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Modeling the Highway Transportation of Spent Fuel

Ivor Glen Harrison
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a dissertation written by Ivor Glen Harrison entitled "Modeling the Highway Transportation of Spent Fuel." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Geography.

Bruce A. Ralston, Major Professor

We have read this dissertation and recommend its acceptance:

Thomas Bell, Theodore Schmudde, Michael Bronzini

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Thomas L. Bell

Theodore H. Schmudde

Michael S. [illegible]

Accepted for the Council:

C. W. Minkel

Vice Provost
and Dean of The Graduate School

MODELING THE HIGHWAY TRANSPORTATION
OF SPENT FUEL

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Ivor Glen Harrison

June 1986

DEDICATION

This work is dedicated to my mother and father, Mary and Byron Harrison. From early childhood, they have instilled the virtue of hard work and the importance of an education in me. The accomplishments I have been able to achieve are in large part due to their love and encouragement.

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ABSTRACT

There will be a substantial increase in the number of spent fuel shipments on the nation's highway system in the next thirty years. Most of the spent fuel will be moving from reactors to a spent fuel repository. This study develops two models which evaluate the risk and cost of moving the spent fuel. The Minimum Total Transport Risk Model (MTTRM) seeks an efficient solution for this problem by finding the minimum risk path through the network and sending all the spent fuel shipments over this one path. The Equilibrium Transport Risk Model (ETRM) finds an equitable solution by distributing the shipments over a number of paths in the network. This model decreases the risk along individual paths, but increases society's risk because the spent fuel shipments are traveling over more links in the network.

The study finds that there is a trade off between path risk and societal risk. As path risk declines, societal risk rises. The cost of shipping also increases as the number of paths expand.

The cost and risk of shipping spent fuel from ten reactors to four potential repository sites are evaluated using the MTTRM. The temporary monitored retrievable storage (MRS) facility in Tennessee is found to be the minimum cost and minimum risk solution. When direct shipment to the permanent sites is considered, Deaf Smith, Texas is the least cost and least incident free transport risk location. Yucca Mountain, Nevada is the least risk location when the focus is placed on the potential consequences of an accident on surrounding population or property.

The MTTRM and ETRM provide decision makers at all levels of government with a tool to evaluate the risk of shipping spent fuel. Each level of government and location in the country will have its own preference in the distribution of this risk.

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CHAPTER 1

RADIOACTIVE MATERIALS TRANSPORTATION

Introduction

By the year 2000, the United States will see a substantial upsurge in the movement of high level radioactive spent fuel on its highways. Most of this spent fuel will be moving from nuclear reactors, where it is now stored, to a permanent repository site or an interim storage facility. The purpose of this dissertation is to develop two models for evaluating the risk in transporting spent fuel along highways, where risk is measured by the expected exposure to radiation. The solutions generated by these two models should aid decision makers in choosing among various routing options. To understand the uses of the routing models, it is first helpful to briefly review the background of the nuclear power industry and the regulations governing the movement of spent fuel.

Background of the Nuclear Power Industry

History

The construction of the first nuclear power plants began in the United States in the 1950s (USDOT, 1980). The first commercial nuclear power plant to go on line was the Shippingsport reactor near Pittsburgh, Pennsylvania in 1957 (Beck et al., 1984). By 1985, eighty-six nuclear power plants had been completed and were operating. Sixty additional plants have construction permits and, thirty of these are likely to be completed (Panel on Social and Economic Aspects of Radioactive Waste Management, 1984 and USDOE, 1985b).

The nuclear power plants which are currently being constructed and those which are already in operation in the United States are, for the most part, located east of the Mississippi River (Figure 1.1). The major concentrations are found in the Atlantic coastal states and the states surrounding the Great Lakes. The Pacific coast states also have a small number of reactors. The Great Plains and Rocky Mountain states are more sparsely settled and have other energy sources such as coal, oil, and natural gas. As a result, there are few nuclear power plants located in these two regions.

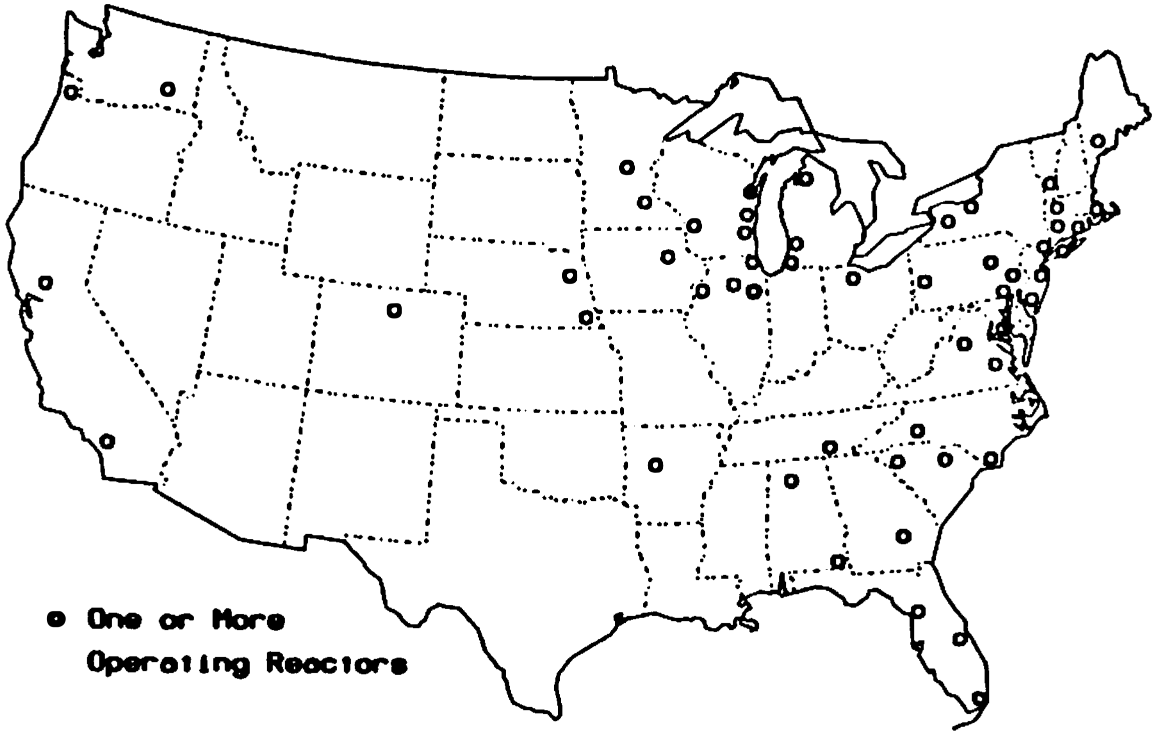


Figure 1.1 Operating Reactor Sites.

Nuclear power has only become a significant part of America's energy supply since the early 1970s (Congressional Research Services, 1977). Nuclear power plants currently generate 140 gigawatts of electricity, and by 1990, energy production will increase to 182 gigawatts (1 gigawatt = 1 million kilowatts) (USDOT, 1980). As the production of electricity by nuclear power plants increases, so does the amount of spent fuel.

Nuclear Fuel Cycle

The nuclear fuel cycle is a two phase process: (1) provision of fuel to reactors and (2) disposal of spent fuel. The first phase of the cycle is called the front end. It involves the mining and milling of ore, conversion and enrichment of the uranium, fuel fabrication into rods, and installation of the rods in the nuclear power plant. The first stage of the processing from mining to milling usually takes place within a very short distance because only one percent of the uranium ore is uranium oxide, the source of nuclear fuel. Each of the steps beyond the milling process takes place in widely divergent parts of the country. The relatively low weight and high value of the processed uranium makes it a profitable commodity to ship over long distances (Rhoads, 1977).

