary

	Costs (millions of dollars)				$/kgU[‡a] PWR	$/kgU[‡b] BWR
	Maintenance	Capital	Shipping	Total		
From plants to Houston and Memphis	53.8	375.1	309.2	738.1	$22	$23
From Memphis and Houston to candidate repository						
Deaf Smith	41.5	299.0	192.5	533.0	$16	$16
Yucca Mountain	55.9	403.2	342.1	801.2	$25	$25
Hanford	56.9	409.9	358.5	825.3	$25	$25

‡a Assumes 460 kg per assembly with 14 assemblies per rail cask for each of 5062 shipments.

‡b Assumes 180 kg per assembly with 36 assemblies per rail cask for each of 5062 shipments.

5. NONRADIOLOGICAL TRANSPORTATION RISKS

The nonradiological risks discussed in this section are deaths and injuries due to nonradiological causes and include those due to vessel casualties. Therefore, unlike the radiological risks presented in this report, the nonradiological risks are not for normal transportation only and include vessel accidents.

The deaths per ton-mile and injuries per ton-mile for water transport are 9.0×10^{-10} and 2.3×10^{-9}, respectively. These are based on data in Gay (1979) and USDOT (1983). Based on statistics from the same sources, the deaths per ton-mile and injuries per ton-mile for rail are 1.5×10^{-9} and 5.8×10^{-8}, respectively. The derivations of these rates are shown in Appendix C.

The nonradiological risks based on these rates are summarized in Table 5.1. The ton-miles are based on round-trip distances.

Table 5.1. Nonradiological Risks[‡a]

Transportation Mode	Ton-miles[‡b] $\times 10^6$	Risk Deaths	Risk Injuries
Water[‡c]	1900	1.7	4.4
Rail--plants to ports[‡d]	37	0.056	2.1
Rail--barge/rail transfer to candidate repository			
Deaf Smith	750	1.1	43
Yucca Mountain	2100	3.2	120
Hanford	2300	3.5	130

[‡a] All figures to two significant digits.

[‡b] Ton-miles based on round-trip distances.

[‡c] Based on 9.0×10^{-10} deaths/ton-mile and 2.3×10^{-9} injuries/ton-mile calculated from data in "National Transportation Statistics, Annual Report 1979," Department of Transportation DOT-TSC-RSPA-79-19, and "Transportation Safety Information Report, 1982 Annual Summary," U.S. Department of Transportation, DOT-TSC-RSPA-83-4 (see Appendix C).

[‡d] Based on 1.5×10^{-9} deaths/ton-mile and 5.8×10^{-8} injuries/ton-mile calculated from data in references listed in footnote c.

6. RADIOLOGICAL TRANSPORTATION RISKS

Radiological risks are calculated assuming that the external radiation is at the limit allowable by regulations. The assumption is conservative and the risk estimates can be considered maximal. These risks are for normal transportation only and include both occupational and population exposure due to gamma radiation. No accident scenarios are considered. This section summarizes the results of the calculations. The methodology, assumptions, and calculational details are presented in Appendix D.

6.1 DOSE TO THE GENERAL PUBLIC

To calculate the dose to the general public during transport by rail and inland waterways it was assumed that the population is uniformly distributed in a strip along the transport route between 30 m and 800 m from the transport. The population densities along the route are based on county-level 1980 population densities. The cutoff of 800 m is used because the dose is negligible beyond 800 m. The population dose for open water (ocean and Great Lakes) was assumed to be negligible.

In addition to the general population dose, the "on-link" population dose was estimated for the rail trip. Both passenger and freight traffic were considered. Freight trains traveling in the same direction as the spent-fuel shipment are not likely to be close enough to the transport to experience any significant exposure. Therefore, only freight trains traveling in the opposite direction were considered. A five-person crew was assumed for each freight train. The number of freight trains was estimated from the number of ton-miles per year along the given route (Federal Railroad Administration data) using national yearly data in Gay (1979) to convert ton-miles to number of trains. Passenger trains traveling in the same direction and in the opposite direction were also included in the on-link population dose estimate. The passenger trains are expected to travel faster than the spent-fuel shipments, so it was assumed that the fuel shipment would wait on a siding for a passenger train to pass. The number of passengers was estimated from the traffic level along each route (Federal Railroad Administration data) using the national yearly data for passenger miles and ton-miles of freight traffic (Gay 1979). For both passenger trains and freight trains the relative speed between the passing train and the spent-fuel shipment is assumed to be 32 km/h, and the relative distance is 10 m.

The population dose during transshipment stops is calculated for the population located between 60 and 800 m from the loading and unloading area, using the 1980 population density of the county in which the transshipment takes place. The transshipment scenarios used to estimate the duration of exposure are described in Appendix A.

6.2 OCCUPATIONAL DOSE

The occupational dose was estimated for the crew members and escorts on the train, for the crew members on the barge, and for the handlers during the loading and unloading operations. It was assumed that five crew members will be traveling with the shipment both on the train and on the barge. Two escorts are included on the train for the loaded portion of rail shipment. For the train trip it was assumed that there will be an empty rail car between the crew and the shipment. Therefore the distance from crew to shipment is 30 m. Only the closest cask is included in the dose estimate because the radiation from other casks would be shielded by all the intervening casks. For the barge the distance from the center of the cask to the crew is assumed to be 46 m. The two casks closest to the crew are included in the dose estimate because their shielding would prevent the radiation from the other casks from reaching the crew. The dose to handlers during the loading and unloading operations was computed by using personnel, time, and distance data described in Appendix A.

6.3 RADIOLOGICAL IMPACTS

The results of the radiation dose calculations are presented in Tables 6.1 through 6.9. Tables 6.1 and 6.2 show dose estimates per shipment (cask) for direct water shipments from various plants to Houston and Memphis. Both occupational and population doses are given. All doses are estimated for the total duration of the specific operation. The total dose for each plant is composed of the doses received during loading of the barge, barge shipment, and unloading. During the loading and unloading operations the occupational dose depends only on personnel and time requirements, and on the distances of various workers from the cask (see Appendices A and D). Therefore, the occupational dose during loading and unloading is the same for all plants and for both destinations. The population dose during loading and unloading depends on the duration of the operation and on the population density in the area. Thus, the population dose for unloading is the same for shipments from all plants going to the same destination. The dose during the loading will, of course, be different for different plants because of different population densities. The occupational dose during barge shipment is estimated for a crew of five workers. The variations in this dose reflect the variations in the duration of the shipment. The population dose during shipment, computed only for the inland waterways, is the same for many of the plants because the same inland route is used for shipment from these plants.

Table 6.3 shows dose estimates for shipments from those plants that require rail shipments in addition to water shipments. In addition to the columns shown in Tables 6.1 and 6.2, two more columns are shown for the occupational and population doses during rail shipment. The additional occupational dose is estimated for a train crew of five workers and two escorts.

Table 6.1. Radiation Dose Estimates per Shipment[‡a] for Direct Water Shipments to Houston (person-rem)

Plant	Load Barge		Barge Shipment[‡a]		Unload Barge		Total	
	Occ.[‡b]	Pop.[‡c]	Occ.[‡d]	Pop.[‡e]	Occ.[‡b]	Pop.[‡c]	Occ.	Pop.
Brunswick	0.083	0.0007	0.034	0.007	0.076	0.013	0.019	0.021
Calvert Cliffs	0.083	0.0015	0.042	0.007	0.076	0.013	0.20	0.022
Crystal River	0.083	0.0008	0.017	0.007	0.076	0.013	0.18	0.021
Farley	0.083	0.0002	0.036	0.071	0.076	0.013	0.20	0.084
Indian Point	0.083	0.0061	0.051	0.84	0.076	0.013	0.21	0.86
Maine Yankee	0.083	0.0011	0.051	0.007	0.076	0.013	0.21	0.021
Millstone	0.083	0.0033	0.047	0.007	0.076	0.013	0.21	0.023
Oyster Creek	0.083	0.0033	0.043	0.007	0.076	0.013	0.20	0.023
Pilgrim	0.083	0.0022	0.049	0.007	0.076	0.013	0.21	0.022
Salem	0.083	0.0016	0.042	0.007	0.076	0.013	0.20	0.022
St. Lucie	0.083	0.001	0.027	0.007	0.076	0.013	0.19	0.021
Surry	0.083	0.0005	0.039	0.007	0.076	0.013	0.20	0.020
Turkey Point	0.083	0.015	0.021	0.007	0.076	0.013	0.18	0.035

[‡a] A shipment is considered to be a single cask.

[‡b] The occupational dose for loading and unloading is based on personnel and time requirements and distances described in Appendix A.

[‡c] Based on 1980 population density of county surrounding the plant or port.

[‡d] Assumes a crew of five.

[‡e] Based on 1980 county-level population densities along route.

Table 6.2. Radiation Dose Estimates per Shipment[‡a] for Direct Water Shipments to Memphis (person-rem)

Plant	Load Barge		Barge Shipment[‡a]		Unload Barge		Total	
	Occ.[‡b]	Pop.[‡c]	Occ.[‡d]	Pop.[‡e]	Occ.[‡b]	Pop.[‡c]	Occ.	Pop.
Big Rock Point	0.083	0.0064	0.040	0.042	0.076	0.0098	0.20	0.052
Browns Ferry	0.083	0.001	0.020	0.018	0.076	0.0098	0.18	0.029
Cook	0.083	0.0029	0.035	0.042	0.076	0.0098	0.19	0.055
Davis-Besse	0.083	0.0036	0.055	0.042	0.076	0.0098	0.21	0.055
Dresden	0.083	0.0007	0.028	0.027	0.076	0.0098	0.19	0.038
Fitzpatrick	0.083	0.0026	0.060	0.042	0.076	0.0098	0.22	0.054
Ginna	0.083	0.0011	0.059	0.042	0.076	0.0098	0.22	0.053
Kewaunee	0.083	0.0014	0.040	0.042	0.076	0.0098	0.20	0.053
Nine Mile Point	0.083	0.0011	0.060	0.042	0.076	0.0098	0.22	0.053
Palisades	0.083	0.001	0.037	0.042	0.076	0.0098	0.20	0.053
Point Beach	0.083	0.0006	0.039	0.042	0.076	0.0098	0.20	0.052
Sequoyah	0.083	0.001	0.025	0.026	0.076	0.0098	0.18	0.036
Zion	0.083	0.021	0.034	0.042	0.076	0.0098	0.19	0.072

‡a A shipment is considered to be a single cask.

‡b The occupational dose for loading and unloading is based on personnel and time requirements and distances described in Appendix A.

‡c Based on 1980 population density of county surrounding the plant or port.

‡d Assumes a crew of five.

‡e Based on 1980 county-level population densities along route.

Table 6.3. Radiation Dose Estimates per Shipment[‡a] for Rail Shipments to Port and Barge Shipments to Houston (person-rem)

Plant	Port	Rail Shipment[‡a]		Loading Barge		Barge Shipment[‡a]		Unload Barge		Total	
		Occ.[‡b]	Pop.[‡c]	Occ.[‡d]	Pop.[‡e]	Occ.[‡f]	Pop.[‡c]	Occ.[‡d]	Pop.[‡e]	Occ.	Pop.
Hatch	Charleston	0.052	0.010	0.083	0.0055	0.032	0.007	0.076	0.013	0.24	0.036
McGuire	Charleston	0.054	0.016	0.083	0.0055	0.032	0.007	0.076	0.013	0.24	0.041
North Anna	Norfolk	0.045	0.031	0.083	0.088	0.032	0.007	0.076	0.013	0.24	0.14
Peach Bottom	Baltimore	0.015	0.082	0.083	0.18	0.042	0.007	0.076	0.013	0.22	0.28
Robinson	Charleston	0.038	0.0098	0.083	0.0055	0.032	0.007	0.076	0.013	0.23	0.035
Summer	Charleston	0.033	0.0092	0.083	0.0055	0.032	0.007	0.076	0.013	0.22	0.036
Susquehanna	Baltimore	0.040	0.080	0.083	0.18	0.042	0.007	0.076	0.013	0.24	0.28
Three Mile Island	Baltimore	0.022	0.090	0.083	0.18	0.042	0.007	0.076	0.013	0.22	0.29
Vermont Yankee	Albany	0.023	0.0068	0.083	0.0092	0.059	0.577	0.076	0.013	0.24	0.60

[‡a] A shipment is considered to be a single rail cask.

