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Transportation Analysis for the Concept of Regional Repositories

D. S. Joy
B. J. Hudson

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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
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ABSTRACT

Over the past several years, planning associated with the National Waste Terminal Storage (NWTS) program assumed the use of one or two large, centrally located repository facilities. Recently, an alternative approach has been proposed which consists of the use of multiple, smaller regional repositories.

In this report, several regional concepts were studied and the transportation requirements for the shipment of spent fuel to the regional repositories were estimated. In general, the transportation requirements decrease as the number of repositories increase. However, as far as transportation is concerned, the point of diminishing returns is reached at approximately one repository in each of three to four regions. Additional savings beyond this point are small.

A series of sensitivity studies is also included to demonstrate the impact on the total transportation requirements of varying cask capacity, rail speed, or truck speed. Since most of the projected fuel shipments are to be made by rail, varying the capacity of the rail cask or varying average rail transport speed will have a major effect on overall transportation requirements.

1. INTRODUCTION

Over the past several years, planning associated with the National Waste Terminal Storage (NWTS) program assumed the use of one or two, large, centrally located repository facilities. Recently, an alternate approach has been proposed which consisted of the use of multiple smaller regional repositories. Southern Science Applications, Inc. (SSAI) has been conducting a study for the Office of Nuclear Waste Isolation (ONWI) to evaluate the regional definitions, predictions of total inventories for each region, and estimation of the transportation requirements for different regional repositories.

The transportation analysis group at Oak Ridge National Laboratory (ORNL) was asked by both SSAI and ONWI to assist in performing some of the detailed transportation calculations for the regional repository study. This report summarizes the logistics analysis conducted at ORNL between May and July 1979. The SSAI report will include a summary of the transportation analysis performed at both SSAI and ORNL. However, it was felt that a more detailed description of the ORNL contribution would be a useful backup document for this project.

2. TRANSPORTATION SCENARIOS

A transportation scenario is defined as a set of assumptions or requirements that will describe how spent fuel assemblies are to be transported from reactors to repositories. The scenario will define the annual shipment schedule, the set of destinations, the transportation system to be used, etc.

Several regional repository concepts will be discussed in this report. Each concept will form a separate case. The ground rules for determining the annual shipment schedule and selecting the transportation mode are the same for each case. The only differences between cases are the repository sites.

For most cases, three separate logistics runs were made. The three runs differ only in the rules used to evaluate which reactors are allowed to ship to a particular repository. These runs are discussed in detail in Sect. 2.5. Sections 2.1 through 2.4 describe the basis for setting up the shipping schedules and the transportation assumptions used in the analysis.

2.1 Nuclear Generating Capacity in the United States

A nuclear generating capacity of 325 GWe in the year 2000, which corresponds to the 1978 DOE midrange capacity projection,[1] was assumed for this analysis. All reactors that are expected to be in commercial operation by 1990 are identified in the nuclear data base, which is an integral part of the ORNL spent fuel logistics model.[2] Detailed information for these reactors, including the actual and estimated spent fuel discharge and on-site fuel storage capacities, was obtained from Nuclear Assurance Corporation (NAC).[3]

Several 1000-MW "expansion" reactors were added to the nuclear data base so that the capacity projections outlined by NAC could be extended to the time frame covered in the DOE capacity projection (1990 to 2010). The geographical distribution of the expansion reactors followed the regional growth projections reported in Nucleonics Week,[4] which are based on the nine National Electric Reliability Council (NERC) regions. The geographical distribution of the expansion reactors is summarized in Table 1. The projected nuclear generating capacity for the United States between 1980 and 2010 is shown in Table 2.

Table 1. Geographical distribution of expansion reactors

NERC Region	Increase in capacity from year 1990 to 2010 by region (%)
Northeast Power Coordinating Council (NPCC)	8.44
Mid-Atlantic Area Council (MAAC)	6.22
Southeastern Electric Reliability Council (SERC)	23.50
East Central Area Reliability Council (ECAR)	17.10
Mid-America Interpool Network (MAIN)	7.70
Mid-Continent Area Reliability Council Agreement (MARCA)	3.92
Southwest Power Pool (SPP)	9.00
Electric Reliability Council of Texas (ERCOT)	8.22
Western Systems Coordinating Council (WSCC)	15.90

Table 2. Projected nuclear generating capacity

Year	Total capacity (GW)	Capacity by reactor type (GW)	
		PWR	BWR
1980	72.4	48.5	23.9
1985	141.6	92.8	48.8
1990	179.4	121.7	57.7
1995	250.4	166.7	83.7
2000	325.4	216.7	108.7
2005	380.4	253.7	126.7
2010	419.4	279.7	139.7

2.2 Spent Fuel Shipping Schedule

The rate at which spent fuel assemblies would be shipped from operating reactors to a federal repository is a function of the spent fuel discharge rate and storage capability at the individual reactor site. Historically, the utilities have been expanding the capacity of the storage pools to meet the increasing storage requirements being imposed on them as a result of the indefinite deferral of fuel reprocessing and the lack of off-site fuel storage facilities. Many utilities have announced continuing plans for expanding storage capacities at reactor sites. For the transportation studies described in this report, it was assumed that all reactors would provide sufficient capacity to allow a minimum cooling period of 7 years prior to shipment. In addition, all reactors that would be in operation prior to 1983 are assumed to be capable of storing all discharged spent fuel through the year 1990.

It was assumed that the first repository will be operational in 1990 and that fuel discharged from the reactors in 1983 will be shipped to a repository in that year. In order to avoid an initial surge of shipments, it was also assumed that any fuel discharged prior to 1983 (long-cooled inventory or backlogged fuel) will be retained at the reactors until the year 2000. Any inventory of long-cooled fuel is assumed to be shipped at a uniform rate between 2000 and 2010. Transporting the long-cooled fuel in this manner reduces the impact on the cask fleet requirements.

An example of a typical fuel shipment schedule for a generating region is illustrated in Table 3. For computational purposes, the reactors within a relatively small geographic area are clustered into a single point source, hence, the terminology of a generating region. The particular generating region selected for this example represents the pressurized-water reactors (PWR) located in North and South Carolina and is composed of 17 reactors plus an additional 14 expansion reactors. The projected spent fuel shipments to a single centralized repository from all domestic reactors are listed in Table 4.

2.3 Transportation and Economic Assumptions

Several transportation and economic parameters must be defined so that optimal shipping patterns and transportation costs can be evaluated. Historically, all of the spent fuel shipments made in the United States have been transported by rail or truck. Since very little attention has been given to barge shipments, and since barge transport is limited to the coastal areas and a few of the major waterways, utilization of barge transportation was not included. Two spent fuel cask designs were defined for this study. All rail shipments are assumed to be transported in a cask similar to an NLI 10/24 rail cask [capacity, 10 PWR or 24 boiling-water reactor (BWR) assemblies]. Truck shipments are assumed to be made using a legal-weight truck cask capable of transporting a single PWR or two BWR assemblies. The transportation assumptions associated with each cask are itemized in Table 5.

These casks were designed to transport short-cooled fuel (120- to 150-day cooled) and to limit the radiation exposure at a point 6 ft from the edge of the vehicle to 10 mrem/hr. In this study, all spent fuel shipped has been cooled for a minimum of 7 years. The surface radiation exposure for these casks has been estimated to be 1.7 mrem/hr; the radiation exposures to the public reported here are based on this level.

Table 3. Spent fuel shipment schedule for a selected generating region

Year	Number of spent fuel assemblies	
	Discharged	Shipped
Prior to 1983	836	
1983	296	
1984	361	
1985	349	
1986	565	
1987	691	
1988	769	
1989	904	
1990	919	296
1991	1117	361
1992	1179	349
1993	1246	565
1994	1306	691
1995	1438	769
1996	1499	904
1997	1565	919
1998	1563	1117
1999	1694	1179
2000	1754	1319
2001	1822	1379
2002	1883	1511
2003	1949	1572
2004	2075	1638
2005	2142	1636
2006	2202	1767
2007	2207	1827
2008	2331	1895
2009	2397	1956
2010	2395	2055

Table 4. Spent fuel shipment schedule for all U.S. reactors

Year	Shipments (MTU)
1990	2,649.3
1991	3,166.3
1992	3,503.4
1993	4,038.9
1994	4,280.5
1995	4,673.8
1996	4,774.5
1997	5,051.7
1998	5,125.0
1999	5,463.1
2000	6,989.3
2001	7,476.0
2002	7,994.0
2003	8,505.2
2004	8,951.0
2005	9,357.0
2006	8,827.1
2007	10,318.7
2008	10,813.4
2009	11,108.7
2010	11,560.3

Table 5. Transportation assumptions

	Rail	Truck
Cask capacity		
PWR Assemblies	10	1
BWR Assemblies	24	2
Shipping weight, lb		
Loaded	220,000	50,000
Empty	200,000	48,300
Cask lease rate, $/day	2500	500
Average transit speed, mph	7	35
Total loading and unloading times, hr	120	72
Cask availability, days/year	300	320

Another factor required to estimate the radiation exposure to the public is the population density along the transportation route. These data are included in the discussion of the various regional repository cases.

The cost correlations currently incorporated in the spent fuel logistics model are based on data collected in mid-1978. All rail shipments are assumed to be made as general commerce (i.e., no special trains are required). The economic impact of special trains could be approximated by including an additional charge of $21/mile. It should be noted that the transportation distances reported for each case represent the total round-trip mileage.

No attempt was made to determine actual transportation routes for the spent fuel shipments. However, transportation distances are estimated by calculating the great-circle distance (crow flight distance) between the reactors and the various repositories and then increasing these distances by 25% for a truck shipment and 33% for a rail shipment.[5]

Whether a particular shipment would be transported by rail or truck was determined by the transportation systems available at the reactor site. All shipments from all reactors having rail service were assumed to be made by rail; shipments from reactors without direct rail service were assumed to be made by truck. Over the period 1990 to 2010, this assumption results in approximately 80% of the spent fuel being shipped by rail. However, the modal mix received at any particular repository is a function of the reactors that will be shipping to that particular facility.

2.4 Modal Assumptions

An important consideration is the optimal modal mix that will minimize the total transportation cost of shipping to the repositories. Since the utility companies would be responsible for paying these costs, they would obviously select the mode of transportation that would minimize the cost to them. On the other hand, the cost of operating the receiving facilities at the repository would be minimized if all shipments were received by rail rather than by truck or by combination of rail and truck.

To determine the modal mix, which would be selected by the utility companies, the costs of making a shipment by a rail or by a truck cask are tabulated in Table 6 as a function of the one-way shipping distance. The data in Table 6 are based on a single shipment for each type of cask. So that the cost data can be compared, the differences in the payloads of the two casks must be considered. Ten truck shipments would be required to move the same amount of PWR fuel as a single rail shipment. Multiplying the truck costs by this ratio, it becomes obvious that all shipments of 50 miles or more would be transported by rail. A similar analysis can be made for shipments of BWR fuel by noting that it would require 12 truck shipments to equal a single rail-cask shipment.

The data reported in Table 6 indicate that the basic modal assumption resulted in the optimal transportation mix for the economic parameters used in this study. However, it must be emphasized that the optimal transportation mode is a function of several parameters such as carrier cost, cask lease rate, average transportation speed, and handling time at either end of the shipment. A change in any of these parameters could have a significant impact on modal considerations. Reference 6 describes the sensitivity of transportation costs as a function of some of the basic transportation parameters.

3. TRANSPORTATION ANALYSIS OF VARIOUS REGIONAL REPOSITORY CONCEPTS

To evaluate the impact of regional repositories on spent fuel transportation, several cases were defined for various regional groupings of reactors. Three cases included only a single, central repository so that a base line could be established for a comparison of other regional breakdowns. Widely scattered single-repository sites were also included so that the sensitivity of the transportation parameters with repository location could be estimated.

Four other cases investigated the transportation requirements for various geographic regions. One of these considers a three-region concept, two others were defined for different five-region concepts, and the last utilizes nine regions.

Table 6. Comparison of rail and truck shipping costs

One-way distance (mile)	Rail[a] ($)			Truck[b] ($)		
	Carrier	Cask lease	Total	Carrier	Cask lease	Total
50	7,634	14,000	21,634	863	1560	2423
100	8,273	15,475	23,748	1076	1620	2696
200	9,467	18,450	27,917	1510	1740	3250
400	11,855	24,400	36,255	2368	1975	4343
600	14,244	30,350	44,594	3227	2215	5442
800	16,653	36,300	52,953	4090	2450	6540
1000	19,084	42,250	61,334	4955	2690	7645
1400	23,881	54,175	78,056	6675	3165	9840

[a]Cost based on a single shipment (10 PWR or 24 BWR assemblies).

[b]Cost based on a single shipment (1 PWR or 2 BWR assemblies).

Three separate logistics runs were made for all multiregion cases. Run A represents only intraregional shipments. It was assumed that sufficient storage capacity would be provided at the reactors to store discharged fuel until the regional repository was opened. In run B, the reactors were allowed to ship to the nearest repository. It was also assumed there would be sufficient storage at the reactors to enable the utility companies to store all fuel until the repository at the optimal site becomes available. This run defines a set of "optimal" regional boundaries for the repository sites. Since the same repository sites are used in runs A and B, the economic impact of predefining arbitrary regional boundaries can be evaluated.

Run C is similar to run B in that each reactor will make shipments to the destination that will minimize its transportation costs; however, it was assumed that sufficient capacity was not available at the reactors to store the spent fuel until the optimal repository is available. In this case, all reactors with fuel cooled for seven or more years will begin making fuel shipments in 1990. Since all repositories are not opened simultaneously in that year, a particular reactor might have to make shipments to a repository other than the closest one. However, shipments will be made to the available repository that will result in the lowest transportation cost. After all repositories are open, runs C and B become identical. The impact of repository opening dates can be evaluated by comparing runs B and C.

In addition to the regional repository cases, several sensitivity runs were also made. In these runs, some of the basic transportation assumptions were changed to evaluate the impact of these variations on transportation costs and cask fleet sizes. A second set of sensitivity runs were made in which the repository opening dates varied.

3.1 Single-Repository Scenarios

The transportation requirements for shipping all the spent fuel to a single repository need to be identified to provide a base point for evaluating the advantages of the regional repository concept. To assess the range of costs that might be encountered for different repository locations, three different runs were made with a different repository site identified for each run. It is important to note that the repository sites are identified solely for the purpose of calculating transportation costs. The use of a particular site does not infer that either the Department of Energy (DOE) or ONWI is considering that site as a possible repository location.

The single-repository sites selected are: (1) central Illinois (Normal, Illinois); (2) Gulf Coast (Minden, Louisiana); and (3) Pacific Northwest (Richland, Washington).

The central Illinois site is located near the centroid of the nuclear generating capacity for the year 1990 and represents the single-repository location that would minimize transportation distances for all U.S. reactors. The Gulf Coast site was selected to represent a repository in a salt dome or bedded salt formation. The cost figures for this location would be typical of a repository located anywhere in the south-central part of the country. The Pacific Northwest site was included because it represents the most remote location from the majority of the nuclear reactors within the continental United States.

The transportation costs, radiation exposure, and transportation distances for the three individual repository sites are summarized in Table 7, and the corresponding cask fleet requirements are listed in Table 8.