The fuel rods normally stay in the reactor for a period of three years (USDOE, 1986). The back end of the nuclear fuel cycle begins when the energy producing ability of the fuel rods has been depleted. At this point, the highly radioactive rods must be removed from the reactor and deposited in a storage area. Reactors have temporary storage facilities on their premises, but the capacity of many of these older nuclear power plants to handle this spent fuel is diminishing because they are running out of on-site storage space (Jacob and Kirby, 1985). This situation has been eased somewhat by the shipment of spent fuel between various reactor storage facilities (De Steese and Rhoads, 1978). Some irradiated fuel is also being shipped to the former nuclear fuel reprocessing plants at Morris, Illinois and West Valley, New York (Resnikoff, 1983).

By 1985, 10,000 metric tons of spent fuel had accumulated at temporary reactor storage facilities. By the year 2000, the quantity of spent fuel will grow to 40,000 metric tons. Eventually, the spent fuel must be removed to a permanent storage facility where it will need 10,000 years to decay to a safe state (Beck et al., 1984).

In addition to the spent fuel generated by the nuclear power plants run by utilities, there are a number of other generating sources. Fuel from eighty smaller research and isotope manufacturing reactors is being transported to government facilities at the Savannah River Plant (SRP) near Aiken, South Carolina and the Idaho National Engineering Laboratory (INEL) near Idaho Falls, Idaho. The United States also accepts spent fuel from foreign reactors. Most of this fuel enters the United States at Portsmouth, Virginia and is shipped to the SRP or the INEL. Other shipments are trucked into the United States from Canada. Finally, the military has 156 nuclear reactors, 128 of which are used on submarines and aircraft carriers. Spent fuel from these reactors is shipped directly to the INEL facility from eight shipyards (Resnikoff, 1983).

The Nuclear Waste Policy Act of 1982 gives the Department of Energy (DOE) the responsibility for establishing permanent repository sites for spent fuel. Eventually, there will be two sites selected for permanent storage. The first repository will have a capacity of up to 70,000 metric tons (Graham, 1984). The candidate locations for the first site are Deaf Smith County, Texas, Hanford, Washington, and Yucca Mountain, Nevada (USDOE

1984a, USDOE 1984b, and USDOE 1984c) (Figure 1.2). The final decision on the first repository should be made by DOE in 1990 (Panel On Social and Economic Aspects of Radioactive Waste Management, 1984). After the construction of the facility is completed, in 1998, spent fuel shipments should show a marked increase in number and distance traversed because the spent fuel will be transferred from reactor sites across the United States to the repository (Table 1.1).

Since most reactors are located in the East and the potential repository site locations are found in the West, substantial distances must be traversed in order to move the spent fuel to its final resting place (De Steese and Rhoads, 1978 and Jacob and Kirby, 1985). The Great Plains and Rocky Mountain states are particularly concerned about the final selection of the first repository location because some of them will likely be corridors for the shipment of spent fuel from the reactors to the site which is chosen (Nuclear Waste Transportation, 1984). They will be bearing much of the transport risk of nuclear power, without receiving many of the benefits (Zeigler et al., 1984).

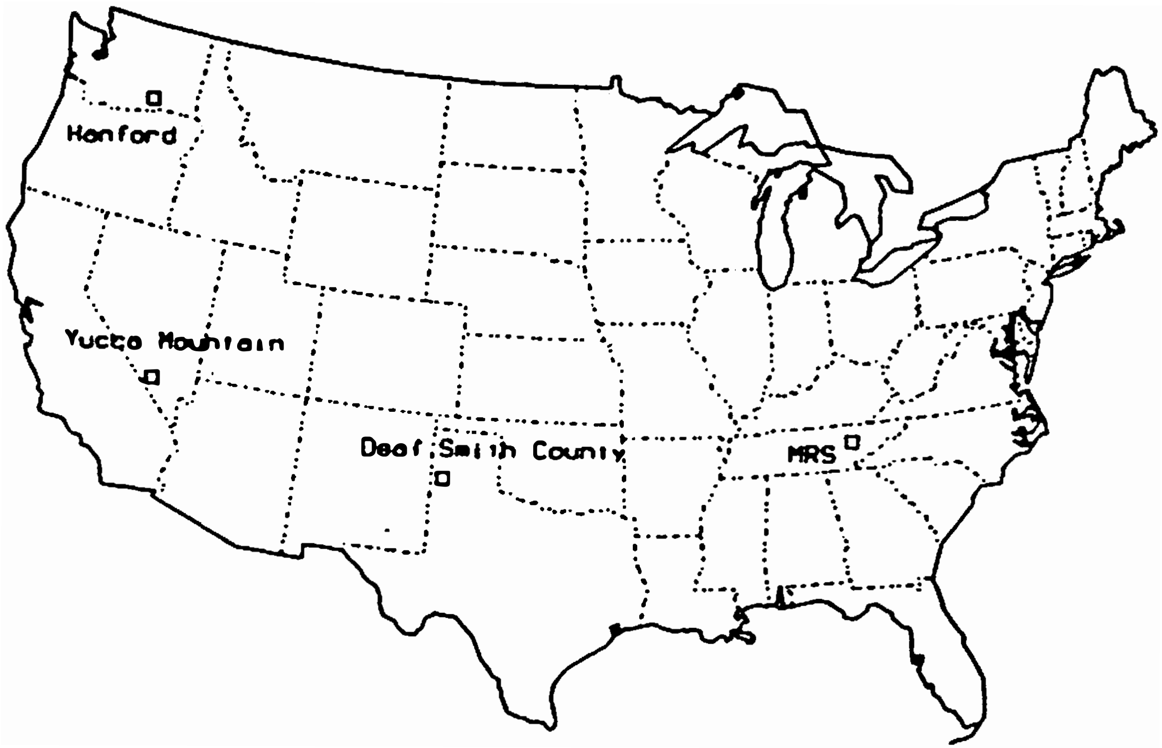


Figure 1.2 Candidate Repository Sites and MRS.

Table 1.1

ANNUAL NUMBER OF SPENT FUEL SHIPMENTS

Year	Number
1980	96
1985	520
1990	1,085
1998-2025	6,405 annually

Source: Resnikoff, Marvin. The Next Nuclear Gamble. New York: Council on Economic Priorities, 1983.

DOE has also proposed the construction of an interim storage facility for spent fuel (USDOE, 1985c). This monitored retrievable storage (MRS) facility would be used to collect the spent fuel from the reactors. The fuel would be repackaged into uniform containers and placed in temporary storage facilities until the permanent repository is finished. The fuel would then be loaded on unit trains and shipped to the permanent repository site. Three candidate sites in Tennessee have been selected by DOE for the MRS facility. Two are near Oak Ridge and the third site is at the abandoned Hartsville nuclear power plant.

Spent fuel shipments are made by truck, rail, and barge. Current estimates show that approximately thirty percent of the spent fuel in the United States will be moving by truck when the MRS facility or permanent repository is completed (Hoskins, 1985 and USDOE, 1985c).