[‡b] Assumes a crew of five and two escorts.

[‡c] Based on 1980 county-level population densities along route and 1978 traffic levels along rail routes.

[‡d] The occupational dose for loading and unloading is based on personnel and time requirements and distances described in Appendix A.

[‡e] Based on 1980 population density of county surrounding the plant or port.

[‡f] Assumes a crew of five. No escorts on ocean shipments.

The dose estimates are summarized in Tables 6.4, 6.5, and 6.6. These tables also show the total number of shipments expected from each plant, obtained from the WASTES model runs by Pacific Northwest Laboratory (McNair 1985). The total doses in the last two columns of these tables were obtained by multiplying the per-shipment doses by the appropriate number of shipments.

Table 6.7 shows the dose estimates for rail shipments from Memphis and Houston to candidate repository sites at Deaf Smith, Yucca Mountain, and Hanford. The estimated doses to Hanford and Yucca Mountain are about the same. The doses to Deaf Smith are somewhat lower, mainly because the Deaf Smith site is closer to Memphis and Houston than the other two candidate repository sites.

The total radiological risks are summarized in Table 6.8. The risk, which is expressed as latent cancer fatalities, is obtained from the dose by using the conversion factor of 10^{-4} cancer deaths per rem (ICRP 1977). The table shows that the total risk due to the shipment of all the spent fuel from all of the plants is at most 0.075--much less than one cancer fatality.

The estimated dose to the maximally exposed individual also is shown in Table 6.9. Four typical individuals were considered in this estimate. The first is an individual living along the waterway near Houston, 30 m from the shipment route, exposed to 3,240 shipments moving at 7 km/h. The second is an individual living along the waterway near Memphis, 30 m from the shipment route, exposed to 1,822 shipments moving at 4 km/h. Both these individuals would receive a dose of about 7 millirem. The third individual is a person on a passenger train passing the transport twice every day, once in each direction (e.g., an engineer on the passenger train). The passenger train is assumed to be traveling 10 m from the transport at 32 km per hour and to be exposed to all 5,062 shipments. The total dose to such an individual is about 4 millirem. The fourth individual is a person exposed to all 5,062 shipments, living 30 km from a train traveling 24 km/h. This individual would receive a dose of about 2 millirem. Using the conversion factor of 10^{-4} cancer death per rem, the risk of dying from cancer to the maximally exposed individual is less than 10^{-5}.

6.4 EFFECT OF USING LOLO ON RADIOLOGICAL RISKS

Using LOLO instead of RORO decreases both the occupational and population risks during loading and unloading. The occupational dose for loading is reduced from 0.083 person-rem to 0.081 person-rem and for unloading from 0.076 person-rem to 0.058 person-rem. The reduction is due to reduced crew and greater distances from the cask. The population dose during loading and unloading is reduced because of the slightly shorter time required for LOLO. The population dose for LOLO is 96% of that for RORO during loading and 92% during unloading. The total reduction in occupational dose for all shipments is 100 person-rem, or a decrease of 10%. The total reduction in population dose for all shipments is 10 person-rem, or a decrease of 2%.

Table 6.4. Summary of Radiation Dose Estimates for Direct Water Shipments to Houston[a]

Plant	Per Shipment[b] (person-rem) Occ.	Per Shipment[b] (person-rem) Pop.	Number of Shipments[c]	Total (person-rem) Occ.	Total (person-rem) Pop.
Brunswick	0.19	0.021	241	47	5.0
Calvert Cliffs	0.20	0.022	180	36	3.9
Crystal River	0.18	0.021	97	17	2.0
Farley	0.20	0.084	125	24	11.0
Indian Point	0.21	0.860	120	25	100.0
Maine Yankee	0.21	0.021	140	29	3.0
Millstone	0.21	0.023	253	52	5.9
Oyster Creek	0.20	0.023	108	22	2.5
Pilgrim	0.21	0.022	106	22	2.4
Salem	0.20	0.022	222	45	4.8
St. Lucie	0.19	0.021	201	37	4.2
Surry	0.20	0.021	144	29	3.0
Turkey Point	0.18	0.035	200	36	7.1
Total			2,137	421	150

[a] All dose estimates shown to two significant digits.

[b] Totals from Table 6.1. One cask is one shipment.

[c] Obtained from WASTES model run by Pacific Northwest Laboratory (McNair 1985).

Table 6.5. Summary of Radiation Dose Estimates for Direct Water Shipments to Memphis[‡a]

Plant	Per Shipment[‡b] (person-rem) Occ.	Per Shipment[‡b] (person-rem) Pop.	Number of Shipments[‡c]	Total (person-rem) Occ.	Total (person-rem) Pop.
Big Rock Point	0.20	0.052	14	3	0.7
Browns Ferry	0.18	0.029	313	56	9.1
Cook	0.19	0.055	182	35	9.9
Davis-Besse	0.21	0.055	77	17	4.3
Dresden	0.19	0.038	257	48	9.7
Fitzpatrick	0.22	0.054	127	28	6.9
Ginna	0.22	0.053	72	16	3.8
Kewaunee	0.20	0.053	91	18	4.8
Nine Mile Point	0.22	0.053	131	29	6.9
Palisades	0.20	0.053	114	22	6.0
Point Beach	0.20	0.052	120	24	6.3
Sequoyah	0.18	0.036	156	29	5.7
Zion	0.19	0.073	168	32	12.0
Total			1,822	356	86

‡a All dose estimates shown to two significant digits.

‡b Totals from Table 6.2. One cask is one shipment.

‡c Obtained from WASTES model run by Pacific Northwest Laboratory (McNair 1985).

Table 6.6. Summary of Radiation Dose Estimates for Rail Shipments to Port and Barge Shipments to Houston[‡a]

Plant	Port	Per Shipment[‡b] (person-rem)		Number of Shipments[‡c]	Total (person-rem)	
		Occ.	Pop.		Occ.	Pop.
Hatch	Charleston	0.24	0.036	161	39	5.8
McGuire	Charleston	0.25	0.041	28	7	1.1
North Anna	Norfolk	0.24	0.140	145	35	20.0
Peach Bottom	Baltimore	0.22	0.280	312	67	88.0
Robinson	Charleston	0.23	0.035	83	19	2.9
Summer	Charleston	0.22	0.035	2	-	0.1
Susquehanna	Baltimore	0.24	0.280	175	42	49.0
Three Mile Island	Baltimore	0.22	0.290	103	23	30.0
Vermont Yankee	Albany	0.24	0.600	94	22	56.0
Total				1,103	254	250

‡a All dose estimates shown to two significant digits.

‡b Totals from Table 6.3.

‡c Obtained from WASTES model run by Pacific Northwest Laboratory (McNair 1985).

Table 6.7. Radiation Dose Estimates for Rail Shipments from Barge/Rail Transfer to Candidate Repository Sites

Transfer	Candidate Repository	Per Shipment[a] (person-rem)		Number of Shipments[d]	Total (person-rem)	
		Occ.[b]	Pop.[c]		Occ.	Pop.
Houston	Deaf Smith	0.022	0.021	3,240	240	70
Houston	Yucca Mountain	0.044	0.043	3,240	353	144
Houston	Hanford	0.043	0.042	3,240	360	140
Memphis	Deaf Smith	0.019	0.018	1,822	153	35
Memphis	Yucca Mountain	0.025	0.023	1,822	195	46
Memphis	Hanford	0.025	0.023	1,822	199	46

[a] A rail cask is considered to be one shipment.

[b] Assumes a crew of five and two escorts.

[c] Based on 1980 county-level population densities along route and 1978 rail traffic levels on route.

[d] Based on WASTES model for rail shipments using 14/36 rail cask.

Table 6.8. Total Radiological Impacts[‡a]

	Risk	
	Occ.	Pop.
Water shipments to Houston and Memphis		
Dose (person-rem)[‡b]	1000	490
Latent cancer fatalities[‡c]	0.10	0.049
Rail Shipments from Houston and Memphis to candidate repository		
Deaf Smith		
Dose (person-rem)	390	100
Latent cancer fatalities[‡a]	0.039	0.010
Yucca Mountain		
Dose (person-rem)	550	190
Latent cancer fatalities[‡a]	0.055	0.019
Hanford		
Dose (person-rem)	560	190
Latent cancer fatalities[‡a]	0.056	0.019

[‡a] All figures shown to two significant digits.

[‡b] The rail portions of these shipments contribute 36 person-rem to the occupational dose and 57 person-rem to the population dose.

[‡c] Using the conversion factor of 10^{-4} deaths per rem (CRP 1977).

Table 6.9. Radiation Dose to Maximally Exposed Individual

	Dose (mrem)
Waterway near Houston[‡a]	7.1
Waterway near Memphis[‡b]	6.5
Railway on-link[‡c]	3.7
Railway off-link[‡d]	1.7

[‡a] Living along the waterway near Houston, 30 m away, exposed to 3,240 shipments moving at 7 km/h.

[‡b] Living along the waterway near Memphis, 30 m away, exposed to 1,822 shipments moving at 4 km/h.

[‡c] A person on a passenger train passing the transport every day twice, once in each direction (e.g., an engineer on the passenger train). The passenger train is assumed to be traveling 10 m from the transport at 32 km/h and exposed to all 5,062 shipments.

[‡d] A person exposed to all 5,062 shipments living 30 km from the train traveling at 24 km/h.

APPENDIX A. DESCRIPTIONS OF ROLL-ON/ROLL-OFF (RORO) AND LIFT-ON/LIFT-OFF (LOLO) BARGE/RAIL TRANSFER OF SPENT-FUEL SHIPPING CASKS

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A.1 RAIL CASK ROLL-ON/ROLL-OFF OPERATIONS

A.1.1 Introduction

This section examines the work elements, personnel requirements, time commitments and proximities associated with the roll-on/roll-off (RORO) barge loading or unloading of four integrated cask/railcars.

An integrated cask/railcar shipping system consists of a shielded container, complete with energy absorbers, as appropriate, and a rail transport vehicle that has provisions for cask support and cask tiedown. It may include a pivot structure for cask rotation (but not the rotation equipment) and other ancillary features such as a personnel barrier or sunshade. The railcar system for barge transport additionally has provisions for affixing it to the vessel deck (the actual tiedown ligaments are unlikely to be integral with the railcar).

A.1.2 Assumptions

1. Land/water or water/land transfers take place at a port facility specifically intended for barge/rail intermodal service (i.e., carfloat, rail access) (Fig. A.1).

2. Although port union workrules may require a large crew, only the minimum number of workers required for the job is specified in this study. Presumably, excess workers would be paid and kept away from the transfer operations to reduce exposure.

3. The transport system is "fully engineered," meaning that all components are designed for ease in handling and operation, thus keeping close-proximity time to a reasonable value. Advanced techniques such as robotics are not considered.

A.1.3 Description of Loading

1. Due to the workforce requirements and the need to coordinate a large number of organizations, it is assumed that the four loaded cask/railcar systems are delivered to a storage track at the transfer site 24 hours in advance of the loading operations. Delivery involves the railroad and probably a field service engineer and a health physics technician.