As expected, the minimum transportation requirements are associated with the central Illinois location. Utilization of a site in this particular area would minimize the transportation distances from the reactors. Since all of the transportation impacts are assumed to be a function of distance, minimizing the distance will minimize costs, public radiation exposure, and cask fleet size.

Table 7. Transportation summary for single-repository sites

	Central Illinois	Gulf Coast	Pacific Northwest
Transportation cost, \$ x 10^6	1888.7	2305.4	3993.9
Radiation exposure to public, man-rem[a]	24.70	33.22	68.27
Total transportation distance, cask-mile x 10^6			
Rail	44.80	58.20	113.83
Truck	110.87	160.72	359.22

[a]Based on uniform population density of 69 people/sq mile.

Table 8. Cask fleet requirements for single-repository sites

Year	Central Illinois		Gulf Coast		Pacific Northwest	
	Rail	Truck	Rail	Truck	Rail	Truck
1990	20	30	25	34	44	54
1991	24	32	31	36	55	57
1992	27	35	33	40	61	64
1993	34	39	40	45	69	73
1994	36	39	43	45	74	72
1995	40	43	48	51	80	80
1996	41	45	48	53	81	85
1997	44	45	53	53	88	84
1998	44	47	53	55	89	87
1999	48	48	57	57	95	90
2000	61	60	74	70	123	112
2001	66	59	80	70	136	111
2002	72	63	86	74	146	117
2003	78	61	93	72	158	113
2004	83	60	100	71	170	112
2005	87	63	104	74	177	117
2006	93	59	112	70	190	111
2007	99	59	119	70	202	110
2008	105	63	125	74	211	117
2009	108	61	129	71	219	113
2010	113	63	134	75	227	118

The impact of using a different repository site depends on the particular site being considered. Placing a repository in the southern part of the United States (e.g., the Gulf Coast region) would increase transportation costs by approximately 22%, increase the cask fleet requirements by approximately 19%, and increase the radiation exposure by 34%. If a more remote location (e.g., the Pacific Northwest) was considered, the transportation requirements would be approximately doubled. A more detailed analysis of the actual geographic population distribution would probably show that the radiation exposure for shipments to the Pacific Northwest site, as shown in Table 7, are being overestimated. Although the transportation distances increase significantly for this site, most of the increase is associated with the portion of the shipment in the western part of the country where the population density is significantly less than 69 people/sq mile (see Table 7).

3.2 Three-Region Case

In this case, the country was divided into three regions and a repository site was selected within each region. Each region is named for its general geographical location (northeast, southeast, and west), and the geographical boundaries of the regions are shown in Fig. 1. Regional repository sites (defined for the purpose of calculating transportation information) are listed in Table 9. Each of the repositories is to be opened at a different date. The western repository was assumed to be opened in 1990 and the southeastern and northeastern repositories follow in 1993 and 1995 respectively. All repositories are assumed to remain open through the year 2010.

As shown in Table 10, there is approximately an equal amount of nuclear generation capacity in each region. In the year 2000, 34% of the generating capacity is in the northeast region, 30% in the southeast region, and 36% in the western region. Due to the geographical distribution of the nuclear reactors and the desire to define regions with approximately equal generating capacity, the western region encompasses the entire area west of the Mississippi River plus the states of Wisconsin and Illinois (Fig. 1).

Fig. 1. Boundaries for the three-region case.

Table 9. Repository locations for three-region case

Region	Location[a]	Latitude	Longitude	Population density (per sq mile)	Opening date
Northeast	Youngwood, PA	40.21	79.50	208	1995
Southeast	Waynesboro, GA	33.30	81.80	86	1993
West	Byers, CO	39.60	104.00	37	1990

[a]Repository sites are identified solely for the purpose of calculating transportation data. The identification of a particular site does not imply that either the DOE or OWNI is considering a repository in that vicinity.

Table 10. Regional nuclear generating capacity for three-region case

Year	Capacity (GW)		
	Northeast	Southwest	West
1980	24.0	25.7	22.5
1985	42.6	50.7	48.4
1990	61.0	60.8	57.5
1995	83.0	78.8	88.5
2000	109.0	96.8	119.5
2005	125.0	112.8	142.5
2010	138.0	122.8	158.5

The amount of fuel shipped to each repository over the time period of 1990 to 2010 for each of the three runs is shown along with the other transportation data in Tables 11 and 12.

In run A, all shipments were made to the repository sited within the same region as the reactor making the shipment. The transportation data are summarized on a regional basis for this run in Fig. 2. An approximately equal amount of fuel would be shipped to each repository since the distribution of fuel being shipped to the repositories almost equals the regional distribution of nuclear generating capacity.

However, the regional transportation costs do not show a similar distribution. Due to the size of the western region, the average shipping distance to the western repository is significantly larger than to the other repositories. The transportation distances for rail shipments to the western repository make up almost 70% of the total rail transportation distance. Although the western reactors generate only 35% of the spent fuel shipments, they would have to pay almost 50% of the total transportation costs.

Table 11. Transportation data for three-region case

	Run A	Run B	Run C
Inventory, metric tons of uranium			
Northeast	49,178	68,452	60,093
Southeast	45,069	43,111	43,942
West	51,381	34,065	41,593
Transportation cost, $\$ \times 10^6$	1505.4	1437.7	1545.7
Radiation exposure to public, man-rem	20.89	19.32	22.43
Total transport distance, cask-mile $\times 10^6$			
Rail	32.92	30.21	33.13
Truck	61.60	57.72	74.79
Fraction of fuel received by rail, wt %			
Northeast	69.1	73.8	74.5
Southeast	73.4	75.2	75.5
West	94.5	95.8	90.6

Table 12. Cask fleet requirements for three-region case

	Run A		Run B		Run C	
Year	Rail	Truck	Rail	Truck	Rail	Truck
1990	10	5	6	3	30	41
1991	13	5	7	3	37	44
1992	14	5	8	3	41	48
1993	23	20	18	17	31	36
1994	25	19	19	16	33	37
1995	33	36	31	35	31	35
1996	34	38	32	37	32	37
1997	36	38	34	37	34	37
1998	36	38	34	38	34	38
1999	39	40	37	39	37	39
2000	54	58	53	58	48	49
2001	58	58	57	57	52	48
2002	62	60	61	60	56	51
2003	68	59	66	59	61	50
2004	71	58	70	58	65	49
2005	75	60	73	60	68	51
2006	80	58	78	58	73	49
2007	85	57	82	57	77	48
2008	88	59	86	60	81	51
2009	91	59	89	59	84	50
2010	95	61	92	60	87	51

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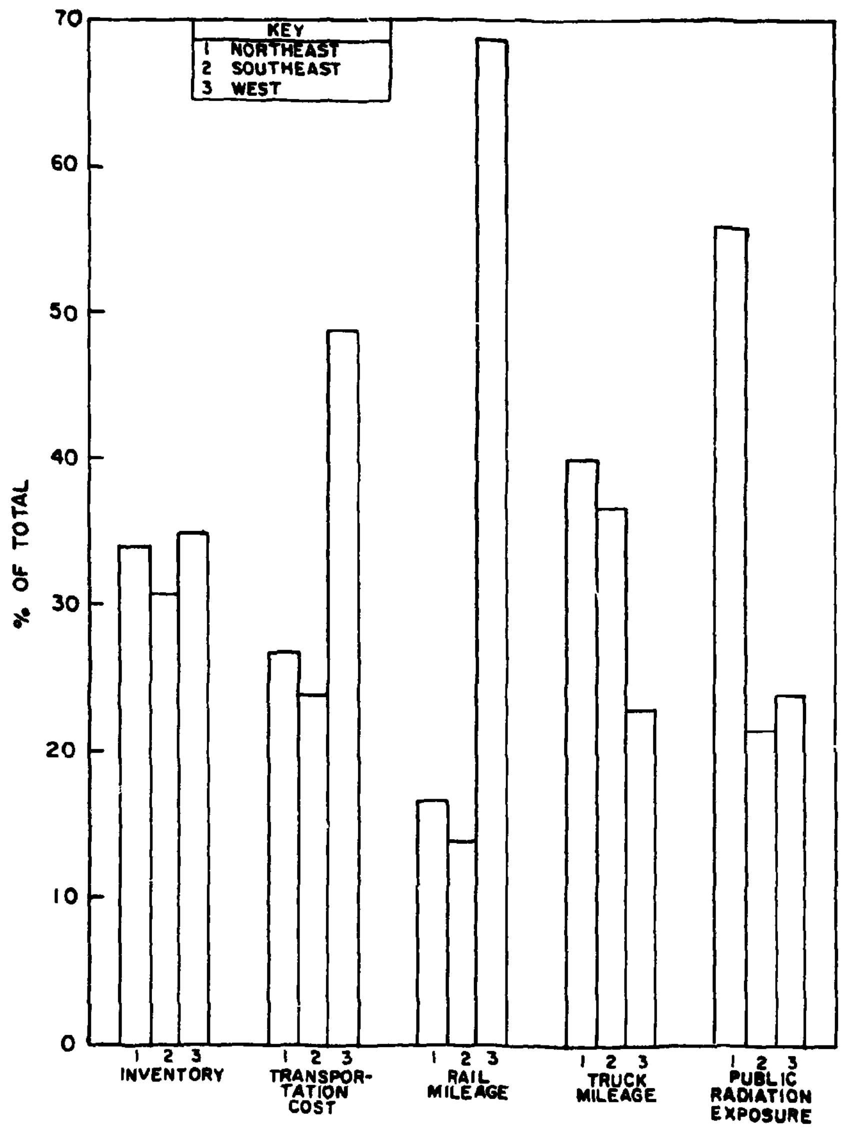

Fig. 2. Regional distribution of transportation parameters for the three-region case: run A.

Most of the radiation exposure (approximately 56%) is associated with the shipments in the northeastern region. This is due to the much higher population density and to the higher percentage of truck shipments in that section of the country.

Run B represents the situation in which the fuel shipments are routed to the destinations that would minimize transportation costs. Looking at the optimal destinations for each reactor, a new set of regional boundaries (transportation boundaries are shown in Fig. 3) can be drawn for the same set of repositories. It should be noted that in Fig. 3 the symbols used to denote the reactor locations also denote the original regional definitions. The major change in the regional boundaries has been a shift of the eastern boundary of the western region where the reactors in Wisconsin, Iowa, and Illinois have been moved into the northeastern region. The southeastern region remains essentially the same. The regional transportation data for run B are shown in Fig. 4. Moving the regional boundaries results in a larger percentage of the fuel being shipped to the northeastern repository. The amount of fuel shipped to the western repository was reduced by a corresponding percentage. The western region still has a higher average transportation cost than the other regions: that is, 24% of the fuel shipments, and 34% of the total transportation costs. The rail transportation mileage is still predominately in the western region but the skewness of the distribution is not as pronounced as for run A.

A comparison of the total cost for runs A and B shows that the original regional definitions resulted in a cost penalty of $\$67.7 \times 10^6$, but this is only 4.7% higher than the optimal cost. The cask fleet requirements for the optimal transportation run (run B) are significantly lower than run A between 1990 and 1995; however, after 1995, when all repositories are open, the differences in cask fleet size are relatively small.

Run C is a measure of the impact of limited reactor storage and of repository opening dates. All reactors with fuel cooled ≥7 years begin fuel shipments in 1990 for this run. Because all repositories are not open in that year, shipments to repositories other than the closest are utilized. As various regional repositories begin operation, shipments

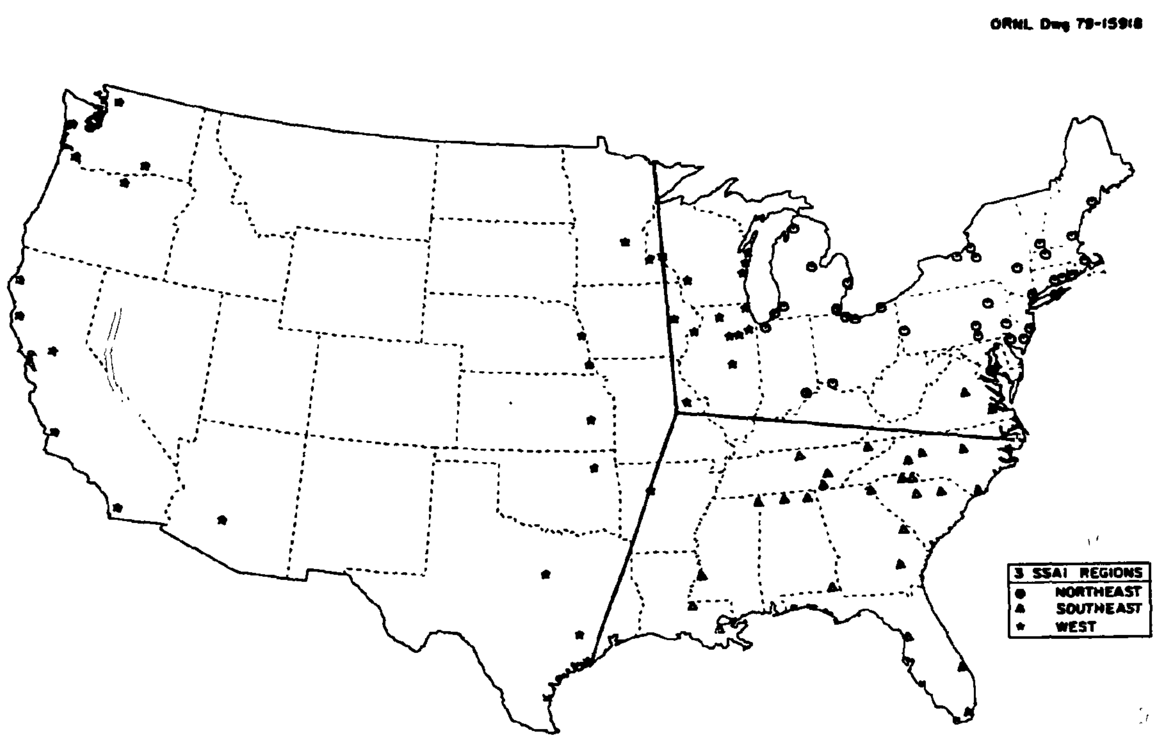

Fig. 3. Optimal transportation boundaries for the three-region case.