Regulations Governing the Movement of Spent Fuel

Federal Regulatory Agencies

Responsibility at the federal level for the safe transport of radioactive material lies primarily with the Department of Transportation (DOT) and the Nuclear Regulatory Commission (NRC). A "Memorandum of Understanding" between the two agencies was signed in 1966

and revised in 1973. This memorandum divides the regulatory authority over radioactive material movements between them. DOT is responsible for regulating the safety standards in the shipment of radioactive material, while the NRC regulates the packaging design, construction, and testing standards (Rhoads, 1977). Some routing regulations overlap the jurisdiction of both agencies.

Nuclear Regulatory Commission Regulations

In 1979, the NRC's Office of Nuclear Safety and Safeguards published regulations requiring shippers of high level radioactive materials such as spent fuel to avoid movements through or near metropolitan areas of 100,000 or more population. An exception would be made to this ban if: (1) no peripheral highway route was authorized for trucks; (2) any other route would result in an excessive increase in travel time; or (3) other highways were not as safe as the ones running through the population center. The degree of safety on the highway would be determined by its quality, the accident rate, and the volume of traffic. If movement through the urban area is approved by the NRC, additional measures would be required for the shipment. These measures would include armed escorts, nonstop travel

through the city, and the exclusive use of interstates (Kasun, 1979).

Department of Transportation Regulations

In 1980, the Materials Transportation Bureau (MTB) of the DOT adopted a similar set of rules. These regulations state that any truck carrying a large quantity of radioactive material is required to operate a on preferred route. A preferred route is any highway designated as such by the appropriate state agency and any interstate highway which has not been replaced by a state designated route.

Data collected by the Federal Highway Administration shows that the chances of having an accident involving an injury or a fatality on an interstate are 75 percent less than that of a noninterstate highway. Since the interstates have been proven safer, the MTB requires that motor carriers hauling spent fuel stay on these arteries as much as possible (FR7149, January 31, 1980).

The rules also require that a truck carrying high level radioactive material use a circumferential interstate route around an urban center, if one exists. If no interstate bypass exists, states can designate any highway of interstate quality which goes around the central city as a preferred route. If neither case exists, then the

shipment would move through the central city interstate (FR7140, January 31, 1980).

The regulation requiring that large shipments of radioactive material move on interstate bypass routes around central cities results in a trade off between increased distance and lower population density. Given similar road conditions, the results of this policy would be increased exposure for the transport crew and greater probability that an accident will occur because of the longer distances traveled. On the other hand, the lower population density along the interstate will result in less normal exposure for the general population and diminished consequences if an accident does occur (FR7145, January 31, 1980). That is, there is a trade off between path length and potential exposure.

State and Local Regulations

State and local legislative bodies have become more concerned about the regulation of hazardous material movements through their own jurisdictions as the flow has increased on the nation's highways. The Legislative Data Base compiled at Oak Ridge National Laboratory, a DOE facility in Oak Ridge, Tennessee, lists 468 pieces of state and local legislation regulating the movement of

radioactive material in its last annual report. These regulations may be placed in one of five major categories: (1) requirement for escorts, (2) prenotification of local authorities that a shipment of radioactive material is moving through their jurisdiction, (3) special permits, licenses, or insurance, (4) prohibition of the movement of high level radioactive material through part or all of the jurisdiction's territory, and (5) weight restrictions on roads and bridges (Fore et al., 1984).

Local regulations which restrict the movement of radioactive material merely shift the problem to another location without improving the overall safety standards of the transport system. In many cases risk may be increased because local or state regulations require the spent fuel to travel longer distances over poorer quality highways. If enough legislative roadblocks are set up by state and local governments, the shipment of radioactive material may be halted altogether. A case in point is that of the movement of spent fuel from the Chalk River reactor in Ontario, Canada to the Savannah River Plant in South Carolina.

Until 1979, spent fuel was trucked from the Chalk River reactor to the Savannah River Plant, crossing the St. Lawrence River by the Ogdensburg Bridge in New York

(Figure 1.3). This route to the SRP covered 1,196 miles and took about twenty-seven hours to complete. In 1980, the Ogdensburg Bridge and Port Authority banned the movement of radioactive materials across the bridge. As a result of this move, Nuclear Assurance Corporation (NAC), which was hauling the spent fuel, asked the NRC to approve five additional routes for possible movement of spent fuel. These routes passed through Michigan, New York, and Vermont. Shortly after learning about the application, the Michigan State Fire Safety Board and Department of Public Health passed stringent regulations on the movement of spent fuel in that state so as to close off access to the traffic from Chalk River. In New York, the Thousand Islands Bridge Authority and the New York Thruway Authority also barred shipments on their facilities. In 1982, NAC began shipping spent fuel through Vermont to SRP. After eight of eleven scheduled shipments through Vermont were made, the governor ordered a halt to these movements. NAC then intended to move the remaining three shipments through New York, but before this could be accomplished, the governor of that state ordered that no more spent fuel shipments from Canada could be moved through the state. The next closest place to enter the United States would be through Duluth, Minnesota. This trip would require

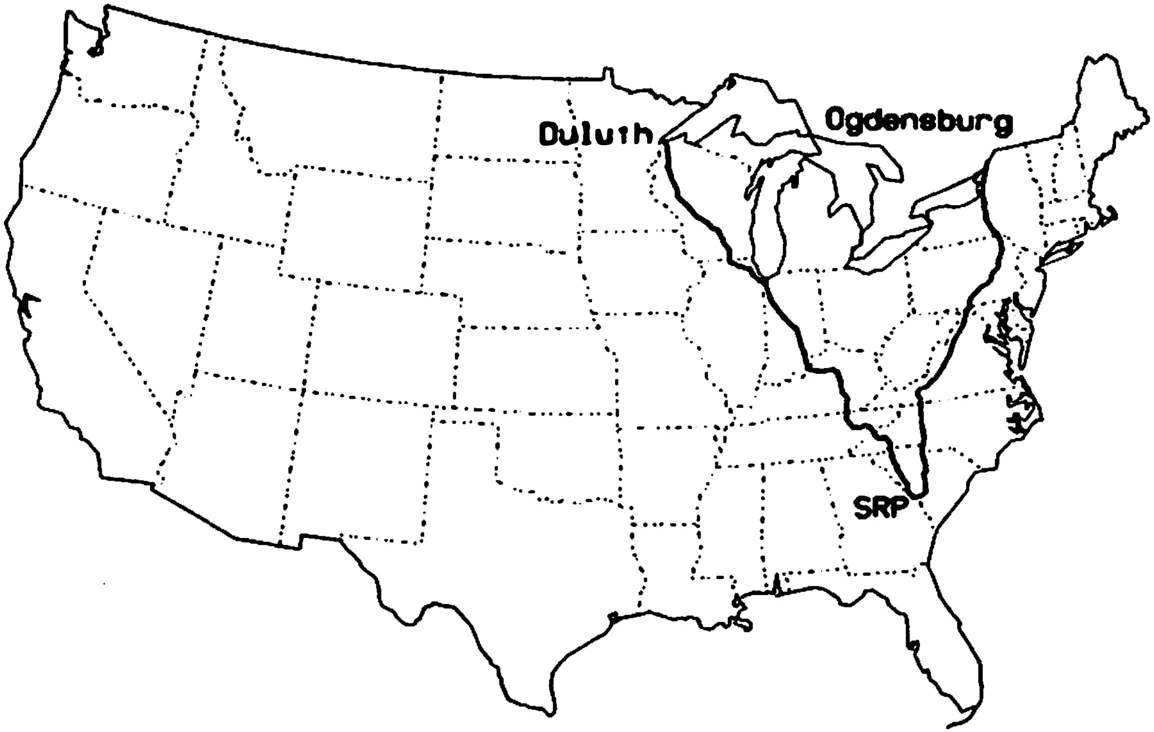


Figure 1.3 United States Routes Between Chalk River and SRP.

fifty-five hours to complete over a distance of 2,384 miles (Figure 1.3). This alternative proved to be too costly for the NAC to undertake.