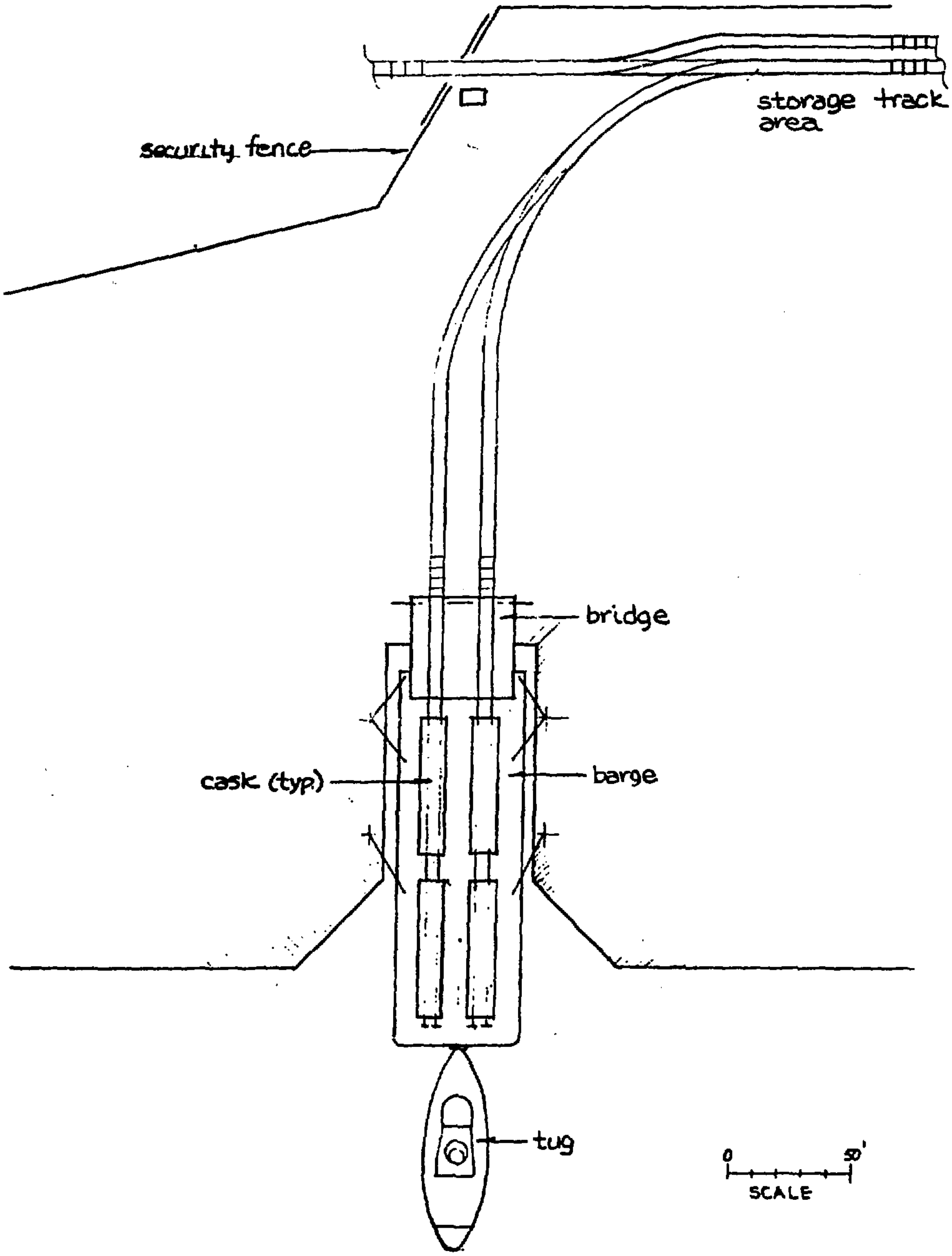

Figure A.1. RORO Rail-Barge Transfer Site

2. The rigging crew is assembled and instructed. Inventory is taken and equipment and tools are checked out.

3. The barge is positioned at the carfloat, the carfloat bridge is lowered or raised and the barge is trimmed for to a minimum incline. The carfloat bridge is locked to the barge and the barge is tied in place when rail alignment is achieved.

4. The first railcar to be loaded is engaged by an appropriately sized switching engine. To reduce the weight concentration on the end of the barge, a buffer car (i.e., an empty flat car) can be interposed between the engine and the cask car.

5. The cask car is slowly moved onto the barge, and barge ballasting is performed to maintain an acceptable barge-bridge relationship. At this point, the tug may be asked to apply force on the barge to help stabilize it.

6. The car is spotted on the barge deck and blocked in preparation for tiedown. The switching engine is disconnected. Four scenarios are proposed for railcar placement.

<u>Scenario</u>

1	Load and spot all railcars on barge then perform tiedown operations after all are in place.
2	Load, spot, and tie down railcars one-by-one.
3	Load and spot two railcars, tie down those two units, then load, spot, and tie down the remaining two units.
4	Load and spot railcars and begin tiedown operations immediately after placement of the first unit (coincident operation).

Scenario 1 minimizes railroad personnel/equipment time, but increases exposure of riggers due to accumulation of cask cars on barge. Switch engine assistance is required only on the last two cars.

Scenario 2 maximizes railroad personnel/equipment time and reduces rigger exposure for the entire operation due to progressive buildup of cask cars on barge. It permits switching engine assistance for all units.

Scenario 3 is a variation of 2. Scenario 3 permits row-by-row work on cask cars. It is an improvement over Scenario 2 in railroad use. There is some increase in worker exposure to cask car accumulation. This scenario permits switching engine assistance at all times, if needed.

Scenario 4 minimizes total elapsed time for operation. There is a slight increase in exposure over Scenario 2 but less than Scenarios 1 and 3. Industrial hazard is increased due to the coincidence of tiedown and spotting operations on a (slightly) moving vessel.

When (or if) rail-barge intermodal shipping is contemplated, a more detailed study of the loading options should be performed to establish the most efficient method consistent with safety.

7. The tiedown operations involve jacking the railcars to partially (or completely) unload the springs and then securing the car frame to the barge deck with ligaments (i.e., cables or rods and turnbuckles). The large sizes of the ligaments might mean that power assistance is required; however, the operations are primarily manual.

8. After tiedown, an inspection by a marine surveyor (representing the insurer) and the U.S. Coast Guard is performed. A final radiation survey is also performed by the Health Physics Technician in conjunction with the cask field service engineer's preshipment mechanical inspection.

9. The barge is prepared for its voyage by final ballasting, securing of hatches, and other operations. Weather enclosures might be part of the shipping system and would be installed at this time.

10. There could be a waiting period while escort vessels are placed, shipping lanes are cleared, or other procedural matters are conducted.

11. Just before shipping, the barge is disconnected from the carfloat bridge, released from the carfloat, and maneuvered by the tug.

12. Rigging for the voyage takes place in clear water and involves crewmen on the barge. While in tow, the barge is unoccupied.

A.1.4 <u>Description of Unloading</u>

1. The Port Authority and Coast Guard prefer to minimize the waterborne period, so it can be assumed that there would be little waiting time before unloading.

2. The barge is re-rigged from the towing configuration and maneuverd into the carfloat by tug. The bridge is positioned and the barge is loaded with ballast as necessary to minimize bridge-barge angle, align rails, lock bridge to barge, and secure barge to carfloat. The tug is recalled when roll-off operations begin.

3. Casks and cars are inspected, a radiation survey is performed, and paperwork is done.

4. The riggers are assembled and instructed, and tools and equipment are assembled.

5. Cask cars are unloaded from the barge using a switching engine and a buffer car. The barge is loaded with ballast to account for weight distribution change. See Item 6 in Sec. A.1.3, Description of Loading, for the suggested scenarios, which, when reversed, apply to unloading. The analyses of the scenarios also apply.

6. The individual railcar systems are moved to a storage track location in preparation for shipment. It is assumed that there is an 8 hour hold before pickup by the railroad.

A.1.5 Time, Distance, and Personnel

Tables A.1 through A.3 summarize the operational steps and estimate the personnel required, their time spent on each task, and their proximity to the casks. The time and distance figures are based on two cask cars end-to-end, with the distance measured perpendicular to the mid-length of the car string. A more detailed exposure estimate would require a dose rate map and a time-and-motion study of individual workers. Figure A.2 is a sketch of a typical railcar system, extracted from Hutchison (1983). The system used would be similar to the one shown except that there would not be a cooling system.

A.2 RAIL CASK LIFT-ON/LIFT-OFF OPERATIONS

A.2.1 Introduction

This section examines the work elements, personnel requirements, time commitments, and proximities associated with the lift-on/lift-off (LOLO) barge loading or unloading of four palletized (skid-mounted) large spent-fuel shipping casks. A typical 100-ton shipping cask is illustrated in Figure A.3. The palletized spent-fuel transport system is rail car or heavy-haul trailer mounted for overland movement; rail is assumed in this task. The pallet contains the cask and its associated support structures; a personnel barrier could also be included, although it is not illustrated. The pallet is secured to its transporter in a fashion that permits ready removal for intermodal transfer.

Due to the similarity in operations, this LOLO analysis relies substantially on the RORO analysis presented in Section A.1. Tug attendance is optional during loading/unloading, but is assumed in this analysis.

A.2.2 Assumptions

1. See RORO analysis, Section A.1.

Table A.1. Personnel Requirements for RORO Operations

Railroad	
3	crewmen (spotting/loading/unloading)
Water Carrier	
3	tug crewmen (tug operations)
2	barge crewmen (ballasting, no travel w/barge)
Riggers	
4	workers (tiedown installation and removal)
1	supervisor
Port Personnel	
1	Port Authority representative (administrative)
2	security guards
2	carfloat bridge operators
1	carfloat operations supervisor
4	longshoremen (mooring)
1	longshoreman supervisor
Others	
1	cask field service engineer (cask operations)
1	health physics technician (monitoring)
1	Coast Guard representative
1	marine surveyor
Total = 28	

Table A.2. Analysis of Activities for RORO Loading[‡a]

Step	Elapsed Time (hr)	Type of Personnel	Number of Personnel	Time (hr)	Average Distance (ft)
1. Spot cars in holding area	1	Railroad	1	1	50
		Railroad	2	0.5	10
2. Hold cars	24	Security	2	Included in Step 10	
3. Assemble equipment and crew	4	Riggers	5	4	300
4. Position barge, connect bridge	2	Tug crew	3	2	400
		Longshoremen	5	2	400
		Bridge operators	3	2	400
		Port Authority Rep.	1	1	400
5. Radiation survey casks (done after Step 1)	2	Field engr.	1	2	10
		Health physics tech.	1	2	10
6. Move casks to/on barge	4	Railroad	1	4	50
		Railroad	2	2	10
		Tug crew	3	4	100
		Barge crew	2	4	30
		Longshoremen	5	4	30
		Bridge operators	2	4	30
		Field engr.	1	4	20
		USCG rep.	1	4	30
		Port Authority rep.	1	4	30
7. Tie down casks to barge	8	Riggers	4	8	10
		Rigging sup.	1	8	20
		Field engr.	1	8	20
8. Preshipment checkout	2	Health physics tech.	1	2	10
		Field engr.	1	2	10
		Marine surveyor	1	2	10
		USCG rep.	1	2	10
		Rigging sup.	1	2	10
9. Disconnect from bridge and dock, rig for shipment	3	Bridge operator	2	2	30
		Longshoremen	4	2	30
		Tug crew	3	3	30
		USCG rep.	1	2	30
		Marine surveyor	1	2	30
		Port Authority rep.	1	2	30
		Field engr.	1	2	30
10. Total security for operation		Security	2	48	250
Total	50		28		

‡a Four casks.