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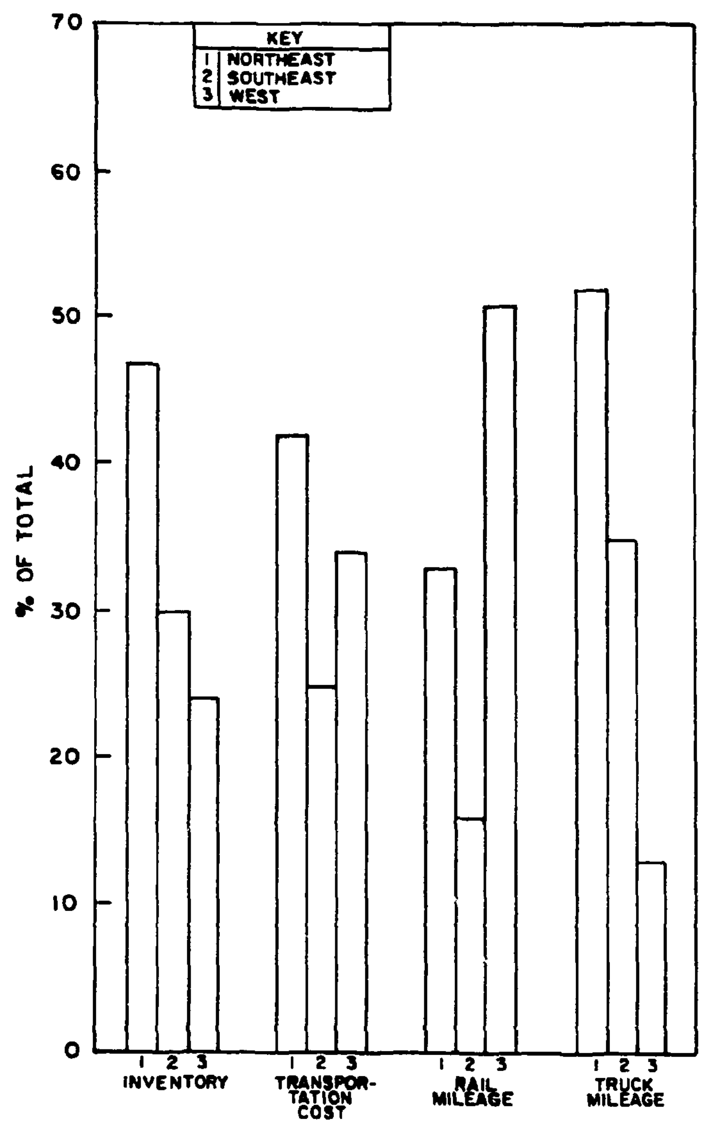

Fig. 4. Regional distribution of transportation parameters for the three-region case: run B.

are made to those that result in the lowest transportation cost. After all repositories are open, run C becomes nearly identical to run B. The repository opening schedule was assumed to be: western, 1990; southeastern, 1993; and northeastern, 1995. Hence, in 1990 all reactors make fuel shipments to the western repository. Starting in 1993, each reactor has a choice of destinations. They can ship either to the western or the southeastern repository. Again, the criteria of minimizing transportation costs determine which destination will be selected.

The transportation data for this run are summarized in Fig. 5. A larger amount of fuel is stored in the western repository in this run as compared to run B because it is the only repository available between 1990 and 1992. The amount of fuel stored at the southeastern repository remains essentially constant since the amount of fuel being shipped from the southeast to the west between 1990 and 1992 balances the shipments from the northeast to the southeast between 1993 and 1994.

The regional distribution of transportation parameters for run C are not directly comparable to those reported for runs A and B. The data reported in all cases represent shipments received at a particular regional repository. In runs A and B, all shipments are intraregional shipments even though the regional definitions are different. In run C, shipments cross the regional boundaries until all repositories are open. Hence, some of the regional impacts include shipments from other sections of the country.

The total transportation cost for run C was $\$108 \times 10^6$, or 7.5% higher than for run B. This difference represents a penalty that would be incurred by shipping to a more distant repository in the early part of the study period rather than continued storage of fuel at the reactors until a closer repository opens. The actual difference between runs B and C is somewhat less than stated above, because the cost of providing sufficient storage capacity at the reactors has not been estimated.

Regional radiation exposures are not reported for runs B and C. In these runs, shipments cross the regional boundaries defined for run A and

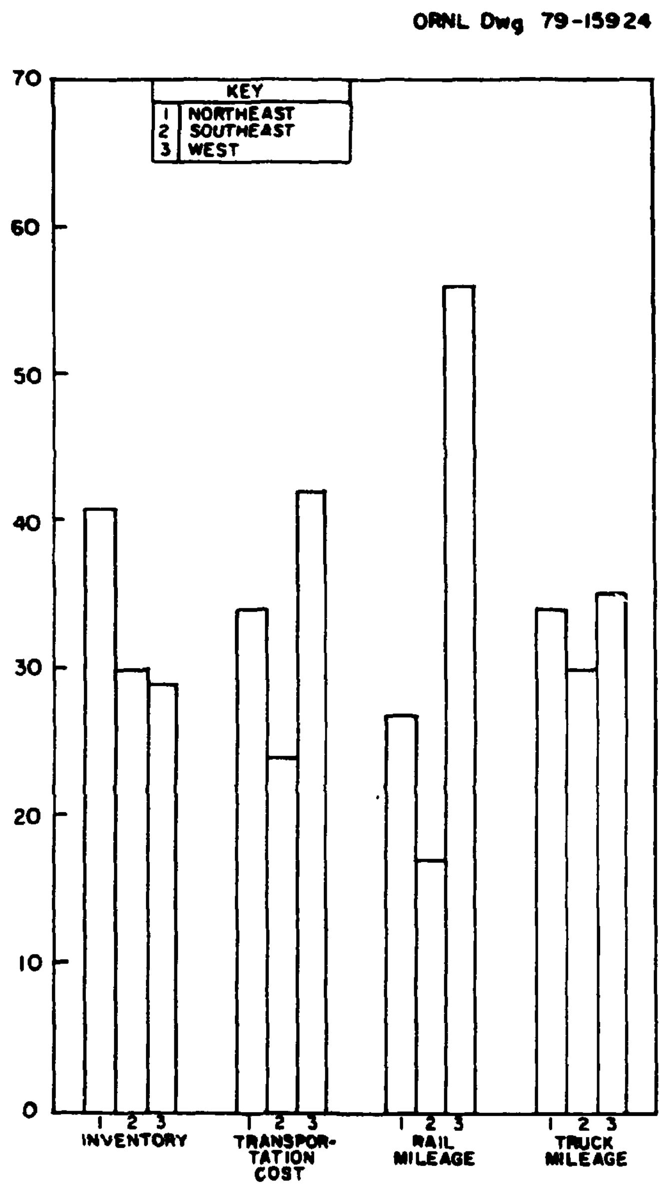

Fig. 5. Regional distribution of transportation parameters for the three-region case: run C.

population densities were not available for runs B and C. However, the total radiation exposures for the entire United States are estimated and reported in Table 11.

Cask fleet requirements, which are summarized in Table 12, are significantly higher for run C between 1990 and 1994. This increase results from the requirement that all shipments start in 1990. As an additional repository opens in 1993, the cask fleet requirements are reduced. This additional repository, which is located in the southeastern part of the country, is nearer to most of the reactors and results in a reduction of the average transportation distance. Another small reduction in the cask fleet requirements occurs in 1995 when the third repository opens.

Between 2000 and 2010, the cask fleet requirements for run C are less than for runs A and B. In run C, fuel is not stored at the reactors between 1990 and 1994 while waiting for a nearby repository to open; therefore, the annual fuel shipments between 2000 and 2010 are less than for runs A and B.

In runs A and B, a larger inventory of long-cooled spent fuel is stored at the reactors than in run C. This fuel is assumed to be shipped between 2000 and 2010, which results in the higher shipping rates in runs A and B.

3.3 Five-Region Case (SSAI)

A case study was made in which the country was divided into five regions. This particular set of regional definitions was proposed by SSAI and, for convenience, it will be referred to as the SSAI five-region case.

The regional definitions are outlined in Fig. 6. The three regions in the eastern part of the country (northeast, southeast, and upper mid-west) encompass a reasonably compact geographical area. The arbitrary division between the Southeast and Gulf Coast regions across the states of Mississippi and Alabama was made to include the entire TVA system in

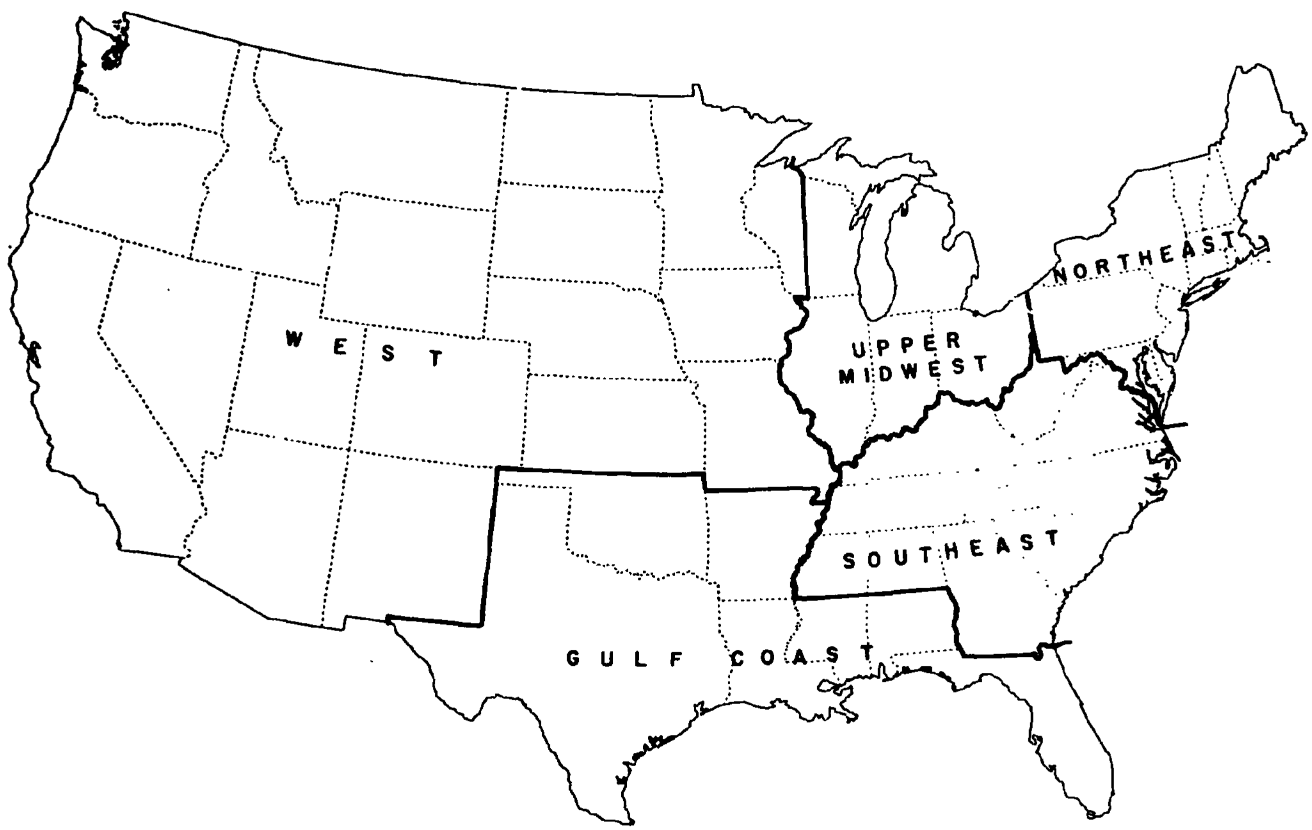

Fig. 6. Regional boundaries for the SSAI five-region case.

the southeast region. The Gulf Coast region is a rather elongated region stretching from Florida to Texas. Again, due to sparsity of nuclear reactors in the west, the western region includes approximately one-half of the country.

The repository sites used to calculate the transportation data for this case are summarized in Table 13.

Table 14 lists the nuclear generating capacity in each of the regions. With the exception of the Gulf Coast region, the generating capacity is spread almost uniformly over the regions. In the year 2000, the relative distribution is as follows:

Northeast	19.8%
Southeast	25.0%
Upper Midwest	21.8%
Gulf Coast	14.3%
West	19.1%

By the year 2010, the Southeast and the Upper Midwest become the dominant regions. The transportation impact of the three runs is displayed in Tables 15 and 16.

Run A represents only intraregional shipments within the SSAI boundaries. The regional distribution of the transportation data for this run is summarized in Fig. 7. An equal amount of fuel is being shipped to the repositories located in the Northeast, Southeast, and Upper Midwest. Lesser amounts are shipped to the Gulf Coast and western repositories. The distribution of fuel shipped to the various repositories is essentially the same as the distribution of generating capacity. In general, the regional distribution of transportation cost is approximately the same as that for the fuel shipments. The biggest exception is the western region where approximately 29% of the total transportation cost is associated with only 18% of the total shipments. Due to the large geographical area included in the western region, the average shipping distance in this region is much longer than for the other regions. Approximately 52% of the total rail mileage required to make all the shipments is associated with shipments to the western repository. Rail shipments to any of the other repositories do not require over 15% of the total rail mileage.

Table 13. Repository locations for SSAI five-region case

Region	Location[a]	Latitude	Longitude	Population density (per sq mile)	Opening date
Northeast	New Palte, NY	41.72	74.09	208	1990
Southeast	Franklin, NC	35.62	82.76	89	1993
Upper Midwest	Hammond, IN	41.31	87.50	165	1992
Gulf Coast	Rayville, LA	32.52	92.00	53	1996
West	Granger, WY	41.39	110.00	29	1994

[a]Repository sites are identified solely for the purpose of calculating transportation data. The identification of a particular site does not imply that either the DOE or ONWI is considering a repository in that vicinity.