Thus, because of state and local restrictions, the shortest distance which could be traveled was double that of the original trip. Instead of making this inordinately long trip, NAC halted shipments of spent fuel from Chalk River and filed a series of complaints against the states and the local jurisdictions which had passed restrictions. In 1984, DOT ruled that the restrictions in New York and Michigan were inconsistent with federal regulations and they should be suspended (FR46632-46637, November 27, 1984). NAC resumed shipments of spent fuel through New York in September 1984, two years after they were suspended (Potter, 1984).

DOT has consistently ruled against state and local restrictions which prohibit the movement of radioactive material on major highways (Jacob and Kirby, 1984). Even with the knowledge that DOT will strike down these laws, localities continue to pass them because they want to insure their own area will be as safe as possible. Routing spent fuel by the shortest path from each reactor will continue to be a source of consternation for state and local governments which are in the primary transport

corridors. Alternate sets of criteria for routing which minimize measures of risk instead of distance or time could provide a more palatable solution to the spent fuel transport question for state and local governments.

The Risk and Consequences of Shipping Spent Fuel

A number of studies have been conducted on the risk of spent fuel transportation to people and property. These studies have concluded that the exposure to radiation does pose a threat to the immediate environment around the spent fuel cask. The dosage from a package of radioactive material depends on the amount of radiation which escapes through the container shielding. The dosage of radioactive material is expressed in rems (roentgen equivalent in man) or milirems (rems/1000). This is a measure of the biological damage done to the average person by radiation (Rees, 1967). The term person-rem or person-milirem refers to the average population dose for the people who have had some exposure to radiation.

Radiation health effects include genetic damage to cells and latent cancer. These conditions may not manifest themselves until many years after the exposure has occurred (FR7140, January 31, 1980). Current theories contend that even low doses of radiation over a long period of time will

have cumulative harmful effects and that all exposures should be minimized whenever possible (De Steese and Rhoads, 1978).

Two types of risk are considered in the literature devoted to the movement of radioactive material. The first is the radiation exposure from normal, incident free transportation. The second category is that of public health risks and economic loss from accidents involving radioactive material.

Incident Free Transportation

Incident free transportation consists of those cases in which nothing unusual occurs while moving a quantity of radioactive material between two locations. No radioactive material is released from containment and no loss of shielding occurs. Nevertheless, incident free transportation does result in radiological impacts. People along the transport route and transport personnel will be exposed to external penetrating radiation that has passed through the packaging and other intermediate shielding (USDOT, 1981).

The estimated total annual population dose from normal radioactive material transportation in 1985 is 25,400 person-rem. The predicted result of this level of

exposure is 3.08 latent cancer fatalities and 4.4 genetic effects annually. While the value of 25,400 person-rem seems quite large, it is rather small when compared to the 40 million person-rem received by the total United States population in the form of background radiation (FR7144, January 31, 1980). The number of deaths must also be kept in perspective when one considers that there are about 5,000 latent cancer fatalities annually from natural background, medical, and industrial exposure (Taylor et al., 1978).

The detrimental effects of radiation exposure in incident free transportation are one of the reasons that DOT and NRC have adopted the transport policies which require that radiation exposure should be kept to a minimum whenever possible. Routes which result in the least exposure to the general population are preferred by both agencies (USDOT, 1981 and Kasun, 1979).

Consequences of an Accident

The consequences of an accident are based on the amount of leakage, the distance over which the leak spreads, the population density of the surrounding region, and the land use in the immediate vicinity (USNRC, 1977). The probability of an accident, the likelihood that

a truck carrying radioactive material will have an accident, is stratified by the severity of accidents (Elder et al., 1978 and Fullwood et al., 1978). From 1971 to 1979, there were 323 highway transportation accidents involving radioactive materials. Of this number, 275 resulted in releases of radioactive material. None of these releases involved spent fuel casks (FR7140, January 31, 1980).

Tests at Sandia National Laboratory in Alburquerque, New Mexico show that high level radioactive containers can stand at least 60,000 pounds of total force without any resulting leaks. The type of accident which would result in a force of this magnitude will occur approximately once every $1.82 * 10^{8}$ miles (Foley et al., 1974).

If, however, a cask is ruptured and radioactive material is released, the degree of dispersion will be determined largely by the atmospheric conditions. Under moderately stable meteorological conditions, the radioactive plume could extend up to six miles from the scene of the accident. Under more turbulent weather conditions, the radiation plume could extend downwind thirty-seven miles contaminating the land and people in its path (Resnikoff, 1983).

Consequences of an Accident - Human Exposure

The effects of contamination can be very complex and long lasting. Direct inhalation causes the most damage because the radiation has a direct effect on the internal organs. The radionuclieds which fall to the soil can be transferred from vegetation, to animals, and eventually to people through the food chain (USNRC, 1977).

Various estimates have been made about the damaging effects an accidental release from a high level spent fuel shipment would have on the population in the surrounding area. DOT estimates $1.75 * 10^{-2}$ annual latent cancer fatalities and an equal number of genetic effects due to radioactive material transport accidents (FR7144, January 31, 1980). NRC estimates that there will be 10^{-3} latent cancer fatalities annually due to accidents (USNRC, 1977).

The likelihood of an accident which would result in the release of a substantial amount of radioactive material in a densely populated metropolitan area is placed at $3 * 10^{-9}$ by the NRC. In the event this tragedy does occur, some individuals would suffer severe radiological damage. The NRC estimates that one early fatality would be expected and as many as sixty people would suffer serious damage to

their health. Latent cancer fatalities resulting from such a major release would be as many as 150 in the following thirty years (USNRC, 1977).

Consequences of an Accident - Economic Cost

If radioactive materials are released in a accident, nearby property could become contaminated. The expense of decontaminating the property and its the unavailability for productive purposes are the major economic impacts of a transportation accident. These costs will vary according to the types of property which are contaminated.

If radioactive material is released from a cask during an accident in a rural area, it will be deposited on the vegetation and soil. People and livestock must leave the area and the first four inches of topsoil should be removed. All water usage in the immediate area would have to come from wells because the surface supply would be contaminated (Resnikoff, 1983).

Accidents in urban areas would also be costly. Nearby public facilities such as schools, hospitals, and government offices would be required to close. People would have to be evacuated from their homes and provided with temporary housing. Businesses, offices, and factories would also be closed for a time to enable the

decontamination of the area. The cost estimates of the shut down time, property damage, and decontamination in an urban area vary widely, from a low of $1.2 billion by the NRC (1977) to a high of $8 billion by Resnikoff (1983).

Existing Hazardous Material Flow Models

A number of network flow models have been developed in recent years to represent the movement of hazardous materials in general. Some of them have incorporated features which assess the risk or seek to minimize it along the route.

Robbins' Minimum Risk Routing Model

Robbins' (1981) minimum risk routing model for the transport of hazardous materials determines a shortest distance and a minimum population route between two points on a network. The shortest distance and minimum population paths are calculated using a linear programming model. Robbins uses a Poisson distribution model to estimate the number of people along each route who would be affected by an accident. He then compares the two route population figures using a Student`s t-test to see if there is a significant difference between the populations exposed to the shipments.