Table A.3. Analysis of Activities for RORO Unloading[‡a]

	Step	Elapsed Time (hr)	Type of Personnel	Number of Personnel	Time (hr)	Average Distance (ft)
1.	Moor barge, connect bridge	2	Tug crew	3	2	50
			Longshoremen	5	2	30
			Bridge operators	3	2	30
			Port Authority Rep.	1	2	30
			USCG rep.	1	2	30
			Field engr.	1	1	
2.	Inspect and survey	2	Health physics tech.	1	2	10
			Field engr.	1	2	10
			USCG rep.	1	1	10
			Marine surveyor	1	1	10
			Port Authority Rep.	1	1	10
3.	Assemble equipment and crew	2	Riggers	5	2	200
4.	Cask tiedown removal	8	Riggers	4	8	10
			Field engr.	1	8	20
			Rigging sup.	1	8	20
5.	Removal of cars from barge	4	Railroad	1	4	50
			Railroad	2	4	10
			Tug crew	3	4	50
			Barge crew	2	4	30
			Longshoremen	5	4	30
			Bridge operators	2	4	30
			Field engr.	1	4	20
			Port Authority Rep.	1	2	30
6.	Hold cars	8	Security	2	Included in Step 7	
7.	Total security for operation		Security	2	26	200
	Total	26		28		

[‡a] Four casks.

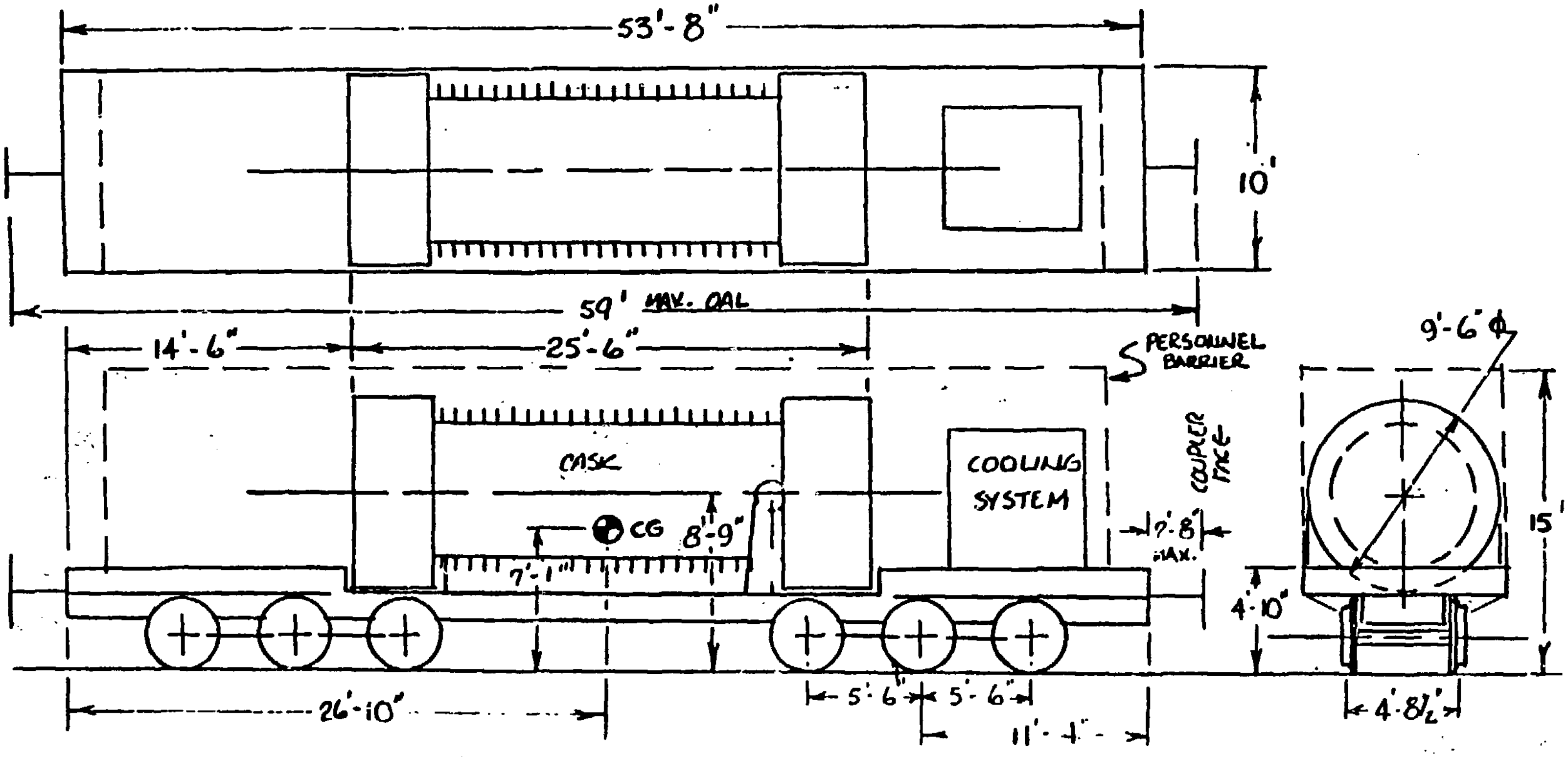

Figure A.2. Typical Railroad Shipping Cask (Source: Hutchison 1983)

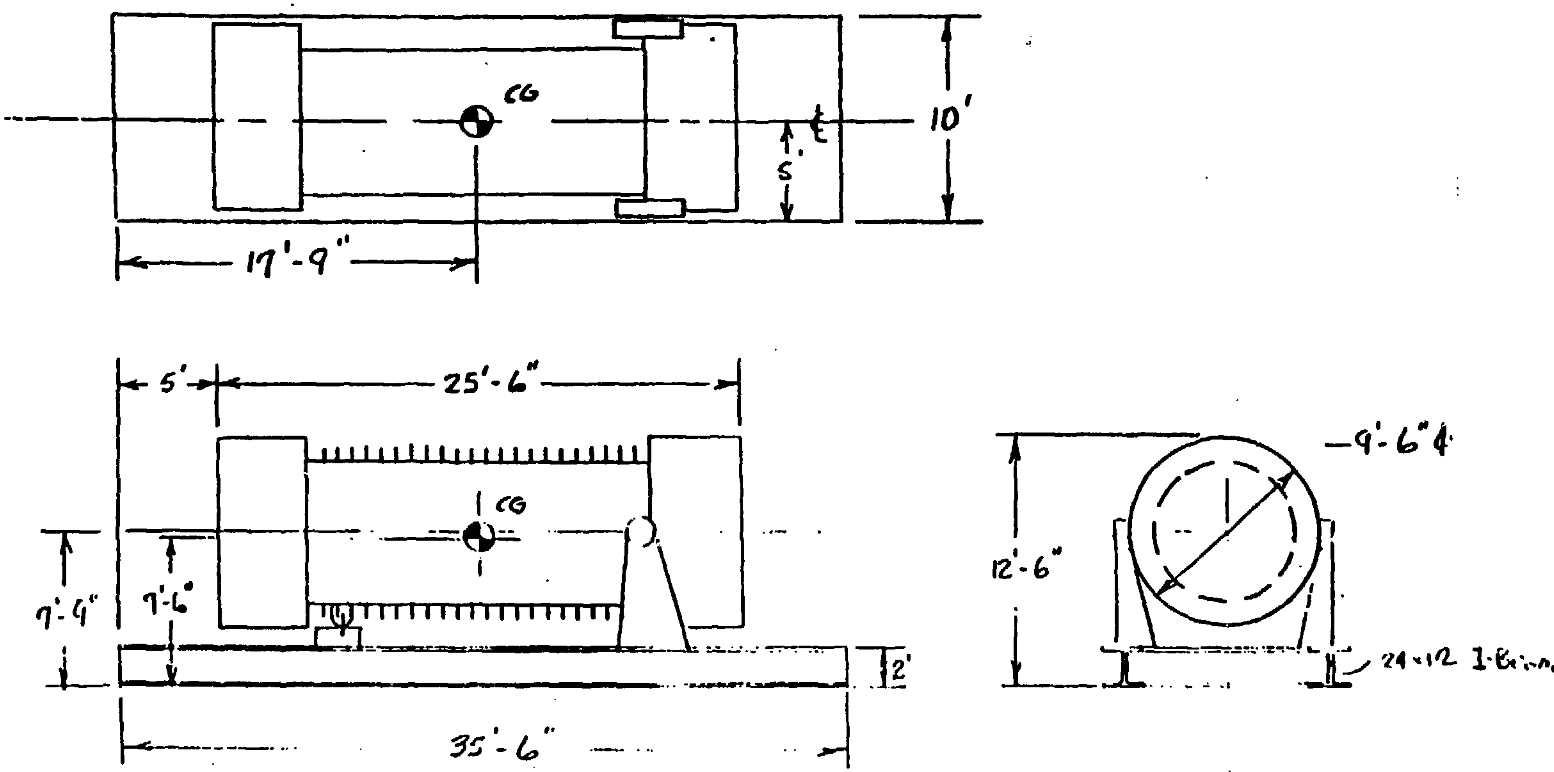

Figure A.3. Palletized Dry Storage Cask (Source: Hutchison 1983)

2. Figure A.4 shows a permanent dockside crane facility. A floating crane or even a pair of land-based mobile cranes could also be used. The layout shown in Figure A.4 is assumed for this analysis.

A.2.3 Description of Loading

1. Cask inspection, preparation for loading, and barge positioning are as described in the RORO analysis.

2. Depending on the dockside crane configuration, the cask transporters (railcars) are moved either singly or in a string to the dock loading area. A buffer car is not required for this operation.

3. Riggers move the pallet-to-railcar tiedowns and install the appropriate lifting structures. These structures are, in turn, connected to the crane hook. If a strongback is used, the above sequence is reversed.

4. The crane lifts the palletized cask and swings it onto the barge deck. Ballasting might be necessary to maintain reasonable barge trim during placement. The riggers assist in the pallet positioning.

5. Once in place the palletized cask is secured to the barge deck by the riggers. Unlike the railcar, the pallet does not require jacking, only lashing.

6. The RORO operation time for cask tiedown is 2 hours per unit; it is about the same for the LOLO operation. In the RORO case the railcar tiedown is more time-consuming than the LOLO pallet lashing. However, this difference is offset by the need to unlash the pallet from its land-transport vehicle in the LOLO scenario, a step not encountered in the RORO analysis.

7. Once the casks are in place, the remaining operations (Steps 8-12) of the RORO analysis (see Sec. A.1.3) are applicable.

A.2.4 Description of Unloading

1. Steps 1-4 of the RORO analysis (Sec. A.1.4) apply to the LOLO case, as well.

2. The unloading is the reverse of the loading described in Sec. A.2.3; pallets are unlashed and subsequently transferred and secured to the land-transport vehicles (i.e., railcars). Ballasting is likely.