Table 14. Distribution of nuclear generating capacity for SSAI five-region case

Year	Regional capacity (GW)				
	Northwest	Southeast	Upper Midwest	Gulf Coast	West
1980	18.2	22.8	14.9	6.1	10.4
1985	29.0	42.3	28.2	17.4	24.8
1990	40.5	51.4	36.8	18.5	32.1
1995	50.5	67.4	53.8	31.5	47.1
2000	64.5	81.4	70.8	46.5	62.1
2005	70.5	95.4	82.8	53.5	78.1
2010	76.5	103.4	92.8	60.5	86.1

Table 15. Transportation data for SSAI five-region case

	Run A	Run B	Run C
Inventory, metric tons of uranium			
Northeast	32,351	32,351	37,016
Southeast	37,348	41,209	39,318
Upper Midwest	31,176	37,575	38,384
Gulf Coast	18,484	15,716	13,541
West	26,270	18,778	17,370
Transportation costs, $\$ \times 10^6$	1197.2	1140.6	1205.8
Radiation exposure to public, man-rem	15.04	13.51	15.36
Total transport distance, cask-mile $\times 10^6$			
Rail	20.43	18.03	20.47
Truck	44.51	42.15	47.39
Fraction of fuel received by rail, wt %			
Northeast	57.6	57.6	60.2
Southeast	74.9	71.0	72.5
Upper Midwest	90.6	92.2	91.4
Gulf Coast	86.0	100.0	100.0
West	94.6	92.4	93.2

Table 16. Cask fleet requirements for SSAI five-region case

Year	Run A		Run B		Run C	
	Rail	Truck	Rail	Truck	Rail	Truck
1990	2	9	2	9	26	30
1991	3	9	3	9	32	31
1992	6	12	8	12	24	31
1993	11	25	12	28	28	32
1994	20	26	19	30	24	30
1995	23	29	21	33	26	33
1996	26	35	24	35	24	35
1997	27	35	26	34	26	34
1998	27	35	26	35	26	35
1999	30	37	29	37	29	37
2000	43	50	40	50	36	45
2001	47	51	44	49	39	45
2002	50	53	47	52	43	48
2003	54	52	51	50	46	46
2004	57	51	54	50	50	45
2005	60	53	57	52	52	48
2006	64	51	60	49	56	45
2007	68	50	63	49	59	45
2008	71	53	66	52	62	48
2009	74	52	69	50	65	46
2010	76	53	71	52	67	48

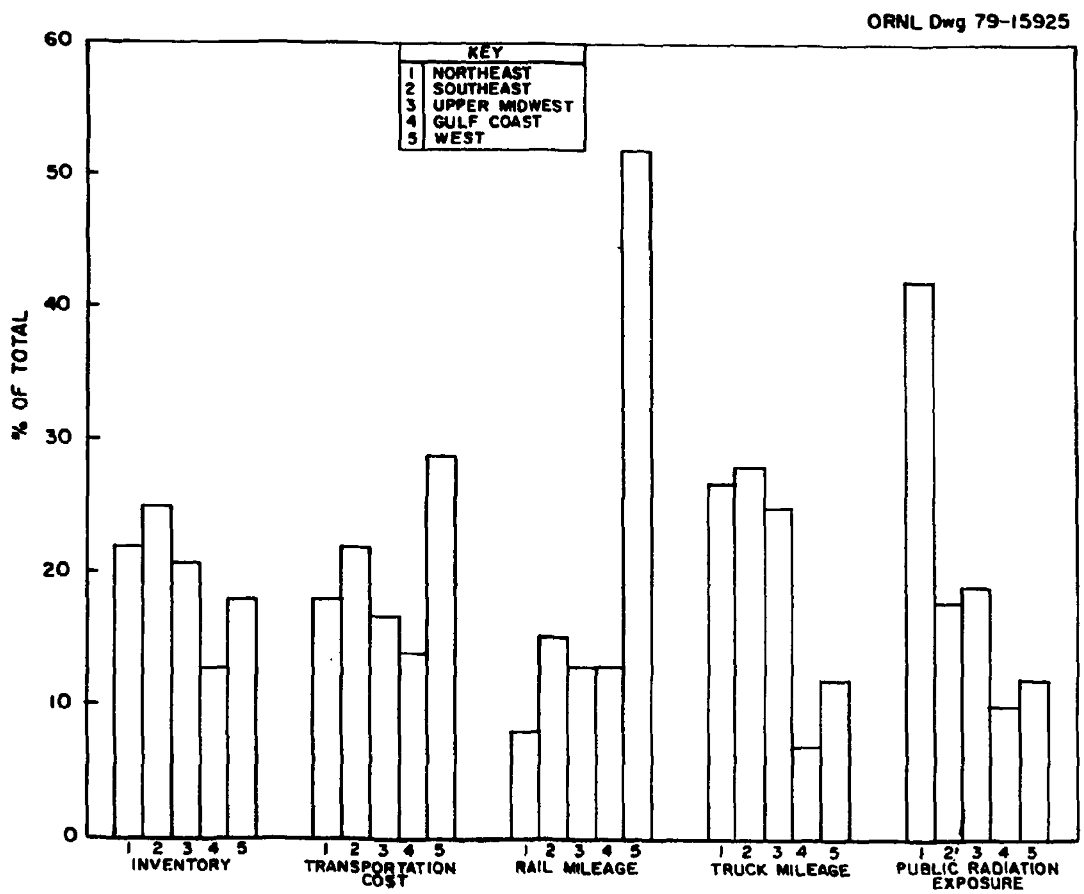

Fig. 7. Distribution of transportation parameters for the SSAI five-region case: run A.

The major portion of the truck mileage (80%) is associated with the shipments to the northeast, southeast, and Gulf Coast repositories. Most of the reactors requiring truck shipments are located in the northeast or southeast regions. Truck shipments from the reactors located in Florida account for the large amount of truck mileage to the Gulf Coast repository.

The largest contributors to the total public radiation exposure are the shipments to the northeastern repository. Two factors, high population density and the large number of truck shipments, are the main reasons for the relatively high population dose. By comparison, shipments to the upper midwest repository contribute only about 50% as much to the population exposure as do shipments to the northeast repository. For each of these regions, the total amount of fuel shipped, the average shipping distance, and the population density are approximately equal. However, about 43% of the fuel shipped to the northeast repository is transported by truck. On the other hand, approximately 91% of the fuel shipments to the upper midwest repositories arrive by rail.

The same set of repository locations were used in run B, but, instead of using the SSAI regional definitions, the destinations that would minimize transportation costs were calculated. By comparing which reactors ship to the individual repositories, a set of optimal transportation regional boundaries (shown in Fig. 8) can be identified. Comparing Figs. 6 and 8, it becomes obvious that a significant change has occurred in many of the regional boundaries. The northeast region remains essentially the same. The southeast region now includes the state of Florida, which formerly was in the Gulf Coast region. The biggest change is in the upper midwest region where the optimal western boundary is now located to include western Wisconsin, Minnesota, Iowa, Nebraska, and Missouri. Reactors in these states were formerly defined to be in the western region.

The total transportation costs for run B (Table 15) are only $\$57 \times 10^6$ less than that observed for the original regional boundaries. This represents a difference of only 4.7%. The cask fleet requirements for run B during the later part of the study period (Table 16) are reduced by about

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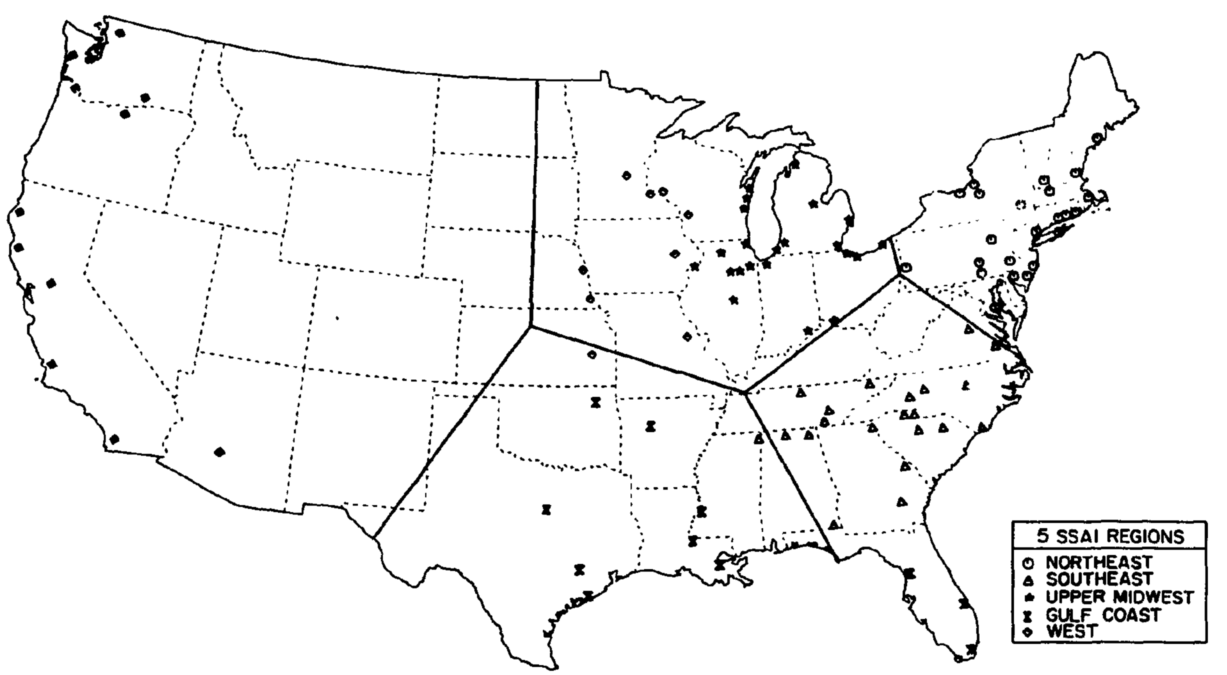

Fig. 8. Optimal transportation boundaries for the SSAI five-region case.

three to five rail casks and one to two truck casks from the fleet sizes calculated for run A. Between 1993 and 1994, the cask fleet sizes for run B exceed those predicted for run A. This increase is caused by the different regional definitions generated in run B. The reactors that move from the western region to the upper midwest and from the Gulf Coast to the southeast ship fuel at an earlier date in run B than in run A. The increased shipping schedule increases the cask fleet requirements during these years.

A regional breakdown of the transportation data is shown in Fig. 9. The regional distribution of fuel shipments and transportation costs correspond to the generating capacity located within the new optimal transportation boundaries. The western region still pays a higher percentage of the transportation costs relative to the percentage of fuel shipments within that region (21% of cost for 13% of shipments). This is essentially the same ratio that was observed in run A.

More than one-half of the truck mileage is now associated with shipments to the southeastern repository. This increase is being caused by the reactors in Florida which require truck shipments that are now included in the southeastern region. Notice that for run B no truck shipments were made to the Gulf Coast repository.

Run C represents the shipping scenario in which shipments from all reactors begin in 1990, and the opening dates of the various repositories are shown in Table 13. In all years, all shipments are directed to the optimal destination among the repositories that are open. The total transportation cost for this case (Table 15) is approximately 6% higher than for case B. The regional distribution of the transportation parameters is shown in Fig. 10. The repository located in the Northeast (which was the first to open) shows an increase in fuel shipments, transportation costs, etc.

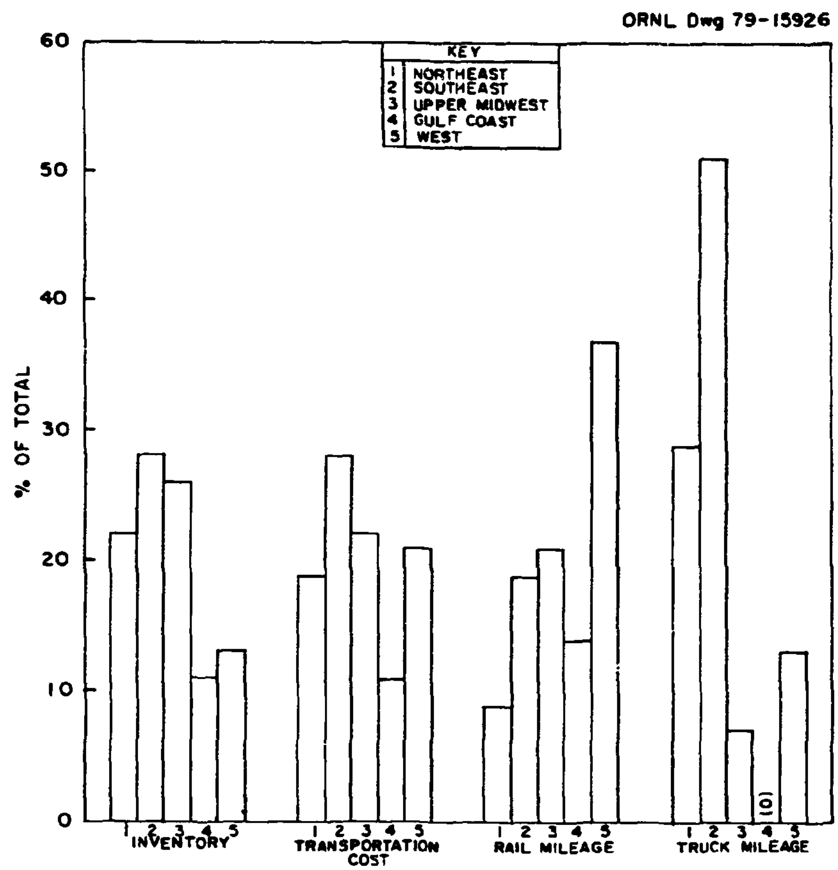

Fig. 9. Regional distribution of transportation parameters for the SSAI five-region case: run B.

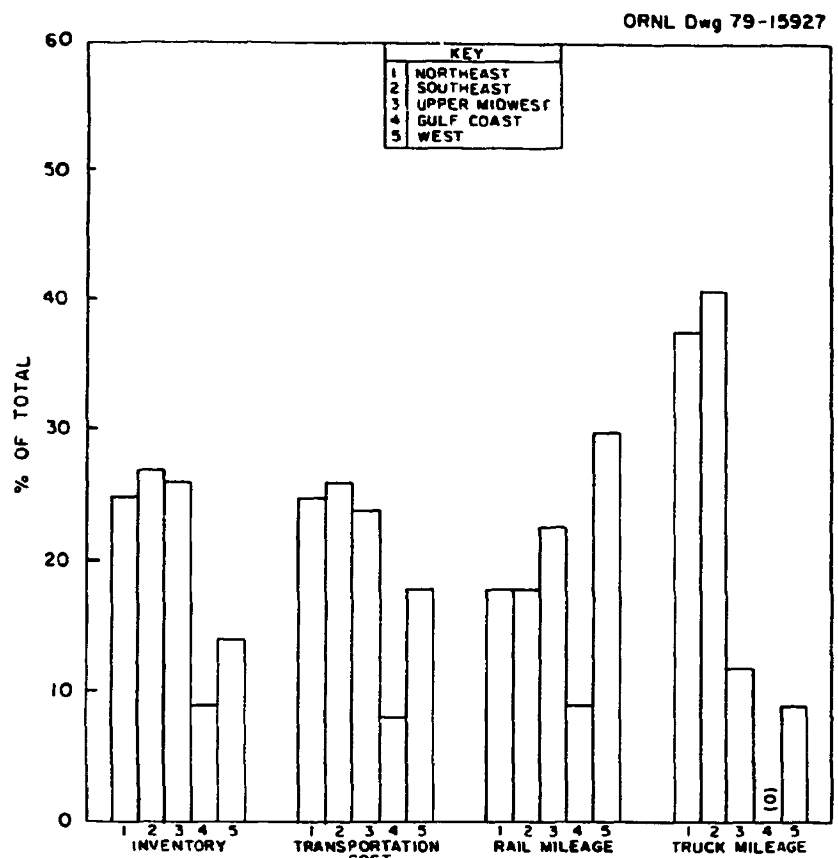

Fig. 10. Regional distribution of transportation parameters for the SSAI five-region case: run C.

3.4 Nuclear Regulatory Commission Five-Region Case

A second five-region case was studied in which the regional boundaries were defined to be identical to the Nuclear Regulatory Commission (NRC) administrative districts. The approximate boundaries of the NRC regions are shown in Fig. 11. Each region is named for the NRC district office in that region (i.e., King of Prussia, Atlanta, Glen Ellyn, Arlington, and Walnut Creek). The repository sites, defined for calculating transportation information, are listed in Table 17.

Table 18 contains a listing of the nuclear generating capacity by NRC regions. The distribution of capacity is not uniform; for example, the Atlanta region contains approximately three times the capacity of the Arlington region. In the year 2000, the projected relative percentages of generating capacity are as follows:

King of Prussia	19.8%
Atlanta	31.5%
Glen Ellyn	25.5%
Arlington	9.0%
Walnut Creek	14.2%

Three separate runs were again made for this regional definition and the results of the calculations are summarized in Tables 19 and 20.

Run A represents the scenario in which all shipments are made to the repository within the same NRC region as the reactor. A regional breakdown of the transportation parameters is shown in Fig. 12. The amount of fuel shipped to each repository corresponds closely to the regional distribution of nuclear generating capacity. The three eastern repositories (King of Prussia, Atlanta, and Glen Ellyn) receive approximately 80% of the fuel shipments. The distribution of transportation costs is very similar to the storage distribution. For the NRC regions, the westernmost region (Walnut Creek) contains only the reactors along the West Coast and the state of Arizona. In this run, the relatively large imbalance between transportation costs and fuel shipments identified in Sects. 3.2 and 3.3 does not occur.