Robbins' work represents an important step in the modeling of general hazardous materials flows, but it cannot accurately be used to represent high level radioactive materials shipments. There are unique hazards posed by radioactive material which have not been incorporated in this model. Robbins only considers the static population along the hazardous materials route. Yet, Yadigaroglu (1974) points out that the people on the highway with the spent fuel shipments receive dosages equal to, or sometimes greater than the dosages, received by people living along the route. Therefore, a means of incorporating people traveling on the highway into the risk formulation should be developed.

Property values along the route should also be considered. An accident which results in a leak of radioactive material not only damages living organisms, it also entails substantial costs to the local government and property owners. Robbins' model does not consider the property factor.

Only two alternate routes are considered by Robbins, a minimum population and a minimum distance path. The high density of the interstate network, especially in the more

densely populated Eastern United States, gives shippers many alternate paths which can be taken without inordinately raising the cost of spent fuel movement.

Robbins does not take into consideration the competition between shipments for certain strategically located links. There is no penalty for multiple shipping along one link. If several origins, destinations, or both exist, some links may be used very heavily by a number of shipments between different places. The high degree of usage along these links is not considered to be a problem in the model; i.e., there are no equity considerations in Robbins' model. There is no provision to shift some of the traffic from these heavily traveled links to lesser congested routes.

Reeves' Covering Model

Reeves (1982) develops a model which determines the optimal location of hazardous materials emergency response centers and assigns flows on a network so as to maximize the coverage by these centers. Two algorithms are used to determine the best location for the centers. The results of both algorithms are compared to determine a set of optimal locations.

Reeves' covering model approaches the topic from a different perspective than Robbins. Its major focus is on accident probabilities and consequences. The model does not consider the damage done from incident free transport. This leaves a significant gap in the analysis of spent fuel shipments because the largest component of the risk factor is the radiation resulting from the normal incident free movement (Maass et al., 1983).

The HIGHWAY Model

One of the major tools used by the Department of Energy to predict the flow of radioactive material shipments is the HIGHWAY model, developed at Oak Ridge National Laboratory (Joy and Johnson, 1983). This model uses a shortest path algorithm designed by Whitaker (1977) to predict routes on the United States highway system. The objective function of the algorithm minimizes a combination of time and distance parameters on each link to find the shortest path. The model has a number of options which allows it to route along preferred highways, find peripheral paths around large cities, and avoid zones which have legislative restrictions on them. After the shortest path is determined, the population is calculated for the total path distance. The RADTRAN model is then used to

find the total risk for that path (Taylor and Daniel, 1983).

The major problem with the HIGHWAY model is that it does not incorporate any form of risk into its initial routing calculations. It is only after the routes are determined that the risk calculations along each path are made. There is no attempt to minimize risk to population or property in this evaluation.

There is no provision for automatically calculating alternate routing patterns in the HIGHWAY model. It does not limit the number of shipments over specific links. The result of this limitation is that if a number of reactors are shipping to one site, the flow pattern will have a tree structure (McGuire et al., 1984). Fewer and fewer links are used as the spent fuel moves closer to its destination. The result is a higher risk value for those people along the shipment routes on the receiving end of the network.

Conclusion

In the following chapters, two models, the Minimum Total Transport Risk Model (MTTRM) and the Equilibrium Transport Risk Model (ETRM) are developed and demonstrated. The MTTRM assigns a least risk path for the shipments from each reactor to a repository. This is an

efficient way to ship the spent fuel because the total risk for society is minimized by exposing a few people to a relatively high degree of risk. In this case, everyone may share the benefits of nuclear power, while only a few suffer the consequences of radiation exposure when the spent fuel is shipped. In some cases, the risk will be totally shifted away from the nuclear power beneficiaries to segments of the population which do not receive any of their power from nuclear reactors.

The ETRM distributes the shipments over a network so that all routes which are used share an equitable minimum risk. Although more people are exposed to radiation, the dosages are at a much lower level than with the MTTRM.

These models overcome many of the shortcomings of the approaches discussed above and address the issues raised in the previous cases. They both consider incident free transport risk and accident risk. The emphasis placed on incident free transport risk and accident risk can be varied by using different weights for each risk factor. This ability to weight different types of risk, enables the model to better reflect the values of society or the decision makers. For example, if there is great apprehension about the possibility of an accident exposing people to radiation, then this factor can be weighted

heavily. The resulting routing pattern will reflect this concern by avoiding these densely populated regions and highway segments with high accident rates.

The probability of an accident occurring and various levels of radiation exposure which might result from different accident severities are also considered. For instance, the consequences of an accident which results in a breech in a cask would be quite severe, but the probability of such an event occurring is very small. Each of these accident probabilities and the detrimental consequences of radiation exposure are reflected in the accident risk calculation.

The versatility of these two models is also an advantage. Even though the MTTRM and ETRM are complex models which are specifically oriented toward spent fuel shipments, they can also be applied to other types of hazardous materials. The elimination of the incident free risk data from the analysis and an alternate probability formulation for the specific type of hazardous material would allow the models to be applied to any type of shipments.

CHAPTER 2

THE EQUILIBRIUM TRANSPORT RISK MODEL AND THE MINIMUM TOTAL TRANSPORT RISK MODEL

The goal of this research is to develop a set of models which will allow decision makers to compare the risk of transporting spent fuel over a network. The traditional model that is applied in this type of research uses the shortest path algorithm, which determines minimum cost, distance, or time routes through a network (Joy and Johnson, 1983). The network over which spent fuel shipments travel is the interstate system. In most cases, interstate highways in the United States run through the centers of metropolitan areas. As a result, a least cost route, which minimizes distance or time, usually sends spent fuel through the heart of many metropolitan areas. This also tends to increase the exposure of high concentrations of population and valuable property to radiation.

Another approach to the routing of hazardous material such as spent fuel is to minimize the risk of shipping. The first step in this process is to determine a measure for risk. In this case, the measure will be in units of radiation. After this, objectives must be chosen. The

objectives used in this research seek to ship spent fuel in a manner which will be efficient or equitable in terms of risk.

Elements of Risk in Routing Spent Fuel

The risk of moving spent fuel can be considered at two levels: (1) incident free transport and (2) the possibility and consequences of an accident. In each of these cases, exposure or threat of exposure to persons and property must be considered.

Incident Free Transport Risk

Incident free transport will expose the people living and working along a highway over which spent fuel is shipped to some radiation. The population density, length of the highway segment, velocity of the truck used, and the amount of radiation emitted from the cask are important inputs in determining the incident free spent fuel transport risk factor for people on the highway periphery. The passengers and drivers on the highway with the spent fuel carrier will also receive some radiation. The important considerations here are the length of the link, the number of vehicles in each lane, and the speed at which these vehicles are traveling.

The risk factor for the truck crew must also be considered. The distance and speed at which the truck travels determine the amount of radiation they receive. At points along the route, the truck crew will stop to rest and eat. Other people at these rest stops or truck stops will also be exposed to the radiation emitted from the casks. The longer the trip, the greater the number of stops the truck will make.

Each of the above situations has been expressed in equation form by DOT (USDOT, 1981). The DOT equations have been modified for these efficiency and equity models because extensive data requirements and computation time would be required for the original formulations. The major modifications for incident free transport risk are in the form of data aggregation. Since the study area covers most of the United States, the population data which is used is at a gross level. The original DOT formulations require a greater level of detail for their calculations.