3. The 8-hr hold period for RORO also applies to this case.

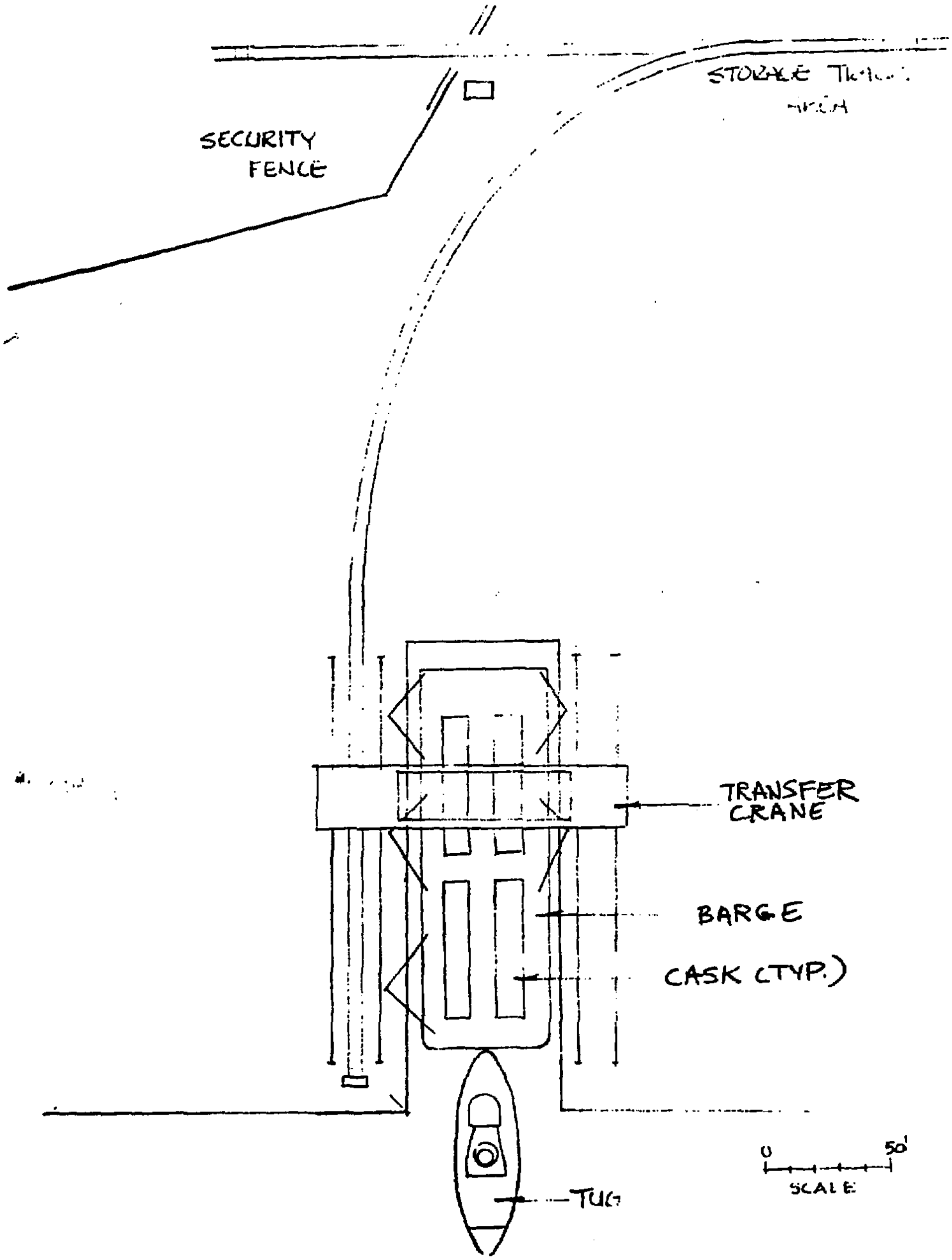

Figure A.4. LOLO Rail-Barge Transfer Site

A.2.5 Time, Distance, and Personnel

The RORO operations require 28 persons. The LOLO operations are nearly identical but do not require the two carfloat operators and one carfloat supervisor. However, they do require a crane operator and an assistant, which means a total of 27 persons are required for the LOLO operations.

Tables A.4 and A.5 summarize the LOLO operations for personnel time and distance. The basis of these tables is identical to that of the RORO operations (i.e., two casks end-to-end with the distance measured normal to the midpoint of the string).

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Hutchison, B. L. 1983. Engineering Risk Analysis of the Extreme Dynamic Accelerations on Deck Cargo Barges at Sea. Sandia National Laboratories Contractor Report SAND83-7442, TTC-0447, Nov. 1983.

Table A.4. Analysis of Activities for LOLO Loading[‡a]

Step	Elapsed Time (hr)	Type of Personnel	Number of Personnel	Time (hr)	Average Distance (ft)
1. Spot cars in holding area	1	Railroad	1	1	50
		Railroad	2	0.5	10
2. Hold cars	24	Security	2	Included in Step 11	
3. Assemble equipment and crew	4	Riggers	5	4	300
		Crane operators	2	4	300
4. Position barge	2	Tug crew	3	2	400
		Longshoremen	5	2	400
		Port Authority rep.	1	1	400
5. Rad. survey of casks (done after Step 1)	2	Field engr.	2	4	10
		Health physics tech.	1	2	10
6. Movement of casks/cars to dockside	2	Railroad	1	2	30
		Railroad	2	2	10
7. Loading of palletized casks onto barge	4	Tug crew	3	4	100
	4	Barge crew	2	4	30
		Longshoremen	5	4	30
		Riggers	5	4	10
		Field engr.	1	4	20
		USCG rep.	1	4	30
		Port Authority rep.	1	4	30
		Crane operators	2	4	50
8. Tiedown of palletized casks	4	Riggers	5	4	10
		Tug crew	3	4	100
		Field engr.	1	4	20
9. Preshipment checkout	2	Health physics tech.	1	2	10
		Field engr.	1	2	10
		Marine surveyor	1	2	10
		USCG rep.	1	2	10
		Rigging sup.	1	2	10
10. Disconnect from dock rig for shipment	3	Longshoremen	5	2	30
		Tug crew	3	3	30
		USCG rep.	1	2	30
		Marine surveyor	1	2	30
		Port Authority rep.	1	2	30
		Field engr.	1	2	30
11. Total security for operation		Security	2	48	250
Total	48		27		

[‡a] Four casks.

Table A.5. Analysis of Activities for LOLO Unloading[‡a]

Step		Elapsed Time (hr)	Type of Personnel	Number of Personnel	Time (hr)	Average Distance (ft)
1.	Moor barge	2	Tug crew	3	2	50
			Longshoremen	5	2	30
			Port Authority rep.	1	2	30
			USCG rep.	1	2	30
			Field engr.	1	2	30
2.	Inspect and survey	2	Health physics tech.	1	2	10
			Field engr.	1	2	10
			USCG rep.	1	1	10
			Marine surveyor	1	1	10
			Port Authority rep.	1	1	10
3.	Assemble equipment and crew	2	Riggers	5	2	200
			Crane operators	2	2	200
4.	Cask tiedown removal, rigging and transfer to railcars	4	Riggers	5	4	10
			Tug crew	3	4	100
			Field engr.	1	4	20
			Crane operators	2	4	50
			USCG rep.	1	4	30
			Port Authority rep.	1	4	30
5.	Tiedown of palletized casks to railcars	4	Riggers	5	4	10
			Field engr.	1	4	20
6.	Movement of railcars to hold area	2	Railroad	1	2	30
			Railroad	2	2	10
7.	Hold cars	8	Security	2	Included below	
8.	Total security for operation		Security	2	24	200
	Total	24		27		

†1 Four casks.

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APPENDIX B. TRANSPORTATION COST CALCULATIONS

The development of the costs of transporting spent fuel are detailed in this appendix. The costs are subdivided into capital and maintenance costs for the railcar/cask system and shipping costs for barge and rail movements.

B.1. MAINTENANCE

The maintenance cost for the railcar/cask system is $125,000 per year as reported in Neuhauser et al. (1984). It is assumed that the railcar/cask system is used 80% of the time, or for 291 days per year. This yields a daily maintenance cost of $430.

B.2 CAPITAL COSTS

The capital costs for the rail/cask system are $5.3 million per railcar/cask system as reported in Neuhauser et al. (1984). The life was estimated at 15 years and the costs were amortized over 15 years at 15%. The capital recovery factor for 15% and 15 years is 0.171. This yields annual capital costs of $906,300 ($5.3 \times 10^6 \times 0.171$). Assuming a use rate of 80% (use for 291 days a year) yields a daily capital cost of $3100.

B.3 SHIPPING COSTS

B.3.1 Water Transportation

The shipping cost for water shipments are based on operating costs for a barge/tug combination. The costs used for the tug are $8000 per day when under power and $5500 per day when idle. The barge costs are $2000 per day. The tug costs are broken down as follows:

Capital	$3200
Fuel and operating	2500
Crew	2100
Misc.	400
Total	$8000

B.3.2 Loading and Unloading

The loading and unloading costs for loading and unloading the railcar/cask systems to and from the barge at ports and loading the railcar/cask system to the barge at plants are shown in Table B.1. These costs are average costs based on figures obtained by Pacific Northwest Laboratory from port personnel at the ports of Baltimore, Norfolk, Charleston, Houston, Memphis, and Wilmington. The labor costs are higher at ports because it is assumed that union rules will require a full stevedoring crew. A selected set of the costs obtained are shown in Table B.2. The costs per cask for loading or unloading at a port is $6290. The cost per cask for loading at a plant is $2925. Based on the costs shown in Table B.2, a representative cost for LOLO loading is $1500 per lift.

B.3.3 Rail Transportation

The shipping costs used for rail are those developed in McNair et al. (1984). They are calculated using the following formula:

Rail shipping cost = (CVL*LOAD/100) + (CVE*EMPT/100) + ESCORT,

where

CVL	=	loaded cask/container shipping cost approximation, $/cwt,
	=	$0.1565 * DIS1^{0.6087}$ (Western)
	=	$0.4025 * DIS1^{0.4304}$ (North Central)
	=	$0.2639 * DIS1^{0.5042}$ (Southern)
	=	$0.3969 * DIS1^{0.4469}$ (Northeastern),
CVE	=	empty cask/container shipping cost approximation, $/cwt,
	=	$0.1477 * DIS2^{0.6077}$ (Western)
	=	$0.3796 * DIS2^{0.4292}$ (North Central)
	=	$0.2472 * DIS2^{0.5042}$ (Southern)
	=	$0.3727 * DIS2^{0.4468}$ (Northeastern),
DIS1	=	specified distance traveled with a full cask/container, mi,
DIS2	=	specified distance traveled with an empty cask/container, mi,
EMPT	=	weight of empty cask/container, lb (40,000 lb minimum),
ESCORT	=	cost of escorts, and
LOAD	=	weight of full cask/container, lb.

The regions are defined in Table B.3. The escort fee, ESCORT, is based on a cost of $20.83 per hour plus a charge of $0.16 per mile as used in McNair et al. (1984). The empty weight, EMPT, is 177,000 lb and the loaded weight is 205,000 lb.

B.4 CALCULATIONS

Details of the rail shipping cost calculations are shown in Table B.4. The parameters used to calculate the shipping costs for water transportation and maintenance and capital costs are shown in Tables B.5 through B.7. Table B.8 gives the round-trip times used to calculate the maintenance and capital costs for rail movements from the transshipment locations to the repository sites.

REFERENCES--APPENDIX B

Neuhauser, K.S., J.W. Cashwell, P.C. Reardon, and G.W. McNair. 1984. A Preliminary Cost and Risk Analysis for Transporting Spent Fuel and High-Level Wastes to Candidate Repository Sites. Sandia National Laboratories, SAND84-1975, TIC-0506, Oct. 1984.

McNair, G.W., B.M. Cole, R.E. Cross, and E.F. Votaw. 1984. Truck and Rail Charges for Shipping Spent Fuel and Nuclear Waste. Draft Report, Pacific Northwest Laboratory, Richland, WA, Nov. 1984.

Table B.1. Costs of Loading and Unloading Railcar/Cask Systems to and from Barge (RORO)[‡a]

At Ports	
Wharfage	$ 760
Dockage	200
Labor	24,000[‡b]
Misc.	200
Total	$25,160 per barge ÷ 4 = $6,290/cask
At Plants	
Labor	$11,700[‡c]
Total	$11,700 per barge ÷ 4 = $2,925/cask

‡a These costs represent average values and are based on figures obtained by Pacific Northwest Laboratory from port personnel at the ports of Baltimore, Norfolk, Charleston, Houston, Memphis, and Wilmington (see Table B.2).