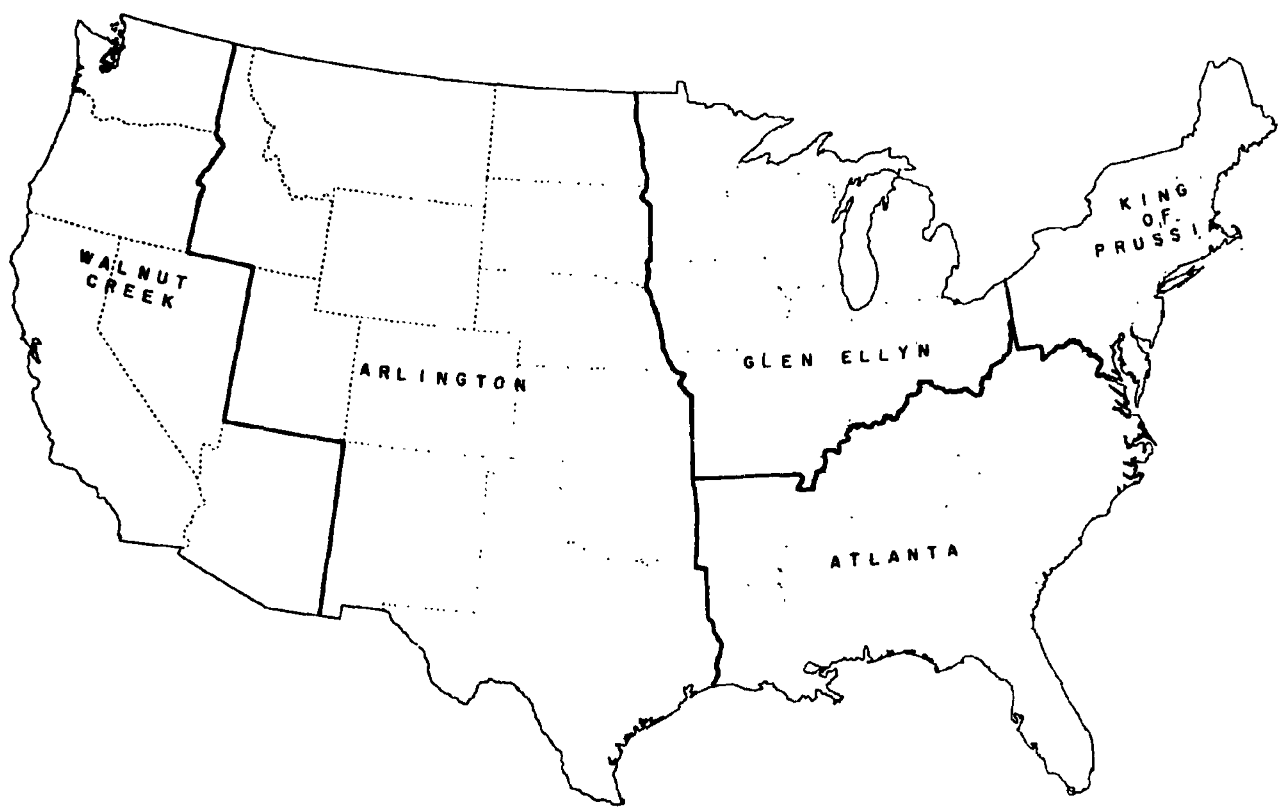

Fig. 11. Regional boundaries for the NRC five-region case.

Table 17. Repository locations for NRC five-region case

Region	Location[a]	Latitude	Longitude	Population density (per sq mile)	Opening date
King of Prussia	Poughkeepsie, NY	41.77	73.73	273	1990
Atlanta	Greenville, SC	34.87	82.35	80	1993
Glen Ellyn	Joliet, IL	41.46	88.12	123	1992
Arlington	Chickasha, OK	35.02	97.88	20	1996
Walnut Creek	Carson City, NV	39.14	119.70	50	1995

[a] Repository sites are identified solely for the purpose of calculating transportation data. The identification of a particular site does not imply that either the DOE or ONWI is considering a repository in that vicinity.

Table 18. Distribution of nuclear generating capacity for NRC five-region case

Year	Regional capacity (GW)				
	King of Prussia	Atlanta	Glen Ellyn	Arlington	Walnut Creek
1980	18.3	27.7	17.6	2.0	6.9
1985	29.1	52.5	33.2	9.2	17.8
1990	40.6	61.6	42.9	10.3	24.0
1995	50.6	82.6	62.9	19.3	35.0
2000	64.6	102.6	82.9	29.3	46.0
2005	70.6	119.6	97.9	36.3	56.0
2010	76.6	130.6	109.9	40.3	62.0

Table 19. Transportation data for NRC five-region case

	Run A	Run B	Run C
Inventory, metric tons of uranium			
King of Prussia	32,351	32,351	37,117
Atlanta	47,091	41,209	39,318
Glen Ellyn	36,923	36,923	38,261
Arlington	10,485	16,367	14,064
Walnut Creek	18,778	18,778	16,808
Transportation costs, $\$ \times 10^6$	1109.1	1097.6	1174.3
Radiation exposure to public, man-rem	14.43	14.05	16.53
Total transport distance, cask-mile $\times 10^6$			
Rail	16.94	16.48	19.33
Truck	38.91	38.91	45.44
Fraction of fuel received by rail, wt %			
King of Prussia	57.6	57.6	60.3
Atlanta	74.6	71.0	72.6
Glen Ellyn	92.1	92.1	91.2
Arlington	100.0	100.0	100.0
Walnut Creek	92.4	92.4	93.3

Table 20. Cask fleet requirements for NRC five-region case

Year	Run A		Run B		Run C	
	Rail	Truck	Rail	Truck	Rail	Truck
1990	2	9	2	9	26	30
1991	3	9	3	9	32	32
1992	8	12	8	12	24	31
1993	14	28	12	29	27	32
1994	15	28	13	28	30	31
1995	21	32	20	32	25	32
1996	24	35	23	35	23	35
1997	25	34	25	34	25	34
1998	25	35	25	35	25	35
1999	28	36	28	36	28	36
2000	39	49	39	49	35	45
2001	43	48	42	48	38	44
2002	46	51	46	51	41	47
2003	49	49	49	49	44	45
2004	52	49	52	49	47	45
2005	55	51	55	51	50	47
2006	59	48	58	49	53	44
2007	62	48	61	48	57	44
2008	65	51	64	51	60	47
2009	67	49	66	49	62	45
2010	69	51	69	51	64	47

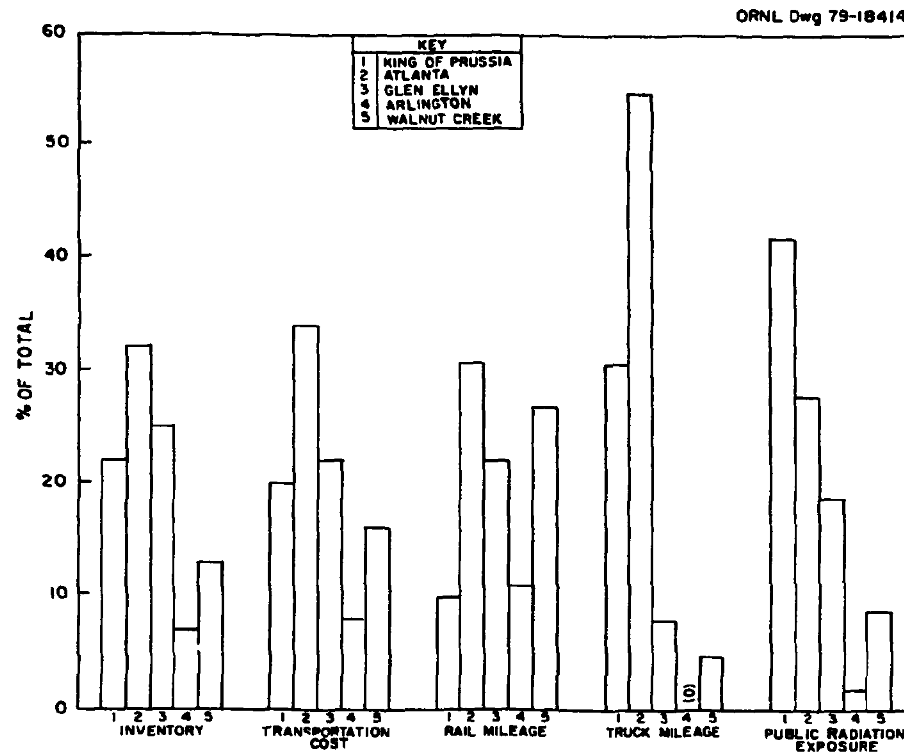

Fig. 12. Regional distribution of transportation parameters for NRC five-region case: run A.

The regional distributions of transportation distance for both rail and truck shipments are approximately as anticipated, considering the amount of fuel being shipped and the regional modal mix being utilized. Most of the reactors utilizing truck shipments are located in the King of Prussia and Atlanta regions and account for the large percentage of truck mileage (∿87%) associated with these two regions. Because the Arlington region contains only reactors utilizing rail transport, no truck casks would be received at that facility.

Most (∿89%) of the radiation exposure to the general public is associated with shipments to the three eastern repositories. The King of Prussia and Glen Ellyn regions have the highest population density, and the King of Prussia region also transports approximately 42% of fuel by truck. The Atlanta region, while having a lower population density (80 persons/sq mile), handles approximately 32% of the total fuel shipments and 25% of these shipments are made by truck.

The optimal transportation boundaries for the same set of repository locations are evaluated in run B. These boundaries are shown in Fig. 13. Although the transportation boundaries appear significantly different than the original NRC boundaries (Fig. 11), only a few reactors are actually being placed in a different region. The major change is the movement of the reactors in western Mississippi, Arkansas, and Louisiana from the Atlanta region to the Arlington region. The definition of the other regions remains essentially the same. The total transportation cost for run B was $\$1097.6 \times 10^6$, which was only $\$11.5 \times 10^6$ (∿1%) less than run A. The other transportation parameters, transportation distances, and cask fleet requirements (Table 20) are essentially identical to the data calculated in run A. For the repository sites identified, the NRC regions correspond very closely to the optimal transportation patterns.

The regional distribution of the transportation data for run B is shown in Fig. 14. Again, there is very little difference between runs A and B except for minor shifts between the Atlanta and Arlington regions.

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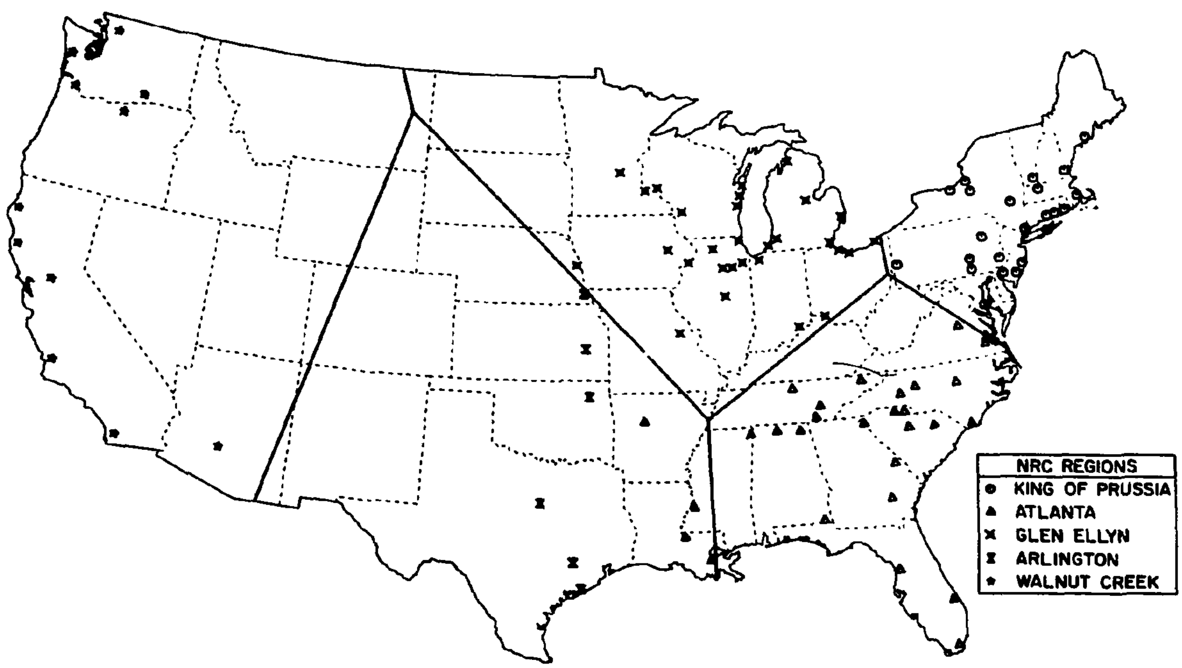

Fig. 13. Optimal transportation boundaries for the NRC five-region case.

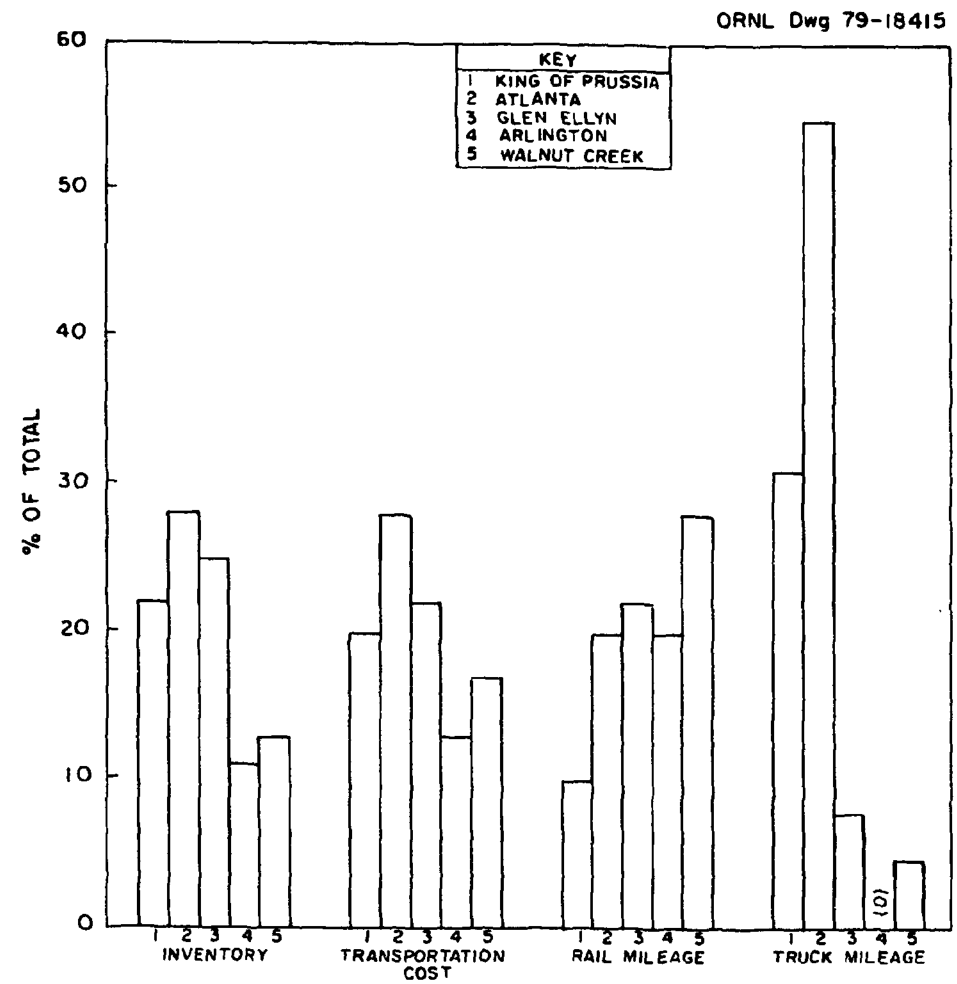

Fig. 14. Regional distribution of transportation parameters for the NRC five-region case: run B.