The exposure factor equations, F_{mji}, for each of the circumstances previously discussed are defined as follows:

Part 1. Dose in pmr to the persons residing or working along the route:

$$F_{1ji} = \frac{p_{5ji}\, d_{ji}}{v_{ji}}\, c_1 , \qquad (2.1)$$

where:

p_{5ji} = Average population density per square mile in a 5 mile band along either side of link ji,

d_{ji} = Length of the link ji in miles,

v_{ji} = Average speed of vehicles on the link ji in miles per hour,

c_1 = DOT's constant conversion factor for use in estimating the incident free radiation exposure factor for people along a link.

Part 2. Dose in pmr to people in oncoming vehicles on the same highway as the spent fuel shipment:

$$F_{2ji} = \frac{d_{ji}\, t_{ji}}{v_{ji}^{2}}\, c_2 , \qquad (2.2)$$

where:

t_{ji} = Average traffic count on link ji in vehicles per hour,

c_2 = DOT's conversion factor for use in estimating the incident free radiation exposure factor for people in oncoming vehicles.

Part 3. Dose in pmr to people in vehicles moving in the same direction as the spent fuel shipment:

$$F_{3ji} = \frac{d_{ji}\, t_{ji}}{v_{ji}^{3}} c_3 , \qquad (2.3)$$

where:

c_3 = DOT's conversion factor for use in estimating the incident free radiation exposure factor for people in vehicles moving in the same direction as the spent fuel shipment.

Part 4. Dose in pmr to the truck crew:

$$F_{4ji} = \frac{0.8\, d_{ji}}{v_{ji}} c_4 , \qquad (2.4)$$

where:

c_4 = DOT's conversion factor for use in estimating the incident free radiation exposure factor for the truck crew and people at truck stops and rest stops.

Part 5. Dose in pmr to people at truck stops and rest stops:

$$F_{5ji} = \frac{0.2\, d_{ji}}{v_{ji}} c_4 . \qquad (2.5)$$

The sum of equations (2.1) to (2.3), along with a combination of (2.4) and (2.5), represent the total incident free transport exposure factor equation.

$$F_{ji} = \frac{p_{5ji}\, d_{ji}}{v_{ji}} c_1 + \frac{d_{ji}\, t_{ji}}{v_{ji}^2} c_2$$

$$+ \frac{d_{ji}\, t_{ji}}{v_{ji}^3} c_3 + \frac{d_{ji}}{v_{ji}} c_4 , \qquad (2.6)$$

where:

F_{ji} = Incident free risk measure per mile along link ji in pmr. (This is an expected exposure rate, but the term expected is not used because incident free exposure will always occur.)

Expected Accident Risk to the Population and Property

The DOT guidelines suggest that the hazardous material truck driver fatality rate, the general truck driver fatality rate, or the hazardous material truck fatal accident rate be used to calculate the expected accident rate for trucks carrying spent fuel (USDOT, 1981). Since data is currently available on the number and location of radioactive materials accidents, this information is used in the accident formulations because it is more applicable to these models (Waste Technology Services Division of Westinghouse Electric Corporation, 1985 and USDOT, 1985). State accident data is combined with the probability of different severities of accidents occurring and the resulting exposures from those accidents, which have been calculated on a nation wide basis (Fullwood, et al., 1978). These probabilities are used to find the amount of exposure which would result from each category of accident in each state (Table 2.1). The expected exposure rate is calculated as follows:

$$r_{ji} = \sum_{q} \frac{U_q e_q}{\sum_q U_q} a_s \text{, for all ji in state s,} \quad (2.7)$$

Table 2.1

ACCIDENT PROBABILITY AND CONSEQUENCES

Severity Category	Accident Probability Per Shipment Mile	Person-milirems of Exposure for Each Accident Category
1	2.4E-8	1.7E-15
2	2.0E-10	1.4E-12
3	1.6E-12	4.1E-11

Source: Fullwood, R. R.; Mendoza, Z.; Ritzman, R. L.; Aron, W.; and Straker, E. A. "Radiological Risk Analysis of Truck and Rail Transportation of Nuclear Wastes." Proceedings of the Fifth International Symposium on Packaging and Transportation of Radioactive Materials. Las Vegas, Nevada: 933-935, May 7-12, 1978.

where:

r_{ji} = Average rate of exposure in pmr for each mile in case of an accident on link ji,

U_q = Probability of a radioactive materials accident of type q in the United States,

e_q = Exposure in pmr for each accident category q,

a_s = Accident rate per mile in state s.

Each portion of the highway has an accident rate, a_s. As the rate increases, the probability that the population and property along the highway will be exposed to a radiation leak due to an accident will increase. Therefore, the risk to the population and property along a link will be influenced by the accident rate.

The damaging effects of a radiation leak resulting from an accident will be felt over a wider area than that of incident free transport. Population density and property type over a much broader area must be considered under these circumstances.

The probability of an accident which releases radioactive material occurring and its consequences to the general public are represented in equation (2.8). The population within a ten mile radius on either side of the highway is considered to be in the vulnerable zone. The population in this zone is multiplied by the expected accident risk.

$$A_{ji} = p_{10ji} \, r_{ji} , \qquad (2.8)$$

where:

A_{ji} = Accidental radiation exposure factor for the general population within a ten mile band along either side of link ji,

p_{10ji} = Average population density in a 10 mile wide band on both sides of link ji.

The probability of an accident which releases radioactivity occurring and its consequences to nearby property are represented in equation (2.9). The land considered is in a ten mile wide zone extending out from either side of the highway. Each land use type will have an economic consequence multiplier associated with it. Land area types include farmland, single family housing, multi-family housing, commercial, parks, and public areas.

The sum of the products of the land area, the economic constant, and the accident rate will determine the risk factor for property on link ji.

$$E_{ji} = \sum_{k} u_{10lji} \, w_{k} \, r_{ji} , \quad \text{for all } k = 1,\ldots,6 \text{ land use types,} \qquad (2.9)$$

where:

E_{ji} = Economic consequence of an accident on link ji in pmr dollars,

u_{10kji} = A land area of type k in a 10 mile wide band on both sides of link ji,

w_{k} = DOT's economic consequence multiplier for land use type k.

The Total Measure of Risk

The criterion used to evaluate each link ji is the total risk factor:

$$\beta_{1} F_{ji} + \beta_{2} A_{ji} + \beta_{3} E_{ji} , \qquad (2.10)$$

where:

β_{1} = Weight parameter for incident free transport risk,

β_{2} = Weight parameter for the expected population exposure in case of an accident,

β_{3} = Weight parameter for the expected economic loss to property in case of an accident.

The beta factors can be used to emphasize the importance of one type of expected exposure over the others. This will give policy makers a greater set of options to use when trying to decide how to route the spent fuel.

Description of the Models

The Efficiency Model

The Minimum Total Transport Risk Model (MTTRM) determines the minimum risk route through the entire network and sends all the spent fuel along this designated path. This solution maximizes risk efficiency by guaranteeing that the risk to all of society is minimized. However, the sacrifice made by the people along this designated path in terms of exposure to radiation and risk of accident may be inordinately high.

Since it is an efficient solution, the MTTRM seeks to minimize risk over the whole network. The path it selects usually avoids highly populated urban areas, often taking peripheral interstates through less populated areas. Once the minimum risk route is found, all the shipments are sent along this one route.