‡b Based on an average stevedoring crew cost of $1000 per gang hour for 24 hours (see Appendix A).

‡c Based on a labor rate of $65 per person-hour and 180 person-hours (see Appendix A).

Table B.2. Port and Loading and Unloading Costs[‡a]

Port	Wharfage	Dockage	Stevedoring	Heavy Lift	Misc.
Baltimore, MD	$800	$16/day	$1000/gang-hr	$2500/8 hr $1740/4 hr	$72
Norfolk, VA	$760	$215/day	$1016/gang-hr	$1000 first pick $500 rest	
Charleston, SC	$207/cask	$500	$642/gang-hr	$144/pick	$356
Houston, TX	$680	$89/day	-	$2250/pick	$158
Wilmington, DE	$736	$157	-	$1900/pick	-

[‡a] Obtained by Pacific Northwest Laboratory from port personnel.

Table B.3. Region Definitions for Rail Shipping Cost Formulas

Region	States[‡a]	
Western	Washington	California
	Colorado	Arizona
	Oregon	
Southern	Texas	Alabama
	Arkansas	Mississippi
	Florida	Tennessee
	Georgia	South Carolina
	Kansas	North Carolina
	Louisiana	Virginia
North Central	Illinois	Iowa
	Minnesota	Missouri
	Nebraska	Wisconsin
Northeastern	Indiana	Connecticut
	Maine	Massachusetts
	Maryland	New Hampshire
	Michigan	New Jersey
	New York	Pennsylvania
	Ohio	Vermont

[‡a] States not shown have no reactors with rail service.

Table B.4. Rail Cost Calculations

Origin/Destination	Region	Distance (mi)	Time (hr)	CVL $/cwt	CVE $/cwt	Transport Cost ($)	Escort Cost ($)	Total Cost ($)
Houston/Deaf Smith	W	650	190	8.1	7.6	30,057	4,062	34,119
Houston/Yucca Mountain	W	2,137	280	16.6	15.6	61,642	6,175	67,817
Houston/Hanford	W	2,312	285	17.5	16.4	64,903	6,308	71,211
Memphis/Deaf Smith	W	899	215	9.8	9.2	36,374	4,623	44,997
Memphis/Yucca Mountain	W	2,097	276	16.5	15.4	61,083	6,086	67,169
Memphis/Hanford	W	2,272	280	17.2	16.2	63,934	6,196	70,130
Hatch/Charleston	S	267	133	4.4	4.1	16,277	2,814	19,091
McGuire/Charleston	S	279	139	4.5	4.2	16,659	2,941	19,600
North Anna/Norfolk	S	230	115	4.1	3.8	15,131	2,433	17,564
Peach Bottom/Baltimore	NE	78	39	2.8	2.6	10,342	825	11,167
Robinson/Charlest	S	195	97	3.8	3.5	13,985	2,052	16,037
Summer/Charleston	S	168	84	3.5	3.2	12,839	1,777	14,616
Susquehanna/Baltimore	NE	206	103	4.3	4.0	15,895	2,179	18,074
Three Mile Island/Baltimore	NE	114	57	3.3	3.1	12,252	1,204	13,456
Vermont Yankee/Albany	NE	118	59	3.3	3.1	12,252	1,248	13,500

Table B.5. Parameters Used to Calculate Costs for Direct Water Shipments from Plant to Houston

Plant	State	Distance (mi)	Load (hr)	Travel Time (hr)	Unload (hr)	Cask Turn-around (hr)	Round Trip	
							Hr	Days
Brunswick	NC	1689	26	193	26	60	498	20.8
Calvert Cliffs	MD	2,118	26	241	26	60	594	24.8
Crystal River	FL	836	26	99	26	60	310	12.9
Farley	AL	895	26	201	26	60	514	21.4
Indian Point	NY	2263	26	294	26	60	700	29.2
Maine Yankee	ME	2,547	26	289	26	60	690	28.8
Millstone	CT	2,371	26	269	26	60	650	27.1
Oyster Creek	NJ	2,171	26	247	26	60	606	25.3
Pilgrim	MA	2,471	26	280	26	60	672	28.0
Salem	NJ	2,108	26	240	26	60	592	24.7
St. Lucie	FL	1,204	26	157	26	60	426	17.8
Slurry	VA	1,979	26	225	26	60	562	23.4
Turkey Point	FL	1,042	26	121	26	60	354	14.8

Table B.6. Parameters Used to Calculate Costs for Direct Water Shipments from Plant to Memphis

Plant	State	Distance (mi)	Load (hr)	Travel Time (hr)	Unload (hr)	Cask Turn-around (hr)	Round Trip Hr	Round Trip Days
Big Rock Point	MI	798	26	229	26	60	570	23.8
Browns Ferry	TN	256	26	116	26	60	344	14.3
Cook	MI	547	26	198	26	60	508	21.2
Davis-Besse	OH	1,308	26	315	26	60	742	30.9
Dresden	IL	405	26	162	26	60	436	18.2
Fitzpatrick	NY	1,660	26	344	26	60	800	33.3
Ginna	NY	1,604	26	336	26	60	784	32.7
Kewaunee	WI	634	26	227	26	60	566	23.6
Nine Mile Point	NY	1,660	26	344	26	60	800	33.3
Palisades	MI	587	26	211	26	60	534	22.3
Point Beach	WI	622	26	223	26	60	558	23.3
Sequoyah	TN	447	26	142	26	60	396	16.5
Zion	IL	528	26	192	26	60	496	20.7

Table B.7. Parameters Used to Calculate Costs for Shipments from Plant to Port by Rail, Port to Houston by Barge

Plant	State	Port		Rail Distance (mi)	Rail Time (hr)	Barge Load Time (hr)	Water Distance (mi)	Water Time (hr)	Barge Inload Time (hr)	Cask Turnaround (hr)	Round Trip (hr)	Round Trip Days
Hatch	GA	Charleston	SC	267	133	50	1,580	181	26	60	764	31.8
McGuire	NC	Charleston	SC	279	139	50	1,580	181	26	60	776	32.3
North Anna	VA	Norfolk	VA	230	115	50	1,966	224	26	60	814	33.9
Peach Bottom	PA	Baltimore	MD	78	39	50	2,108	240	26	60	694	28.9
Robinson	SC	Charleston	SC	195	97	50	1,580	181	26	60	692	28.8
Summer	SC	Charleston	SC	168	84	50	1,580	181	26	60	666	27.8
Susquehanna	PA	Baltimore	MD	206	103	50	2,108	240	26	60	822	34.3
Three Mile Island	PA	Baltimore	MD	114	57	50	2,108	240	26	60	730	30.4
Vermont Yankee	VT	Albany	NY	118	59	50	2,343	310	26	60	874	36.4

Table B.8. Parameters Used to Calculate Capital and Maintenance Costs for Rail Shipments from Transshipment Locations to Candidate Repository Sites

Assumed Transshipment Location		Candidate Repository Location		Cask Turn-around (hr)	Round Trip	
					Hr	Days
Houston	TX	Deaf Smith	TX	60	440	18.3
Houston	TX	Yucca Mountain	NV	60	620	25.8
Houston	TX	Hanford	WA	60	630	26.3
Memphis	TN	Deaf Smith	TX	60	490	20.4
Memphis	TN	Yucca Mountain	NV	60	612	25.5
Memphis	TN	Hanford	WA	60	620	25.8

APPENDIX C. NONRADIOLOGICAL RISK FACTORS

The risk factors for transportation risks are based on cargo ton-mile data from Gay (1979) and on death and injury statistics from USDOT (1983). The data used are from 1972 to 1976. These were the years for which both ton-mile data and death and injury data were available. The data are shown in Table C.1. A total of 3.5×10^{-12} cargo ton-miles and 2002 fatalities for nonvessel casualties plus 1176 for vessel casualties gives a fatality rate of 9.0×10^{-10} per ton-mile. A total of 7555 nonvessel casualty injuries and 651 vessel casualty injuries gives an injury rate of 2.3×10^{-9} per ton-mile.

To calculate the risk, factors for rail estimates based on available data were used, since neither ton-mile nor death and injury data were available for the same years. The number of average yearly rail fatalities for 1981 and 1982 is 1200 and for injuries it is 46,650. Analysis of the ton-mile data for Class 1 railroads for 1967 to 1977 gives an estimate of 0.8×10^{12} cargo ton-miles per year. These estimates give risk factors for rail of 1.5×10^{-9} deaths per ton-mile and 5.8×10^{-8} injuries per ton mile.

REFERENCES--APPENDIX C

Gay, W.F. 1979. National Transportation Statistics. U.S. Department of Transportation DOE-TSC-RSPA-79-19, Aug. 1979.

U.S. Department of Transportation. 1983. Transportation Safety Information Report, 1982 Annual Summary. DOT-TSC-RSPA-83-4.

Table C.1. Water Transport Cargo Ton-Miles, Deaths and Injuries

Year	Cargo Ton-Miles[‡a] (millions)	Fatalities[‡b]		Injuries[‡b]	
		Nonvessel Casualty	Vessel Casualty	Nonvessel Casualty	Vessel Casualty
1972	603,542	348	171	1,243	110
1973	584,691	333	131	1,168	74
1974	586,345	296	199	1,265	104
1975	565,984	348	190	1,216	74
1976	591,853	405	269	1,244	153
1977	599,000	270	216	1,419	136
Total	3,531,415	2,002	1,176	7,555	651

[‡a] Source: Gay (1979).

[‡b] Source: U.S. Department of Transportation (1983).

APPENDIX D. RADIATION DOSE CALCULATIONS

All radiation dose calculations are based on the following formula for the dose rate $\dot{D}$ at a distance r from a point source of radiation (Finley, Aldrich et al. 1980--App. B, Eq. 1):

$$\dot{D}(r) = \frac{K\, e^{-\mu r}\, B(r)}{r^2}\ , \qquad (D.1)$$

where

$\dot{D}(r)$ = dose rate (rem/h),
K = dose rate factor (rem·m^2/h),
μ = attenuation coefficient (m^{-1}), and
B(r) = dose rate buildup factor (dimensionless).

The attenuation coefficient and the buildup factor both depend on gamma-ray energy.

D.1 ESTIMATE OF THE DOSE RATE FACTOR K

The following approximations were used to estimate the dose rate factor K. First, the product of the attenuation factor and the buildup factor was set equal to one. Figure D.1 shows this product as the function of r (distance from source) for three values of gamma energies. The attenuation coefficients and the forms of the buildup factors used in this plot are shown in Table D.1. It is seen that this product is usually smaller than one and decreases rapidly with the distance from the source. The exception occurs for r values smaller than 100 m and for the gamma energies of 0.5 and 1.0 MeV. For these values, this product is close to one. The same assumption is made in the transportation analysis code RADTRAN (Taylor and Daniel 1982). With this approximation the dose rate equation becomes

$$\dot{D}(r) = \frac{K}{r^2}\ . \qquad (D.2)$$

Second, it was assumed that the shielding is such that the radiation level is 0.010 rem/h at 2 m from the midpoint of the edge of the railcar (Figure D.2). Two geometries were used to approximate the cylindrical shape of the inner cask (shaded area in Figure D.2) a point source at the center of the cylinder and a line source along the cylinder axis. These geometries and the corresponding values of the dose rate factors are shown in Table D.2.