Including the effects of repository opening dates, run C increased the transportation cost by approximately 7%. As shown in Fig. 15, somewhat more fuel is received at the repositories located in the King of Prussia and Glen Ellyn regions because these repositories are to be opened before the others. However, most parameters are changed by only a few percent. The biggest difference is the amount of truck traffic arriving at the King of Prussia repository. In the other runs, most of the truck shipments were in the Atlanta region. However, for run C, all of these shipments are sent to the King of Prussia repository in 1990 and 1991. In 1992, there is an approximately equal division of truck shipments between the King of Prussia and Glen Ellyn repositories. After 1992, the Atlanta regional repository is open and all truck shipments from reactors in this region go to the local regional repository. The portion of the truck distance required to transport fuel to the Atlanta repository was reduced from 55% in run B to 43% in run C.

3.5 NERC Nine-Region Case

The fifth case studied included nine repository regions in which the regional boundaries are based on the National Electric Reliability Council (NERC) regions. These regions were identified previously in Sect. 2.1. (see Table 1). The geographical area covered by the individual NERC regions is shown in Fig. 16, some of which extend into Canada. However, for purposes of this study, only the domestic nuclear reactors were considered. The repository site defined for calculating the transportation costs are listed in Table 21.

The distribution of nuclear generating capacity among the NERC regions is shown in Table 22. The largest region is the SERC region, which is located in the southeastern part of the country. The next largest regions are the ECAR (upper midwest) and WSCC (western) regions. With the exception of the MARCA region, the remaining capacity is spread almost uniformly among the other regions. In the year 2000, the projected nuclear capacity is distributed among the NERC regions as follows: ECAR, 14.2%; ERCOT, 6.2%; MAAC, 9.2%; NPCC, 10.1%; MARCA, 3.0%; MAIN, 9.1%; SERC, 26.8%; SPP, 7.3%; WSCC, 14.1%. The general transportation summary of the three individual runs is contained in Tables 23 and 24.

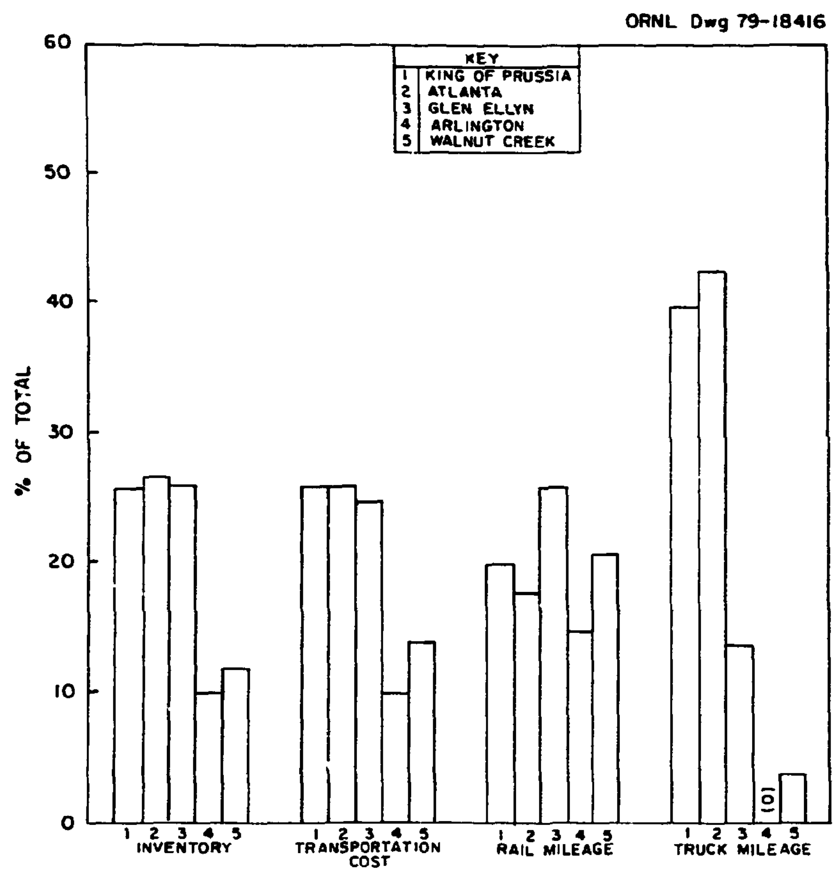

Fig. 15. Regional distribution parameters for the NRC five-region case: run C.

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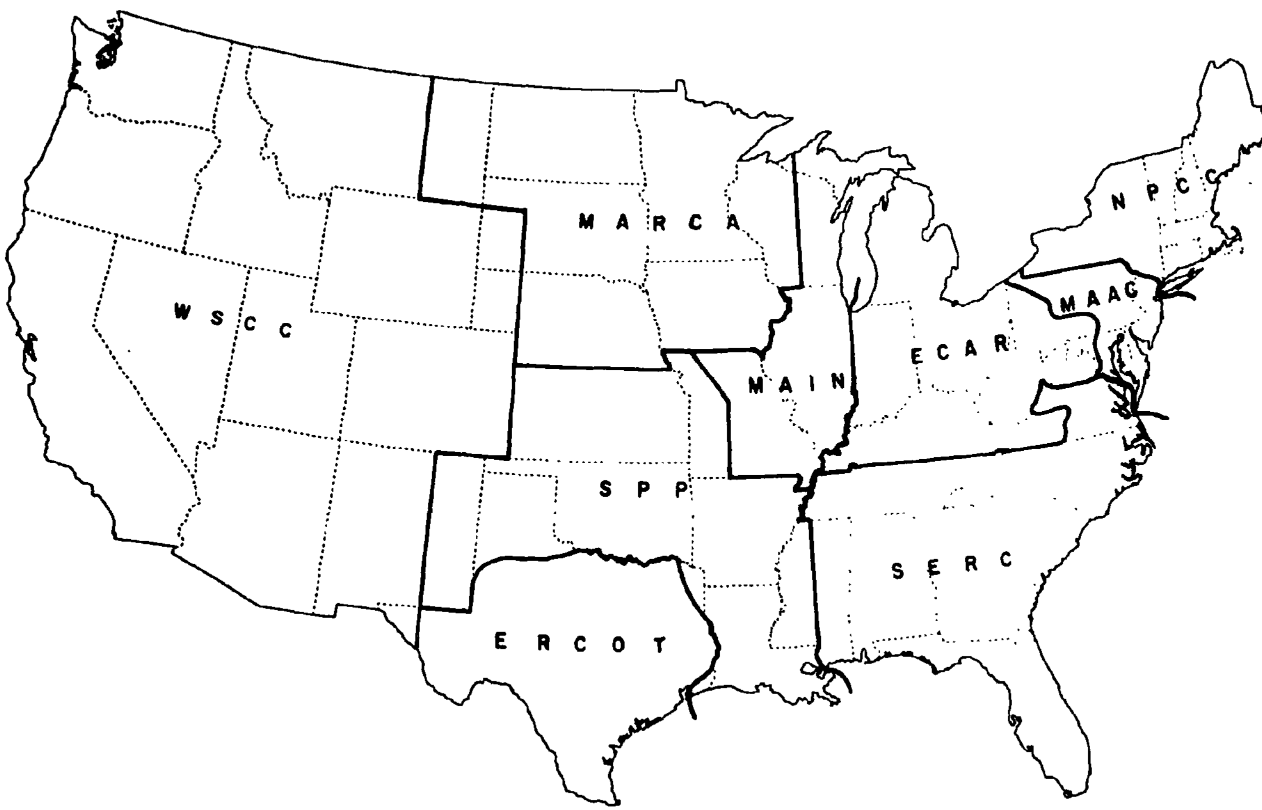

Fig. 16. Regional boundaries for the NERC nine-region case.

Table 21. Repository locations for NERC nine-region case

Region	Location[a]	Latitude	Longitude	Population density (per sq mile)	Opening date
ECAR	Akron, OH	41.11	81.53	182	1992
ERCOT	Waco, TX	31.56	97.20	42	1992
MAAC	Lancaster, PA	40.03	76.18	428	1995
NPPC	Pittsfield, MA	42.39	73.22	255	1993
MARCA	Fort Dodge, IA	42.34	94.18	37	1999
MAIN	Newton, IL	39.01	88.16	139	1996
SERC	Barnwell, SC	33.30	81.39	89	1995
SPP	Shreveport, LA	32.72	93.34	41	1990
WSCC	Richland, WA	46.60	119.60	35	1997

[a]Repository sites are identified solely for the purpose of calculating transportation data. The identification of a particular site does not imply that either the DOE or ONWI is considering a repository in that vicinity.

Table 22. Distribution of nuclear generating capacity for NERC nine-region case

	Regional capacity (GWe)								
Year	ECAR	ERCOT	MAAC	NPCC	MARCA	MAIN	SERC	SPP	WSCC
1980	6.6	1.2	8.3	9.0	3.5	9.1	25.9	1.8	6.9
1985	15.3	6.0	13.7	13.6	4.6	15.8	46.2	8.7	17.8
1990	22.2	6.0	17.0	21.8	4.6	18.6	55.3	9.8	24.0
1995	34.2	13.0	22.0	26.8	6.6	24.6	72.3	15.8	35.0
2000	46.2	20.0	30.0	32.8	9.6	29.6	87.3	23.8	46.0
2005	56.2	23.0	32.0	36.8	11.6	33.6	102.3	28.8	56.0
2010	63.2	26.0	36.0	38.8	13.6	36.6	111.3	31.8	62.0

Table 23. Transportation data for NERC nine-region case

	Run A	Run B	Run C
Inventory, metric tons of uranium			
ECAR	17,962	13,880	18,748
ERCOT	6,776	6,776	9,072
MAAC	14,164	18,144	15,671
NPCC	17,052	16,944	16,789
MARCA	4,981	7,502	5,594
MAIN	15,767	24,791	20,645
SERC	41,209	30,966	27,774
SPP	8,939	7,847	15,804
WSCC	18,778	18,778	15,531
Transportation costs, $\$ \times 10^6$	1056.3	1033.3	1137.4
Radiation exposure to public, man-rem	12.47	11.71	15.04
Total transport distance, cask mile $\times 10^6$			
Rail	14.13	13.55	17.10
Truck	41.11	36.45	47.73
Fraction of fuel received by rail, wt %			
ECAR	85.3	81.8	81.6
ERCOT	100.0	100.0	96.7
MAAC	59.7	61.5	62.2
NPCC	59.6	59.5	59.5
MARCA	100.0	81.0	82.8
MAIN	90.9	79.9	80.4
SERC	71.0	81.6	82.5
SPP	100.0	100.0	83.0
WSCC	92.4	92.4	93.5

Table 24. Cask fleet requirements for NERC nine-region case

Year	Run A		Run B		Run C	
	Rail	Truck	Rail	Truck	Rail	Truck
1990	1	0	1	0	25	34
1991	1	0	1	0	31	36
1992	4	2	4	2	23	32
1993	6	6	5	6	28	34
1994	6	8	5	8	30	34
1995	13	29	10	23	30	33
1996	16	33	16	31	29	35
1997	23	34	23	32	24	34
1998	23	35	23	33	24	34
1999	26	36	25	36	25	36
2000	40	57	40	56	33	44
2001	42	57	43	56	35	44
2002	45	59	45	58	38	47
2003	48	58	49	57	41	45
2004	51	57	51	56	43	44
2005	53	59	54	58	46	47
2006	56	57	57	56	49	44
2007	59	57	59	56	51	44
2008	62	59	62	58	54	47
2009	64	58	64	54	56	45
2010	66	59	67	56	58	47

Run A represents only intraregional shipments within the preferred NERC regional boundaries. The regional distribution of the pertinent transportation parameters is shown in Fig. 17. Most of the fuel will be shipped to the SERC repository, which has, by far, the largest generating capacity and would have to be at least twice as large as any of the other repositories. It is also evident that three of the regions (ERCOT, MARCA, and SPP) would only support rather small repositories. As discussed earlier, only 16 to 17% of the total domestic generating capacity is located in these regions. The distribution of transportation costs follows the distribution of shipments to the repositories. The two exceptions are the SERC region, which incurs 31% of the total cost to move 28% of the fuel, and the WSCC region, which incurs 18% of the total cost to move 13% of the fuel. For the SERC region, the number of truck shipments (approximately 58% of the total truck transportation) is the major reason for the proportionally higher costs observed for this region. Most of the fuel shipments in the WSCC region are made by rail (approximately 92.5%). However, the long shipping distances from the reactors located in southern California and Arizona to the repository located in the state of Washington increase the average shipping costs.

For the NERC regions, there is a large variation in the cask mix arriving at the individual repositories. The two regions located in the northeastern part of the country (MAAC and NPPC) receive approximately 40% of the fuel via truck shipments. At the other extreme, three repositories (ERCOT, MARCA, and SPP) would receive all fuel shipments in rail casks.

Most of the total public radiation exposure (∿31%) is associated with shipments in the SERC region even though the region has a relatively low population density of 89 persons/sq mile. Again, two factors contribute to this condition. First, most of the fuel shipments (∿38%) take place in this region; second, a significant fraction (29%) of these shipments are transported in truck casks.