The objective function for the MTTRM is similar to that of the standard shortest path formulation (Bradley et al., 1977) The sum of the risk factors over all highway segments ji is minimized:

$$Z = \min \sum_{b} \sum\sum_{ji \epsilon N} (\beta_1 F_{ji} + \beta_2 A_{ji} + \beta_3 E_{ji}) x^b_{ji} , \qquad (2.11)$$

s.t.

$$\sum_{i \epsilon N_j} x^b_{ji} - \sum_{i \epsilon N_j} x^b_{ij} = \begin{cases} T^b, & \text{if j is a reactor b} \\ 0, & \text{otherwise, for all b,} \\ -T, & \text{if j is the repository} \end{cases} \qquad (2.12)$$

$$x^b_{ji} \geqslant 0, \quad ji \epsilon N \quad \text{for all b,} \qquad (2.13)$$

where:

Z = Sum of the risk values on the minimum risk paths from each reactor b to a repository,

x^b_{ji} = Number of trips along link ji from reactor b,

N_j = {i ¦ where arc (j,i) exists},

T^b = Total number of trips from reactor b to a repository,

T = Total number of trips from all reactors to a repository,

b = Source node or reactor,

N = Total network.

Constraint (2.12) insures that all the spent fuel will be shipped from each of the reactors, it eliminates the possibility that any spent fuel will be left at an intermediate node, and requires that all of the spent fuel which leaves each reactor be sent to the repository. The MTTRM produces a globally optimal assignment which is the same as the user optimal path, since link risk values are constant.

Since the value of $(\beta_1 F_{ji} + \beta_2 A_{ji} + \beta_3 E_{ji})$ is assumed to be a constant for each link ji, let:

$$c_{ji} = (\beta_1 F_{ji} + \beta_2 A_{ji} + \beta_3 E_{ji}) . \qquad (2.14)$$

The objective function (2.11) then becomes:

$$Z = \min \sum_b \sum\sum_{ji \epsilon N} (c_{ji} x^b_{ji}) . \qquad (2.15)$$

The MTTRM can then be expressed with an objective function, (2.15), subject to (2.12) to (2.13).

The MTTRM model can be modified to generate a shortest distance or least cost route. Link distance is an input variable which can be used to calculate the minimum length path. A freight rate for different regions in the United States can be used to calculate cost of transportation over each link if the least cost path is desired. If all the variables in (2.6) except d_{ji} are assumed to be constant and in (2.10) β_1 is 1.0 and β_2 and β_3 are set to 0, then the results of (2.15) will be a shortest distance or least cost path over the network. This modification of the data and the results it generates leads to the conclusion that a shortest distance or cost model is a simpler form of the MTTRM.

The Equity Model

Another approach to this problem of spent fuel shipments is to maximize equity. Instead of putting the total burden of radiation exposure on the people along one route, the shipments can be divided among several routes. This results in a decrease in efficiency and an increase in cost. The decrease in efficiency stems from the fact that more people in society experience some exposure to the radioactivity emitted by the spent fuel. The increase in cost is caused by the additional shipment miles which are

driven by the spent fuel haulers over the alternate minimum risk routes. The positive result of this approach is that the exposure rate for people along the highways over which spent fuel is first carried can be reduced.

The Equilibrium Transport Risk Model (ETRM) chooses a set of K paths and distributes spent fuel shipments on them so that total risk factor for each path used is equal and minimal. A set of K paths along the links of a network is at equilibrium if (1) the K routes traversed between the origin and destination nodes have the same risk value and (2) there does not exist an alternative unused route between the origin and destination whose risk per unit of flow is less than that of any of the K routes which are traveled. If the path risk values are not equal, then the value along the highest risk path can be lowered by redistributing the shipments along the other lower risk paths until an equilibrium is achieved. The final result of the model is a balanced minimum risk value for each route which is traversed.

The formulation of the ETRM is:

$$Z' = \sum_b D^b = \sum_b \min \sum_{ji \in P_a^b} (\beta_1 F_{ji} + \beta_2 A_{ji} + \beta_3 E_{ji}) x_{ji}^b, \qquad (2.16)$$

s.t.

$$|P_a^b| = K, \text{ and the risk along each path is equal,} \tag{2.17}$$

(2.12), and (2.13).

where:

Z' = Sum of the minimum equilibrium risk path values for all reactors b,

D^b = Minimum equilibrium risk path value for reactor b,

P_a^b = Traversed path number a in the network from reactor b to a repository.

K = the number of paths traversed. That is, the cardinality of the set $\{P_a^b\}$.

Equation (2.16) minimizes the risk values for each reactor b subject to the use of K paths and each path used by shipments from reactor b must have the same risk value.

The objective function (2.16) can be simplified with the use of (2.14). The ETRM objective function then becomes:

$$Z' = \sum_b D^b = \sum_b \min_b \sum_{ji \in P_a} (c_{ji} \, x_{ji}^b) \,. \tag{2.18}$$

The Equilibrium Risk Transport Model then has (2.18) as its objective function and constraints (2.12), (2.13) and (2.17).

Solving the Models

The Minimum Total Transport Risk Model and the Equilibrium Transport Risk Model are solved using the Moore algorithm (Moore, 1959). The MTTRM is solved by finding the least risk path through the network (Appendix A). All the shipments are then sent from the source node to the sink along this least risk route. The number of shipments is then multiplied by the risk factor on each link. This increased risk factor value replaces the current value on each traversed link. This solution gives the minimum risk value for all of society.

The rest of the algorithm solves the Equilibrium Transport Risk Model for $K > 1$ by finding a set of minimum risk paths. After the risk values on the first path have been updated from the original values on the network, Moore's algorithm is used again to find the minimum risk path. If the risk factor value of another path is less than the value of the current revised least risk path, then the total number of shipments is split among the additional path and the previously assigned path(s) so that the risk

factor for all paths is equal (Appendix B). The iterations of the algorithm will continue until the same least risk path is repeated. Any additional iterations will not reduce the objective function value because the same path structures will be duplicated.

The ETRM is a greedy adding algorithm. The greedy procedure recursively adds paths to the solution, starting with the shortest path and sequentially adding paths until K paths have been selected. Therefore, the set of paths at K-1 iteration is always contained in the Kth iteration (Handler and Mirchandani, 1979).

This type of algorithm which generates an equilibrium solution at each iteration is used because the size of the network to which the ETRM is being applied is much larger than the urban setting where the traditional network equilibrium assignment problem is normally used (LeBlanc et al., 1975). The equilibrium algorithm used in LeBlanc et al. (1975) will generate an equilibrium solution to the network traffic assignment problem only at the last iteration, but this end result is not applicable in this research. Usually, only the first few iterations of the ETRM are useful in assigning shipments of spent fuel across the United States because later routes generated by the

algorithm may be too long and costly to use. That is, the reduction in risk is not worth the increase in cost.

The risk values for all of the paths generated by the ETRM can be used to calculate a societal risk value for comparison to the individual path risk. The sum of the products of the minimum equilibrium risk factor for every reactor, D^b, and the number of paths traversed, K, from (2.16) determines the value of societal risk:

$$S = \sum_b K D^b , \tag{2.19}$$

where:

S = Societal risk value.