The above approximations enable one to obtain analytic expressions for certain integrals that would otherwise have to be computed numerically. It is seen that for the geometries considered, the values of the dose rate factor

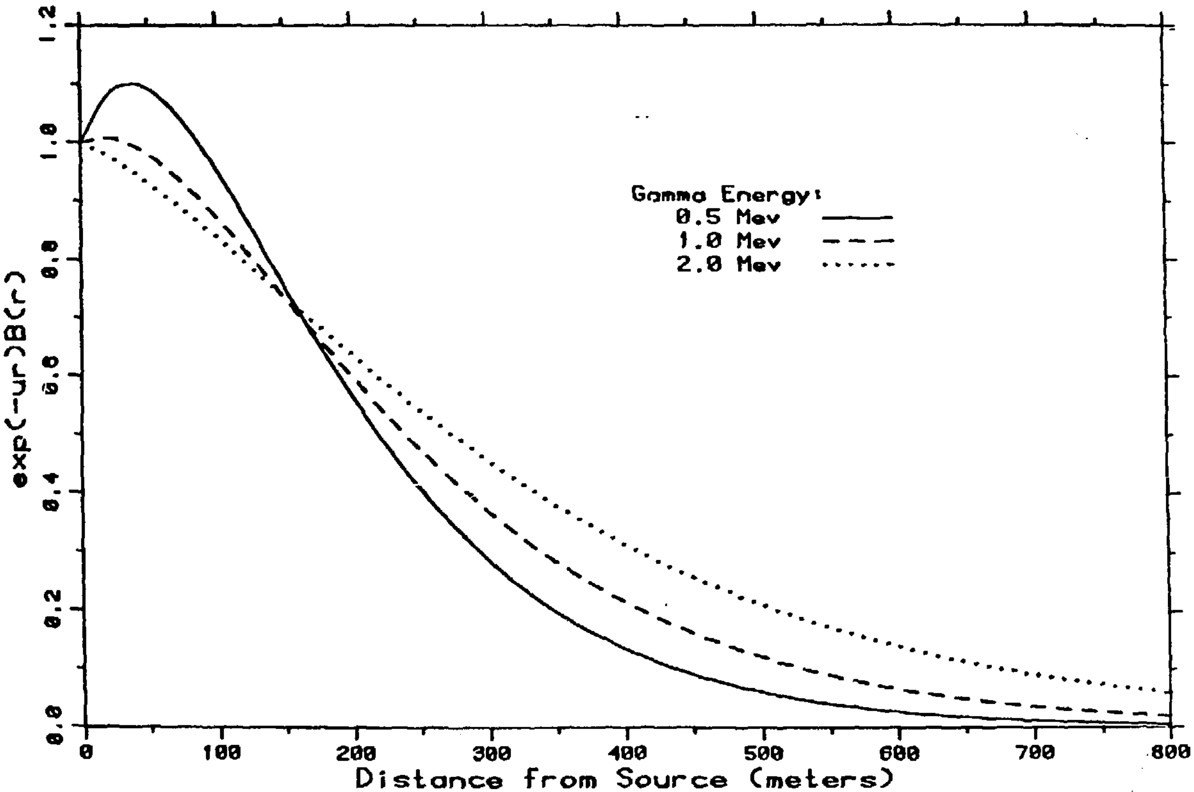

Figure D.1. Product of Attenuation and Buildup Factors for Different Energies

Table D.1. Attenuation Coefficients and Buildup Factors, B(μr), for Three Gamma Energies

$B(\mu r) = 1 + a\mu r \exp(b\mu r)$, where a, b, and μ are given below

E(MeV)	a[‡a]	b[‡a]	μ[‡b]
0.5	1.5411	0.9920	0.0112
1.0	1.1305	0.05687	0.00805
2.0	0.8257	0.02407	0.0056

[‡a] Source: Chen et al. 1981--Table 4.

[‡b] Source: U.S. Dept. Health Edu. Welfare 1970, p. 135.

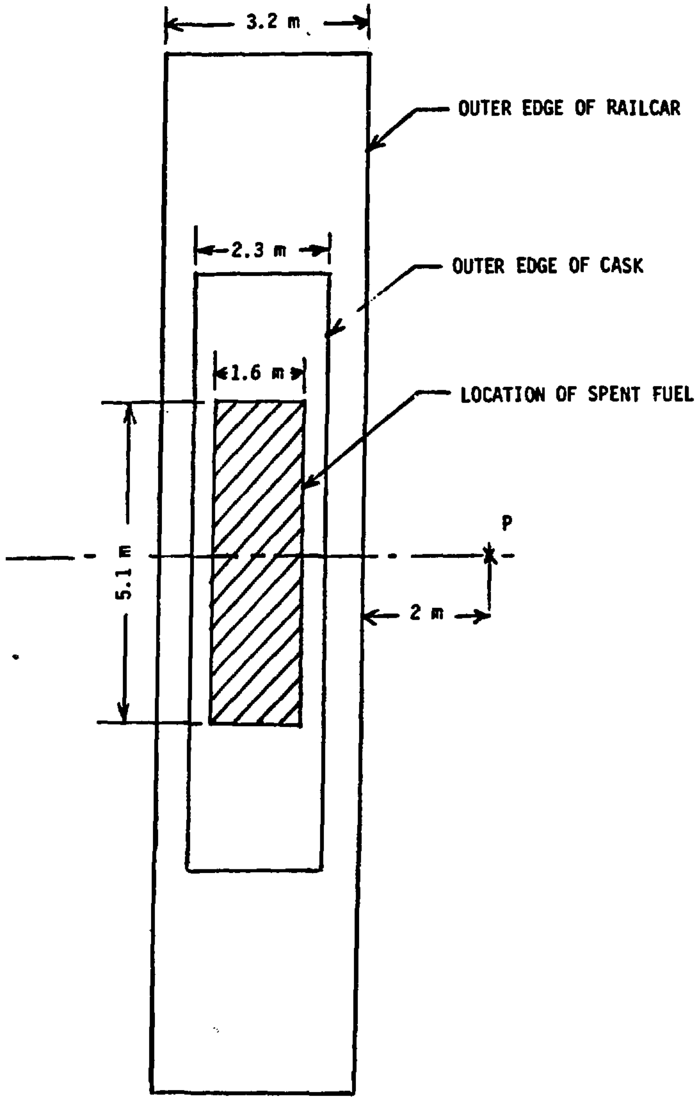

Figure D.2. Railcar/Cask Layout

Table D.2. Dose Rate Factors for Two Geometries[‡a]

Geometry	Dose Rate Factor K (rem-m^2/h)
One point at the center of the cylinder	0.13
A line 5.1 m in length at the cylinder axis	0.15

[‡a] The geometries lead to a dose rate of 0.10 rem/h at 2 m from the edge of railcar and approximate a cylinder 5.1 m in height and 0.8 m radius.

range from about 0.13 to 0.15 rem-m^2/h. In the analyses presented here the value K = 0.15 rem-m^2/h was used, corresponding to a line source 5.1 m in length. The dose rate at point P at a distance r from the center of a line source can be derived in a straightforward manner from Eq. D.2 using elementary calculus. It is given by

$$\dot{D} = \frac{K}{Lx}\left[\tan^{-1}\left(\frac{y + \frac{L}{2}}{x}\right) - \tan^{-1}\left(\frac{y - \frac{L}{2}}{x}\right)\right], \qquad (D.3)$$

where $r^2 = x^2 + y^2$, and L is the length of the line source (Figure D.3). When $r >> L$, Equation D.2 is a good approximation to Eq. D.3. For r = 5L, the difference between using Eq. D.2 and Eq. D.3 is at most 1%. For r > 5L, this difference would be even smaller.

D.2 POPULATION DOSE

The expressions used in calculating the population dose were derived following the procedure of Chen et al. (1981). However, Eq. D.2 was used instead of Eq. D.1, resulting in simple analytic expressions for dose.

The dose during transport by rail and inland waterways to the population residing in two strips between x_{min} and x_{max}, one on each side of the route, is given by

$$Dose_{off\text{-}link} = 2 \cdot 10^{-6} KP\ \Delta T\ \pi\ \ln(x_{max}/x_{min})\ ,\ \text{(person-rem)} \qquad (D.4)$$

where P is the population density in person/km^2, ΔT is the duration of the transport in hours, and x_{max} is the distance to the outer and x_{min} to the inner edge of the strip. (The factor of 10^{-6} in the above equation is needed to convert from m^2 to km^2.) The calculations were performed with K = 0.15 rem-m^2/h, x_{min} = 30 and x_{max} = 800 m. Population data and trip duration data are shown in Table D.3 for water shipments to Houston and in Table D.4 for water shipments to Memphis. The values in Tables 6.1, 6.2, and

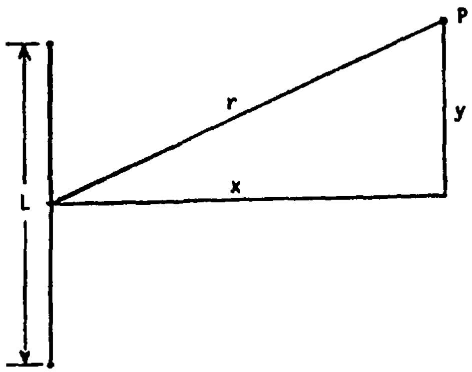

Figure D.3. Geometry for Dose from Line Source

Table D.3. Water Shipments from Plants to Houston

Plant		Inland			Ocean		
		Distance (mi)	Time (hr)	Population (persons/mi^2)	Distance (mi)	Time (hr)	Population (persons/mi^2)
Brunswick	NC	49	11	526	1,640	182	0
Calvert Cliffs	MD	49	11	526	2,069	230	0
Crystal River	FL	49	11	526	787	88	0
Farley	AL	895	201	292	-	-	
Indian Point	NY	94	53	13,112	2,167	241	0
Maine Yankee	ME	49	11	526	2,498	278	0
Millstone	CT	49	11	526	2,322	258	0
Oyster Creek	NJ	49	11	526	2,122	236	0
Pilgrim	MA	49	11	526	2,422	269	0
Salem	NJ	49	11	526	2,059	229	0
St. Lucie	FL	49	11	526	1,155	146	0
Surry	VA	49	11	526	1,930	214	0
Turkey Point	FL	49	11	526	993	110	0

Table D.4. Water Shipments from Plants to Memphis

Plant		Inland			Great Lakes		
		Distance (mi)	Time (hr)	Population (persons/mi^2)	Distance (mi)	Time (hr)	Population (persons/mi^2)
Big Rock Point	MI	482	176	197	316	53	0
Cook	MI	482	176	197	65	22	0
Davis-Besse	OH	482	176	197	826	139	0
Dresden	IL	405	162	140	-	-	-
Fitzpatrick	NY	482	176	197	1,178	168	0
Ginna	NY	482	176	197	1,122	160	0
Kewaunee	WI	482	176	197	152	51	0
Nine Mile Point	NY	482	176	197	1,178	168	0
Palisades	MI	482	176	197	105	35	0
Point Beach	WI	482	176	197	140	47	0
Zion	IL	482	176	197	46	16	0
Sequoyah	TN	447	142	149	-	-	-
Browns Ferry	TN	256	116	131	-	-	-

6.3 in the column "Barge Shipment" were obtained using Eq. D.4 and the data in Tables D.3 and D.4. Tables D.5 and D.6 show population and trip-duration data for rail shipments. The off-link doses calculated from Eq. D.4 are also shown in these tables.

The dose during loading and unloading of barges is given by an expression similar to Eq. D.4:

$$Dose_{load\text{-}unload} = 2 \cdot 10^{-6}\ KP\ \Delta T\ \pi\ \ln(r_{max}/r_{min})\ ,\ \text{(person-rem)} \qquad (D.5)$$

where r_{max} and r_{min} are the outer and inner radii of the populated area. Other symbols are the same as before. Based on the dimensions in Fig. A.1, the value of r_{min} is taken to be 60 m; r_{max} is 800 m. Population densities at plants and at ports are shown in Tables D.7 and D.8. For the loading, the duration is ΔT = 50 hours and for the unloading ΔT = 26 hours. Tables D.7 and D.8 and Eq. D.5 were used to compute the population doses for loading and unloading in Tables 6.1 through 6.3.