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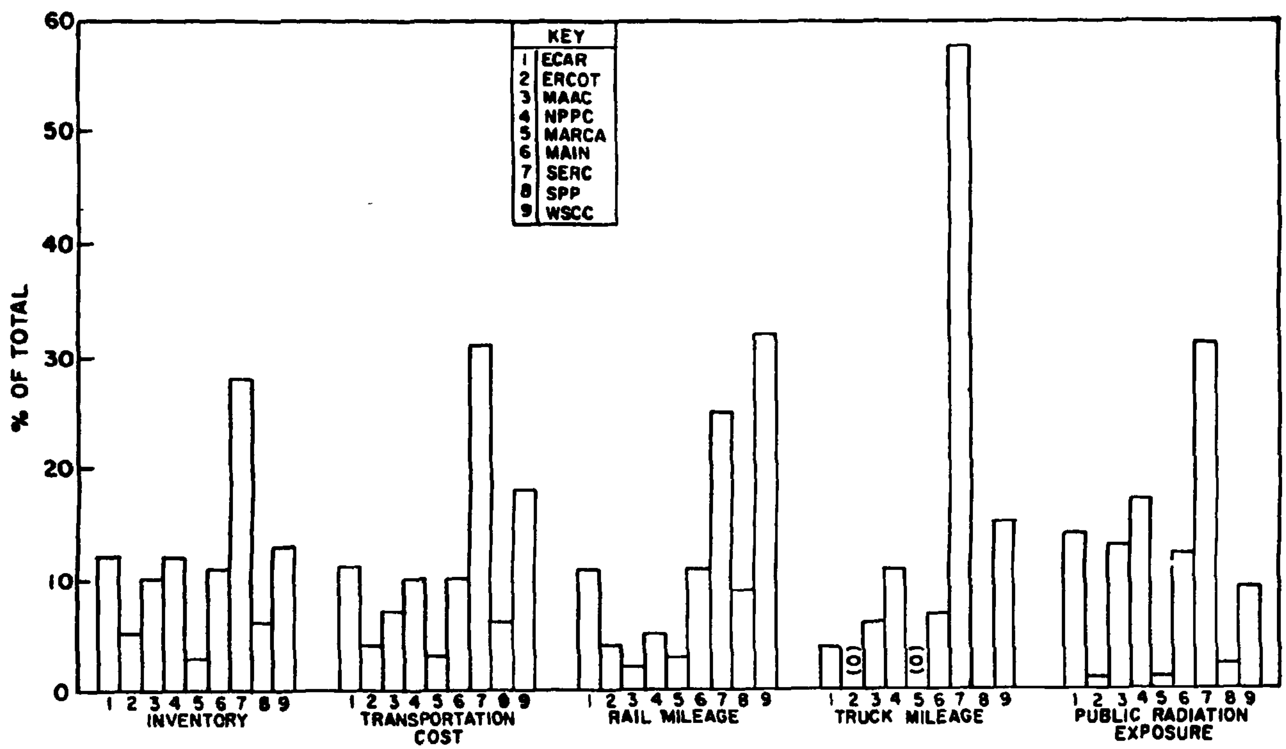

Fig. 17. Regional distribution of transportation parameters for NERC nine-region case: run A.

Run B represents the criteria by which all shipments are made to the nearest repository to define the optimal transportation boundaries for this set of repositories. The transportation boundaries, shown in Fig. 18, show some rearrangement of the regional definitions. The main differences are the expansion of the MAIN region eastward and southward to include several reactors previously in the ECAR and SERC regions; and the southward expansion of the MAAC region into part of the SERC region. The rest of the regions remain essentially the same. Even by rearranging the regions, the transportation cost for run B was almost the same as run A. The difference between the two runs was $23 x 10^6, or 2.2%.

The regional distribution of the transportation parameters for run B is shown in Fig. 19. These distributions are very similar to those previously discussed for run A. A lesser amount of fuel was shipped to the SERC region, only 21% of the total instead of 28%, while an increased amount of fuel (up from 11% to 17%) was directed to the repository in the MAIN region. The remaining distributions are as anticipated based on the amount of fuel transported and the regional rail-truck modal mix.

In run C, all shipments start in 1990 and the shipments must be made to one of the available repositories. The transportation costs for the run increased by 7.7% above that reported in run B. The regional distribution of the transportation parameters for run C is included in Fig. 20.

In this case, a significant proportion of the fuel (~11%) is being shipped to the SPP repository. In the other runs, only a small fraction (5 to 6%) of the fuel shipments went to this particular repository. This increase is a direct result of the particular set of opening dates selected for run C. In 1990 and 1991, the SPP repository is the only repository open. Approximately 37% of the total fuel shipped to the SPP repository is received over this 2-year period. The annual receiving rates at the SPP repository remain high through 1994 at which time the favorably located repositories in the SERC and MAAC regions are opened. Over the last 16 years of the study period, the cumulative fuel receipts at the SPP repository amount to only 46% of the total repository inventory. Since most of the reactors located in the eastern part of the country are

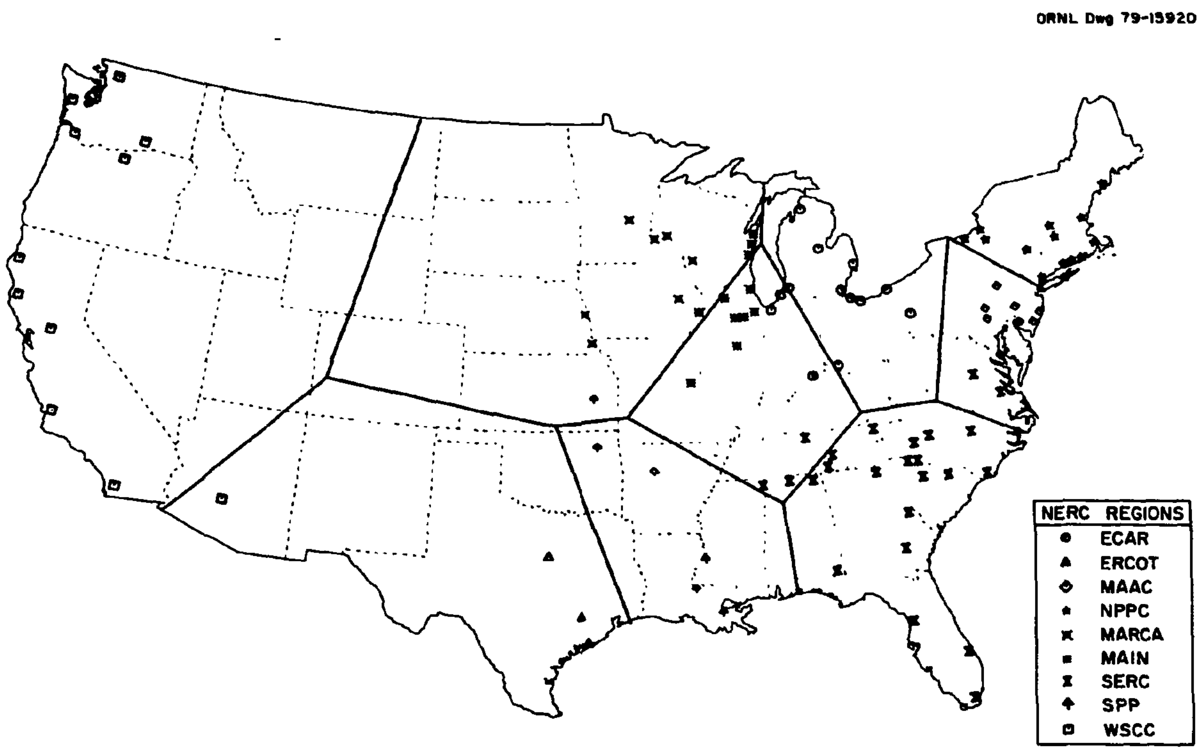

Fig. 18. Optimal transportation boundaries for the NERC nine-region case.

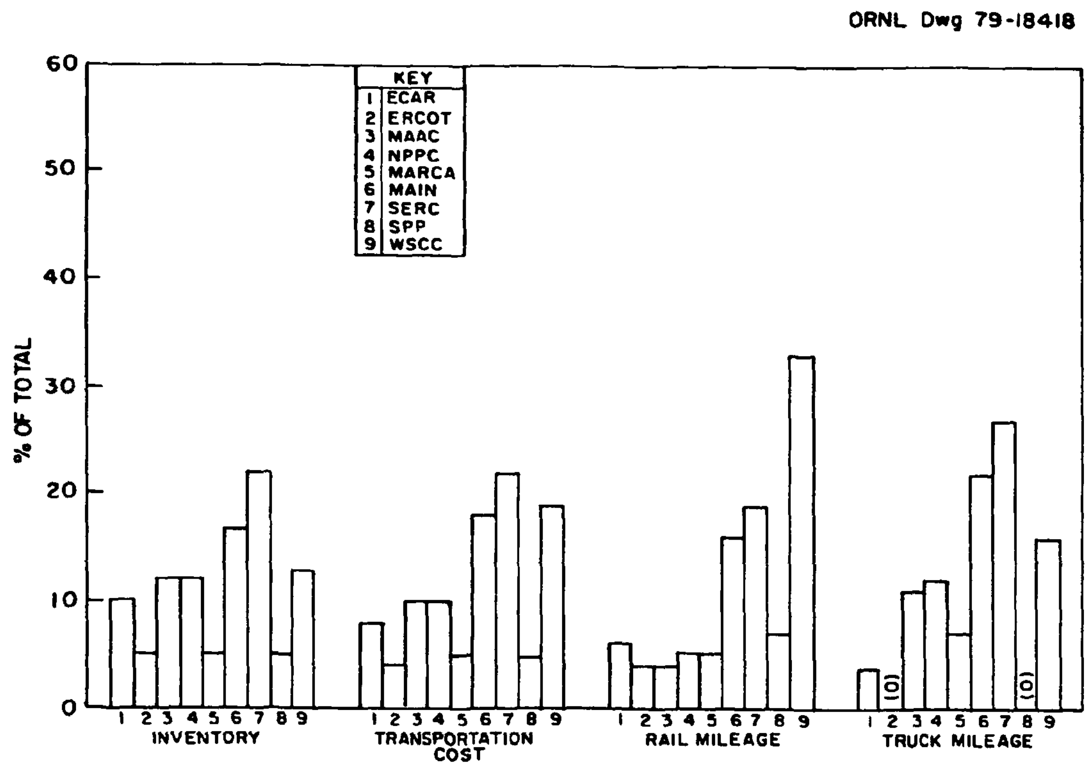

Fig. 19. Regional distribution of transportation parameters for the NERC nine-region case: run B.

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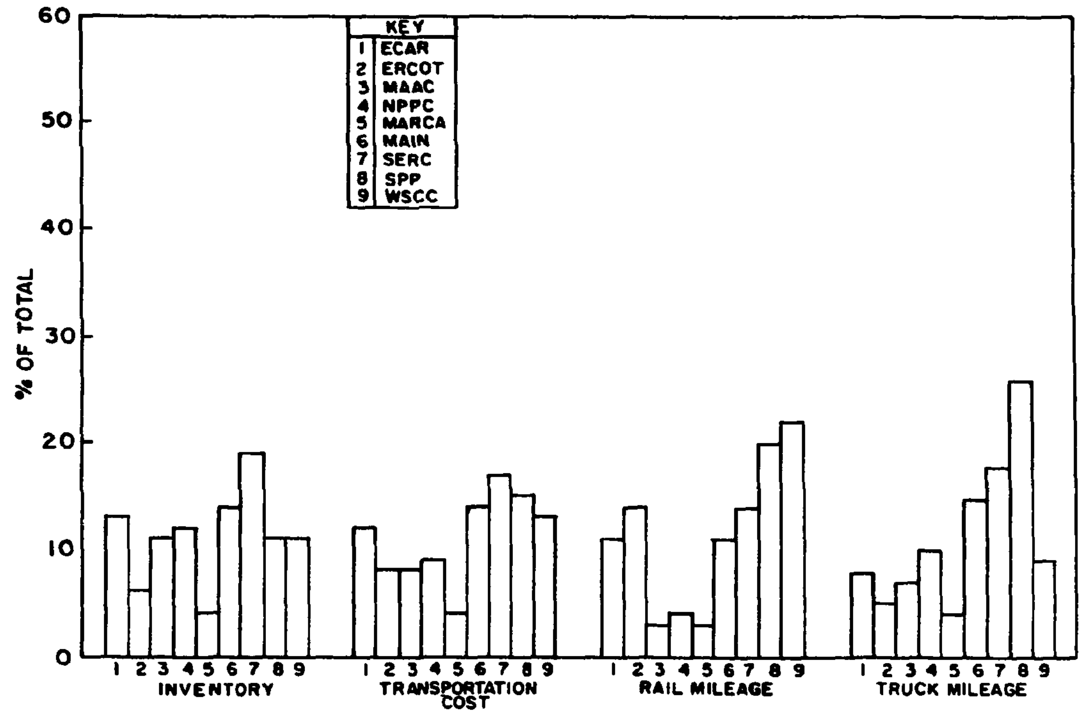

Fig. 20. Regional distribution of transportation parameters for the NERC nine-region case: run C.

shipping fuel to the SPP repository in the first part of the study period, the transportation parameters for this region are proportionally higher in run C than in runs A and B. In general, the repositories that open early (1990 to 1992) will show an increase in the amount of fuel received, and those opening later (1996 to 1999) will have a corresponding decrease.

3.6 Sensitivity Studies: Transportation Assumptions

The transportation data presented for the various cases discussed in Sects. 3.1 to 3.5 are based on several assumptions that were outlined in Sects. 2.3 and 2.4. Some of these assumptions were varied to evaluate the corresponding change in the transportation costs, radiation exposure, and cask fleet requirements.

The information discussed in Sect. 3.1 for the Gulf Coast repository forms the base case for the sensitivity runs, and the pertinent information for this run will be repeated in this section. Four separate runs were made and a single transportation parameter was changed in each run. All other assumptions remained identical to those used in the base case.

In the first run, the average rail speed was increased from 7 to 10.5 mph. Although this represents a 50% increase in the overall speed, it does not necessarily mean that over-the-rail speed would have to be increased by that amount. Careful scheduling of transportation routes and expeditious handling of the shipments, which would reduce the amount of time the shipping cask sits in various rail yards, would have a large impact on the overall average rail speed. For convenience, this will be referred to as the fast-train run.

The average truck speed was reduced from 35 to 25 mph in the second sensitivity run. Recently, there has been much discussion concerning the regulation of truck routes for radioactive materials.[7] Although the precise impact of routing restrictions on transportation distance and average speed is not known, it is generally accepted that the overall transportation time will increase. For purposes of a sensitivity run, a longer transportation time was simulated as a reduction in the average speed.

The third run, all rail, was included to evaluate the impact of eliminating truck shipments. The basic modal selection (Sect. 2.2) assumed truck shipments for those reactors which did not have direct rail access to the plant site. In many cases, these reactors could utilize rail casks by incorporating an intermodal shipment to move the casks from the reactor to the nearest rail line. This run assumed all shipments would be made by rail directly from the reactors and no attempt was made to include any intermodal transportation costs.

A conceptual rail-cask design, which could transport 21 PWR or 48 BWR assemblies, was used for all rail shipments in the fourth run. This design was based on a 5-year cooling time, a 10-mrem/hr exposure 6 ft from the edge of the cask, and a maximum weight not to exceed 100 metric tons. It is physically possible to place this number of assemblies in such a cask, but criticality considerations were not included in the conceptual design criteria. This run, which is called the new-cask run, was included to estimate the impact of a new generating rail cask capable of transporting a significantly increased payload. The new-cask run is included for comparison purposes only and is not intended to imply that a cask of these dimensions or payload is currently being considered. For this run, the standard truck cask was still used for all truck shipments.

The pertinent transportation information and associated cask fleet requirements are summarized for the sensitivity runs in Tables 25 and 26.