The dose to persons passing rail shipments on freight or passenger trains is given by

$$Dose_{on\text{-}link} = 10^{-3}\ \frac{N\ K\ \pi}{x\ V}\ ,\quad \text{(person-rem)} \qquad (D.6)$$

where

N = number of persons passing the shipment,

x = distance from the train carrying exposed individuals to the shipment, and

V = relative speed of the train carrying the exposed persons and the sh' .ment.

The number of persons passing the shipment, N, was estimated from the distance, time and traffic data in Tables D.5 and D.6, and from the average yearly transportation data for 1977 in Table D.9. The number N can be expressed as the sum

$$N = N_{freight} + N_{passenger}\ , \qquad (D.7)$$

where $N_{freight}$ = the number of freight crew passing the transport and

$N_{passenger}$ = number of passengers passing the transport.

Table D.5. Rail Shipments from Plants to Port

Plant	State	Assumed Port	State	Distance (mi)	Time (hr)	Average Annual Traffic (tons/10^6)	Population (persons/mi^2)	Population Dose per Shipment (person-rem)		
								Off-link	On-link	Total
Hatch	GA	Charleston	SC	267	133	11.8	53	0.0085	0.0019	0.010
McGuire	NC	Charleston	SC	279	139	26.1	67	0.011	0.0044	0.016
North Anna	VA	Norfolk	VA	230	115	29.9	195	0.027	0.0042	0.031
Peach Bottom	PA	Baltimore	MD	78	39	58.3	1,673	0.080	0.0028	0.082
Robinson	SC	Charleston	SC	195	97	21.3	62	0.0073	0.0025	0.0098
Summer	SC	Charleston	SC	168	84	13.8	77	0.0078	0.0014	0.0092
Susquehanna	PA	Baltimore	MD	206	103	51.1	591	0.074	0.0064	0.080
Three Mile Island	PA	Baltimore	MD	114	57	55.2	1,253	0.086	0.0038	0.090
Vermont Yankee	VT	Albany	NY	118	59	35.9	59	0.004	0.0026	0.0068

Table D.6. Rail Shipments - Transshipment to Candidate Repository Sites

Transhipment	State	Assumed Repository	State	Distance (mi)	Time (hr)	Average Annual Traffic (tons/10^6)	Population (persons/mi^2)	Population Dose per Shipment (person-mrem): Off-link	On-link	Total
Houston	TX	Deaf Smith	TX	650	190	18.0	76	0.018	0.0042	0.022
Houston	TX	Yucca Mountain	NV	2,137	280	46.9	84	0.028	0.016	0.044
Houston	TX	Hanford	WA	2,312	285	51.9	73	0.025	0.018	0.043
Memphis	TN	Deaf Smith	TX	899	215	33.4	40	0.010	0.0088	0.019
Memphis	TN	Yucca Mountain	NV	2,097	276	53.4	21	0.007	0.018	0.025
Memphis	TN	Hanford	WA	2,272	280	58.0	15	0.0051	0.020	0.025

Table D.7. Population Densities (persons/mi^2) at Plants

Plants to Memphis		Plants to Houston	
Big Rock Point	16.10	Brunswick	27.74
Browns Ferry	42.17	Calvert Cliffs	60.88
Cook	118.94	Crystal River	34.27
Davis-Besse	143.79	Farley	10.0
Dresden	26.83	Indian Point	244.38
Fitzpatrick	104.66	Maine Yankee	45.23
Ginna	42.82	Millstone	133.9
Kewaunee	57.45	Oyster Creek	133.0
Nine Mile Point	42.82	Pilgrim	89.17
Palisades	41.50	Salem	65.97
Point Beach	22.25	St. Lucie	42.11
Sequoyah	40.66	Surry	19.93
Zion	837.28	Turkey Point	620.85

Table D.8. Population Densities (persons/mi^2) at Ports

Loading Barge	
Charleston	115.4
Norfolk	1,841.2
Baltimore	3,782.6
Albany	87.3
Unloading Barge	
Memphis	396.5
Houston	526.1

Table D.9. Transportation Data Used for Calculating On-Link Population Dose

	1977[‡a]	1983[‡b]
Freight ton-miles/10^9	834	838
Freight train-miles/10^6	428	
Passenger miles/10^9	10	11

‡a Source: Gay (1979).

‡b Source: U.S. Department of Commerce (1985).

The values of $N_{freight}$ and $N_{passenger}$ are estimated from the data in Table D.9. It is assumed that there are five crew members per freight train:

$$N_{freight} = 5 \cdot \Delta T \frac{N_{tons}}{2} \frac{(\text{freight train-miles})}{(\text{freight ton-miles})} \frac{(\text{years})}{(\text{hour})} = 1.5 \cdot 10^{-7} \Delta T N_{tons}$$

and (D.8)

$$N_{passenger} = \Delta T \frac{N_{tons}}{2} \frac{(\text{passenger-miles})}{(\text{freight ton-miles})} \frac{(\text{years})}{(\text{hour})} = 6.8 \cdot 10^{-7} \Delta T N_{tons} ,$$

where N_{tons} is the freight traffic along the route in both directions.

The total number of persons passing the transport is therefore given by

$$N = 8.3 \cdot 10^{-7} \Delta T N_{tons} . \quad (D.9)$$

With K = 0.15 rem-m^2/h, x = 10 m, and V = 20 mph (32 km/h) the on-link dose becomes:

$$Dose_{on-link} = 1.22 \cdot 10^{-3} \Delta T N_{tons} \text{ (person-rem)} . \quad (D.10)$$

The values of ΔT (in hours) and N_{tons} are given in Tables D.5 and D.6. The tables also show the on-link population dose during train transport calculated from Eq. D.10.

D.3 OCCUPATIONAL DOSE

To calculate the occupational dose during the rail shipment, it was conservatively assumed that the dose at the end of the railcar would be at the regulatory limit of 2 mrem/hour. The rail cars are about 20 m long, so this assumption would imply that the dose rate is 2 mrem/hour at 10 m from the center of the spent fuel cask. Because it is expected that an empty car will be placed between the engine and the car with spent fuel, and between the caboose and the car with spent fuel, the actual dose rate will be considerably smaller:

$$\dot{D}_{train} = 2\,\frac{10^2}{30^2} = 0.222 \text{ mrem/hour} . \qquad (D.11)$$

There will be seven persons on the train (five crew members and two escorts), and the duration of the shipment is ΔT. In addition, it was assumed that each train will carry four spent-fuel cars (one bargeload), but the dose will be due only to the car closest to the crew members. With these assumptions the dose to the persons on the train per shipment (car) is

$$D_{train} = \frac{7}{4} \cdot 0.222 \cdot \Delta T \text{ person-mrem} , \qquad (D.12)$$

where the trip duration ΔT (hours) is given in Tables D.5 and D.6. The occupational doses computed from Eq. D.12 are shown in Tables 6.3 and 6.6.

The occupational dose for the barge trip was computed for the rail car configuration shown in Figure A.1. Only the two casks closest to the towboat are expected to contribute to the occupational dose. The distance between the center of each cask and the crew is taken to be 46 m (U.S. Nucl. Reg. Comm. 1977--Table 4.11). It is expected that there will be five crew members in the towboat. With these assumptions, the occupational dose per shipment on the barge is

$$D_{barge} = 2 \cdot \frac{5}{4} \cdot \frac{K}{r^2} \Delta T , \qquad (D.13)$$

where Eq. D.2 was used to compute the dose rate. With $K = 0.15$ rem-m^2/hour, and $r = 46$ m,

$$D_{barge} = 0.177 \cdot 10^{-3} \Delta T \text{ person-rem.} \qquad (D.14)$$

The values of ΔT are given in Tables D.3 and D.4. The occupational doses per barge shipment computed from Eq. D.14 are shown in Tables 6.1, 6.2, and 6.3.

The occupational dose during barge loading and unloading operations was computed using data in Tables A.2 and A.3 for RORO, and in Tables A.4 and A.5 for LOLO. The calculations are summarized in Tables D.10 and D.11 for RORO and in Tables D.12 and D.13 for LOLO. The dose rates in these tables were computed using Equation D.3, where $L = 5.1$ m, $y = 9.9$ m, $K = 150$ mrem-m^2/hour, and x is the distance-to-source value in the second column in Tables D.10 through D.13. The dose per barge in the last column was obtained by multiplying the dose rate by the value of person-hours from the first column. In calculating the dose rate, only the contribution of the two casks closest to the handler was included.

Table D.10. Dose to Handlers: RORO Loading

Person-hours[‡a]	Distance to Source (m)[‡a]	Dose Rate (mrem/hour)	Dose per Barge (person-rem)
51	3.0	2.95	150
20	6.1	2.29	46
73	9.1	1.67	122
5	15.2	0.91	5
12	30.5	0.29	4
96	76.2	0.05	5
20	91.4	0.04	1
23	121	0.02	0
	Total Dose per barge		333
	Total Dose per shipment:		333/4 = 83

[‡a] The values of person-hours for a given distance were computed from the data in Table A.2.

Table D.11. Dose to Handlers: RORO Unloading

Person-hours[‡a]	Distance to Source (m)[‡a]	Dose Rate (mrem/hour)	Dose per Barge (person-rem)
45	3.0	2.95	133
20	6.1	2.29	46
60	9.1	1.67	100
22	15.2	0.91	20
62	61.0	0.08	5
		Total Dose per barge	304
		Total Dose per shipment:	304/4 = 76

[‡a] The values of person-hours for a given distance were computed from the data in Table A.3.

Table D.12. Dose to Handlers: LOLO Loading

Person-hours[‡a]	Distance to Source (m)[‡a]	Dose Rate (mrem/hour)	Dose per Barge (person-rem)
59	3.0	2.95	174
8	6.1	2.29	18
65	9.1	1.67	109
9	15.2	0.91	8
24	30.5	0.29	7
96	76.2	0.05	5
28	91.4	0.04	1
17	121.9	0.02	0
	Total Dose per Barge		322
	Total Dose per Shipment:		322/4 = 80.5

[‡a] The values of person-hours for a given distance were computed from the data in Table A.4.

Table D.13. Dose to Handlers: LOLO Unloading

Person-hours[‡a]	Distance to[‡a] Source (m)	Dose Rate (mrem/hour)	Dose (person-rem)
51	3.0	2.95	150
8	6.1	2.29	18
26	9.1	1.67	44
14	15.2	0.91	13
12	30.5	0.29	4
62	61.0	0.08	5
	Total Dose per Barge		234
	Total Dose per Shipment:		234/4 = 58.5

‡a The values of person-hours for a given distance were computed from the data in Table A.5.

D.4 DOSE TO THE MAXIMALLY EXPOSED INDIVIDUAL

The dose to the maximally exposed individual is computed from the following expression:

$$D_{max} = 10^{-3} \frac{K}{V} \frac{\pi}{x_{min}} N_{shipments} \quad (rem) . \qquad (D.15)$$

Here, $K = 0.15$ rem-m^2/hour, and the values of V, the relative speed between the individual and the shipment; x_{min}, the closest conceivable distance from the individual to the shipment; and $N_{shipments}$, number of shipments, are given in Table 6.9 for each of the four scenarios. It is seen from Eq. D.15 that the dose is inversely proportional to both the relative speed and the distance. Thus, because water shipments move considerably slower, the dose to the person living near the waterways is larger than the one to the person near the railways even though fewer shipments use a given waterway.

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