Increasing the rail speed from 7 to 10.5 mph (the fast-train run) reduced the transportation costs by approximately 13% and also resulted in a 21% reduction in the public radiation exposure. In this run, the number of rail shipments and the rail transportation distance remain the same as for the base case. Due to the faster speed, it is possible to complete an individual shipment more quickly and each cask is capable of making more round trips per year. The maximum rail-cask fleet was reduced from 134 in the base case to 102 in the fast-train run. The truck-cask fleet size is the same for either run. The portion of the transportation cost paid to the rail carrier depends only on the number of shipments and the distance. Since these parameters remain unchanged, the

Table 25. Transportation summary for sensitivity studies

Case	Transportation cost ($ x 10^6)	Radiation exposure[a] (man-rem)	One-way transport distance (cask-miles x 10^6)	
			Rail	Truck
Base case	2305.4	33.22	58.20	160.72
Fast train	2016.7	26.12	58.20	160.72
Slow truck	2343.7	37.99	58.20	160.72
All rail shipments	2185.7	27.05	74.58	
New cask	1423.6	74.52	28.27	160.72

[a]Radiation exposure based on a uniform population density of 69 persons/sq mile.

Table 26. Cask fleet sizes for sensitivity studies

Year	Base case Rail	Base case Truck	Fast train[a]	Slow truck[b]	All rail shipments[c]	New cask[a] (rail)
1990	25	34	19	40	36	12
1991	31	36	23	43	43	15
1992	33	40	25	47	47	16
1993	40	45	31	53	55	20
1994	43	45	33	54	58	21
1995	48	51	36	61	66	24
1996	48	53	37	63	66	24
1997	53	53	40	63	71	26
1998	53	55	40	66	72	26
1999	57	57	43	67	77	28
2000	74	70	56	84	98	36
2001	80	70	60	83	104	39
2002	86	74	65	87	112	42
2003	93	72	71	85	119	46
2004	100	71	76	84	125	49
2005	104	74	79	87	130	51
2006	112	70	85	83	136	55
2007	119	70	90	83	143	58
2008	125	74	94	87	150	61
2009	129	71	98	85	154	63
2010	134	75	102	89	160	65

[a]Truck-cask fleet size is the same as for the base case.

[b]Rail-cask fleet size is the same as for the base case.

[c]No truck shipments in this case.

carrier cost is the same as for the base case. Therefore, saving in transportation cost results from a reduction in the number of cask-days required to make the shipments. The cask lease charges are reduced because the cask is used for a shorter period of time for each shipment. The reduction in the radiation dose to the general public results solely from the higher average speed. Thus, anyone residing along the rail routes is exposed for a shorter period of time.

In the slow-truck run, the transportation costs increased by approximately 2%, the radiation exposure increased by 14.4%, and the maximum truck-cask fleet size increased by 14 casks, or 19% over the corresponding values for the base case. The number of rail casks remained the same in both this run and the base case. The same reasoning that was used in the fast-train run can be applied to the slow-truck run; however, since a reduction in transport speed was used in the slow-truck run, all the trends discussed for the fast-rail run operate in reverse.

The relative changes in the transportation parameters for changes in rail or truck speed are functions of the magnitude of the change and the amount of fuel being shipped by each mode. In this study, approximately 80% of the fuel is transported by rail. Hence, the total transportation cost is very sensitive to changes in the rail system and relatively insensitive to perturbations in the truck segment.

Moving all shipments by rail reduced the transportation costs by approximately 5%, reduced the radiation exposure by almost 19%, and increased the rail-cask fleet by 26 casks in 2010. Since no truck shipments were used, the truck-cask fleet requirements are zero. Referring to Table 5 in Sect. 2.3, it was demonstrated that the economic assumption used for these studies favored rail shipments. Hence, if the proportion of fuel being transported by rail could be increased, a savings in transportation cost would be anticipated. Note that the cost figures reported for this run do not include an estimate for the intermodal shipments to get the cask to a rail line, and the actual overall saving would be somewhat less than reported here.

In the new-cask run, a large rail cask, which was assumed to be designed for long-cooled fuel, was used for all rail shipments instead of the standard 10/24 rail cask. The changes in transportation costs and rail transport distances are those expected for a rail cask whose capacity is essentially double that used in the base case. However, the public radiation exposure for this run was increased by a factor of 2.24 over the base case. It should be noted that the rail cask for the base case was modeled to simulate an existing cask. This cask had been designed to limit the exposure to 10 mrem/hr for short-cooled fuel (120 to 150 days). If the cask had been loaded with 7-year-old fuel, the corresponding surface exposure would have been approximately 1.7 mrem/hr. The shielding thickness of the "new" cask was designed to limit the surface exposure to 10 mrem/hr for 5-year-old fuel, and it was assumed for this run that 7-year-old fuel would give essentially the same exposure. The increased capacity reduces the number of shipments by a factor of 2; however, the increased surface radiation is increased by a factor of 5.88. Taking the ratio of these factors and factoring in the relative proportion of rail shipments results in an overall increase in public radiation exposure by a factor of 2.24.

The new-cask design results in a reduction in the cask fleet size of slightly over 50% (134 in the base case vs only 65 in this run).

3.7 Sensitivity Studies: Repository Opening Dates

Since it is not possible to open a number of repositories simultaneously, an estimated schedule of repository opening dates was used for the cases discussed in the previous sections. The particular set of opening dates selected had a very minor impact on the transportation data calculated for runs A and B. For these runs, fuel was assumed to be stored at the reactors until the appropriate repository was available to receive fuel shipments. However, over the study period, the same amount of fuel will ultimately be shipped from each reactor. Therefore, the total transportation costs, total transportation mileage, and total public radiation exposure will also remain the same (i.e., these parameters are not a function of repository opening dates). For runs A and B, the annual cask fleet requirements are a function of the repository opening dates because the annual shipping rates vary.

In run C, the annual shipping rates are not allowed to vary and shipments must be made to an available repository. Under this condition, all transportation parameters are a function of the particular set of opening dates selected. It is easy to hypothesize that the order in which the various repositories are opened could have a significant impact on transportation costs and cask fleet requirements.

To evaluate this impact, several runs were made for the three-region repository case in which various sets of repository opening dates were considered. Run 1 is simply a repeat of the original calculations (run C in Sect. 3.2) using the opening dates given in Table 9. In this particular run, the western repository is opened first in 1990, and the southeastern and northwestern repositories are opened in 1993 and 1995 respectively. In run 2, the southeastern repository is assumed to be opened first in 1990, and the northeastern and western repositories are opened in 1993 and 1995. Run 3 interchanged the opening dates of the southeastern and northeastern repository. The western repository was still assumed to be opened in 1995. A summary of the repository opening dates and the resulting transportation costs are summarized in Table 27.

As expected, run 1 gave the highest cost. Between 1990 and 1992, all shipments went to the western repository. Since a large proportion of the fuel is coming from reactors that are located in the eastern part of the country, the average shipping distance is quite long. In runs 2 and 3, the first repository to be opened is located much nearer to the reactors and the transportation distances are reduced accordingly. The transportation costs for these runs are nearly identical and represent a savings of approximately 4% over that calculated for run 1. The cask fleet requirements for each run are tabulated in Table 28 for the time period 1990 to 1995. Since all repositories are opened in 1995, the cask fleet requirements for each run are identical to those reported for run C in Table 12 during the 1995 to 2010 time period. Between 1990 and 1992, the cask fleet requirements for runs 2 and 3 are significantly less than for run 1. These runs represent a reduction of approximately 25% in rail-cask fleet size and 33% for the truck-cask fleet size. This

Table 27. Repository opening dates and transportation costs for sensitivity studies

	Run 1	Run 2	Run 3
	Opening date		
Repository			
Northeast	1995	1993	1990
Southeast	1993	1990	1993
West	1990	1995	1995
Transportation cost, $\$ \times 10^6$	1545.7	1490.7	1483.1

Table 28. Cask fleet requirements for various repository opening dates

	Cask fleet size[a]		
Year	Run 1	Run 2	Run 3
1990	30/41	23/29	22/28
1991	37/44	29/31	27/30
1992	41/48	31/33	29/32
1993	31/36	33/34	33/34
1994	33/37	36/34	36/34
1995	31/35	31/35	31/35

[a]The notation 30/41 means 30 rail casks and 41 truck casks.

difference can be traced directly to the large number of shipments from the eastern reactors to the western repository. A comparison of runs 2 and 3 indicates a preference for opening the northeastern repository prior to the southeastern repository.

Between 1993 and 1994, the trend in cask fleet requirements changes. For this time period, run 1 gave a lower rail-cask fleet size than runs 2 and 3 but a higher truck-cask fleet size. Runs 2 and 3 are identical for this time period. In run 1, the preference would be to ship to either the western or the southeastern repository. To minimize transportation costs, the reactors west of the Mississippi River would be making shipments to the western repository. In runs 2 or 3, the two choices are the Northeast or Southeast, and shipments from all of the western reactors would be to one of these destinations. Because essentially all of the shipments from the western reactors are made by rail, the increased shipping required to move western fuel to the East (runs 2 or 3) exceeds the effort of moving fuel from the Northeast to the Southeast (run 1); hence, the lower rail-cask fleet size. The reactors requiring truck shipments are located along the eastern coast, which results in a large truck-cask fleet requirement in run 1. Additional logistic runs would be required to determine whether it would be more economical to open the southeastern or the western repository in 1993.

4. SUMMARY AND CONCLUSIONS

Many cases representing different regional repository concepts have been evaluated. As would be expected, the transportation requirements for moving spent fuel from the reactors to a repository decreases as the number of repositories increase (see Table 29). The highest transportation costs are associated with a single repository because this maximizes transportation distance. The single-repository cases are also extremely sensitive to the repository location. Different locations could result in a doubling of the transportation costs and cask fleet sizes. Two different cases, each containing five repositories, showed a much smaller sensitivity to repository location. The transportation impact of the cases varied from 58% to 64% of that associated with the best single repository.

Table 29. Summary of transportation costs for various regional repository concepts

Case	Transportation cost ($ x 10^6)	Relative cost[a]
Single repository		
Central Illinois	1888.7	1.0
Gulf Coast	2305.4	1.221
Pacific Northwest	3993.9	2.115
Three regions	1437.7-1545.7	0.761-0.818
Five regions		
SSAI regions	1140.6-1205.8	0.604-0.638
NRC regions	1097.6-1174.3	0.581-0.6222
Nine regions	1033.3-1137.4	0.547-0.602

[a]Relative costs are normalized based on the cost of shipping all fuel to a single repository located in Central Illinois ($1888.7 x 10^6).

As shown in Fig. 21, the relative transportation costs decrease as the number of repositories increase. The upper curve in Fig. 21 represents the maximum cost for each case (run C), whereas the lower curve represents the minimum cost (run A). However, the reduction reaches a point of diminishing returns. The transportation costs can be reduced approximately 20 to 25% by using three repositories rather than a single repository. Increasing the number of repositories from three to five would only save an additional 17%, and a further expansion from five to nine repositories would only save another 2 to 4%.

The transportation cost for various regional repository concepts is only part of the total economic picture. The cost of constructing, operating, and decommissioning a number of repositories must also be

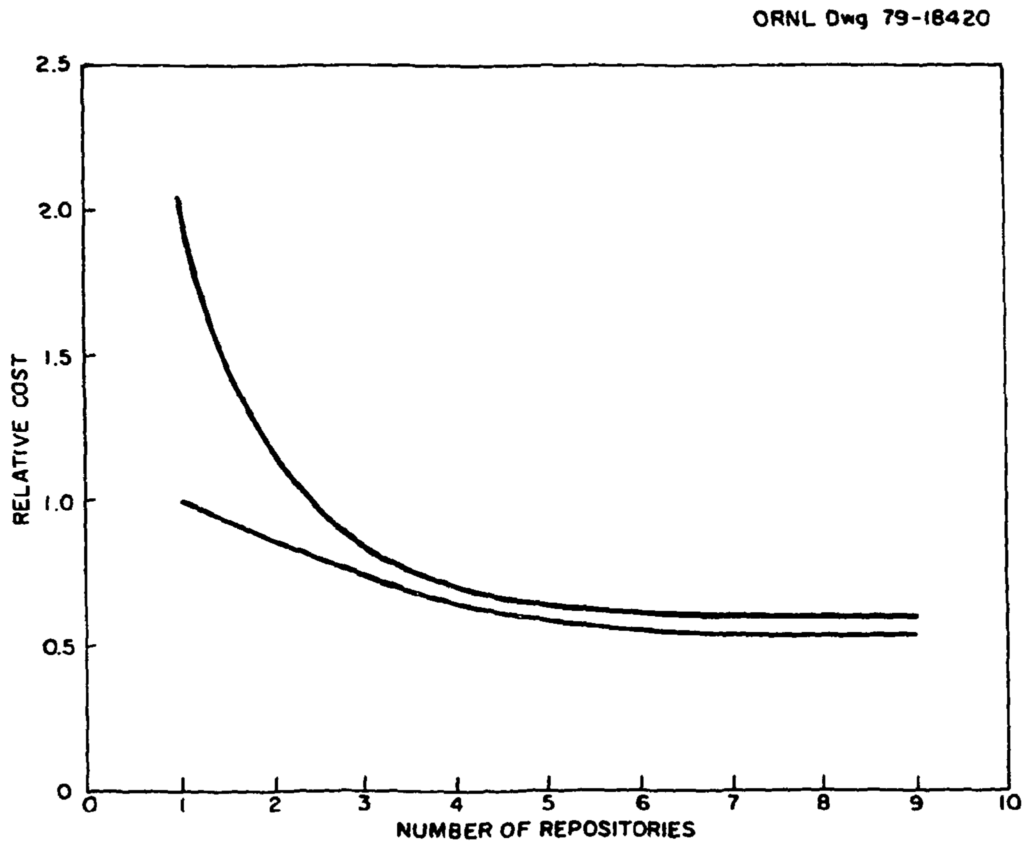

Fig. 21. Relative range of transportation cost vs number of repositories.

considered. In addition to the economics of fuel management, consideration must be given to the social and political impacts of regional or centralized repositories.

Several sensitivity studies were also conducted to determine the impact of changes in some of the basic transportation assumptions. Increasing the overall average speed from 7 to 10.5 mph would have a significant impact on transportation costs and cask fleet requirements. A reduction of truck speed from 35 to 25 mph would only have a minor impact on transportation costs. The selection of transport mode used in this report limited the amount of fuel shipped by truck to approximately 20%. If a combination of factors should arise which would cause a major shift in the relative rail/truck selection, the impact of varying the truck transportation parameters would be much more significant. However, an effort should be made by ONWI and the Transportation Technology Center (TTC) at Sandia Laboratories to ensure the availability of efficient rail service for moving spent fuel shipments.

Since all of the fuel transported was assumed to be cooled for at least 7 years, consideration of the possibility of designing casks specifically for long-cooled fuel seems to be justified. These casks would have an increased payload over the existing generation of shipping casks. A larger cask capacity would reduce the number of shipments and the number of miles a cask has to be transported and would result in a reduced transportation cost. However, these reductions are offset by an increase in the radiation exposure to the transportation workers and to the general public.

In a second set of sensitivity runs, the order in which the repositories are opened is considered. Although the savings in transportation costs (about 4%) are relatively small, the saving in cask fleet requirements could make a big difference during the first few years of repository operation when large initial cask fleets have to be constructed.

5. ACKNOWLEDGMENTS

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