Results of a Sample Problem

Path and Societal Risk

A sample problem for a simple ten node network with one source (node 1), one sink (node 10), and ten shipments is solved using the algorithm described above (Figure 2.1). A single risk factor is used in the sample problem, so:

$$Y_{ji} = F_{ji} + A_{ji} + E_{ji} , \tag{2.20}$$

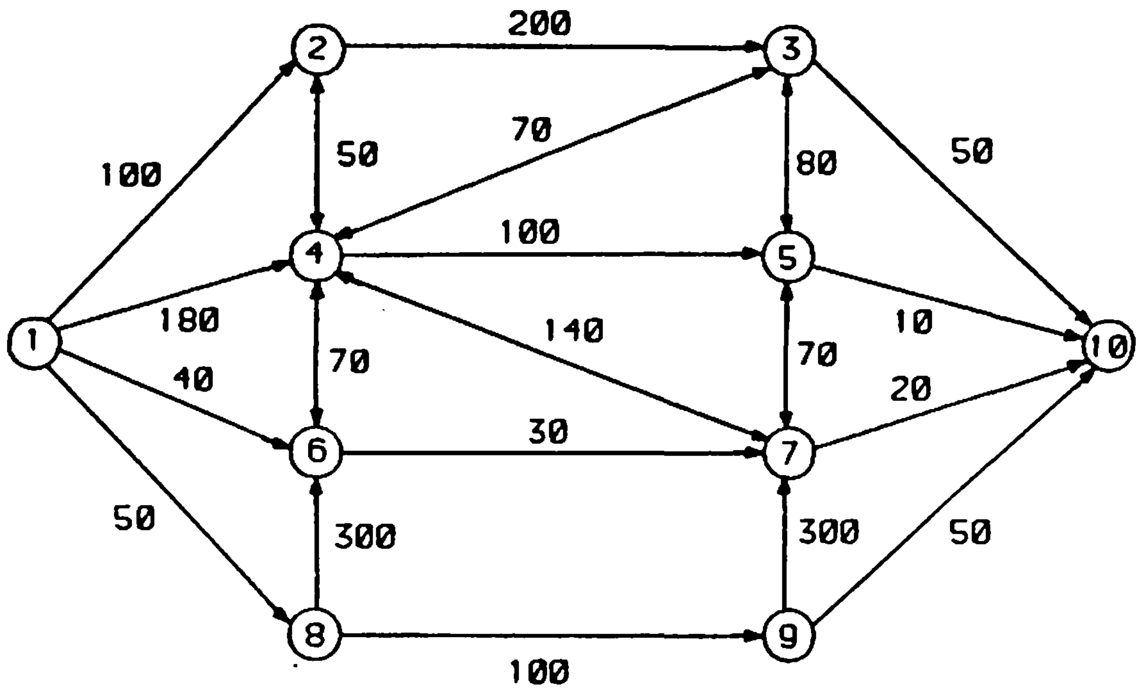


Figure 2.1 Risk Factors.

where:

Y_{ji} = a single risk value for each link ji.

One beta weight parameter is also used in this example problem:

$$\beta_1 = \beta_2 = \beta_3 = 0.6 \ . \qquad (2.21)$$

Thus, at each iteration of the program, the updated risk factor on each link which has been traversed is calculated by multiplying the number of trips by the risk factor and a beta weight parameter of 0.6. That is,

$$D^b_{ji} = \sum_{ji \in P^b_a} 0.6 \ x^b_{ji} \ Y_{ji} \ , \qquad (2.22)$$

where:

D^b_{ji} = risk value along link ji on the minimum risk path from reactor b. Since this is a single reactor example, b=1.

On the first iteration, the least risk path (1-6-7-10) is selected. All 10 shipments are sent along this route. The resulting change in risk value along each link is determined by (2.22). For example, link 1-6 has an initial

risk value of 40. When this value is incorporated into (2.22), the result is:

$$D_{16} = 0.6 * 10 * 40 = 240 .$$

The same principle holds true for links 6-7 and 7-10 (Figure 2.2). The sum of the increase link values is:

$$540 = 240 + 180 + 120 ,$$

(Table 2.2). This is the solution to the Minimum Total Transport Risk Model which minimizes societal risk.

The next series of iterations solves the Equilibrium Transport Risk Model. In the second intention, a lower value route is found. The route (1-8-9-10) has a risk value of 200. The spent fuel loads are then split between these two paths with 6.9 shipments going on path one and 3.1 on path two (Figure 2.3). The path risk value is also decreased from 540 to 372 in the second iteration (Table 2.2). In the third iteration a path of (1-2-4-5-10) is chosen. The change in shipment paths results in 5.6 shipments being sent over the first path, 2.5 over the second, and 1.9 over the third (Figure 2.4). The path risk value again declines to 300 (Table 2.2). The final

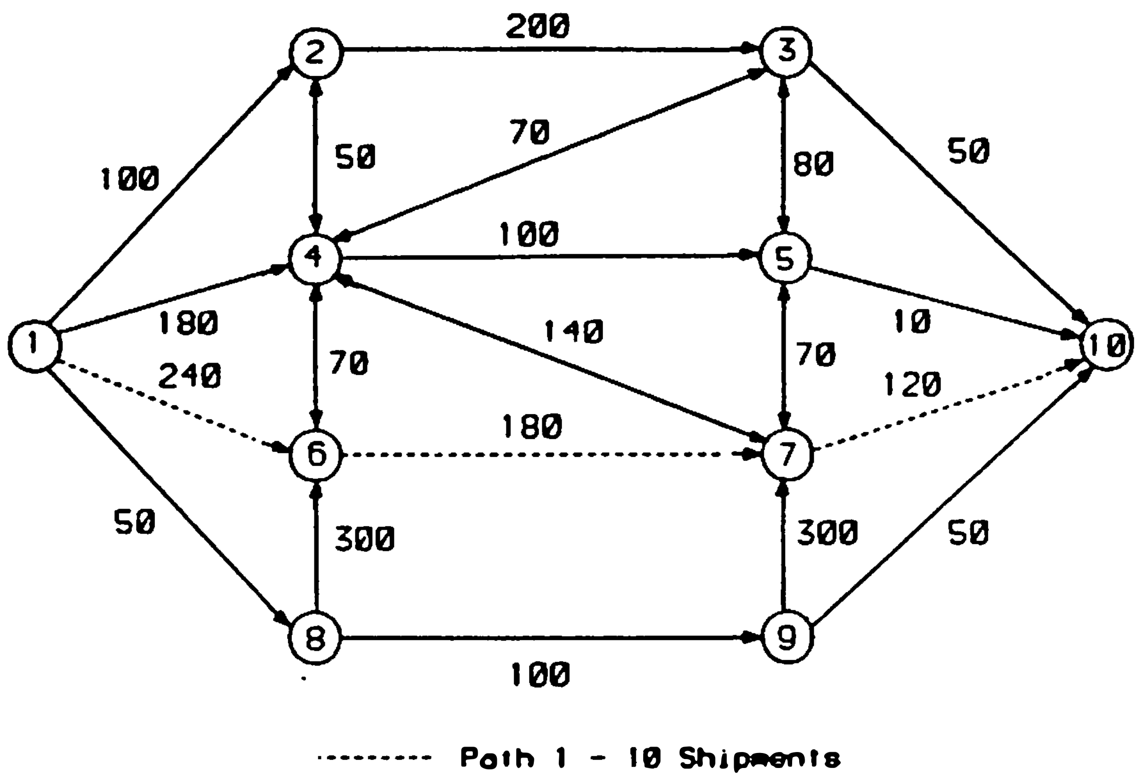


Figure 2.2 Risk Factors - 1 Path.

Table 2.2

RISK FACTORS

Number of Paths	Path Risk	Societal Risk
1	540	540
2	372	744
3	300	900
4	254	1,016

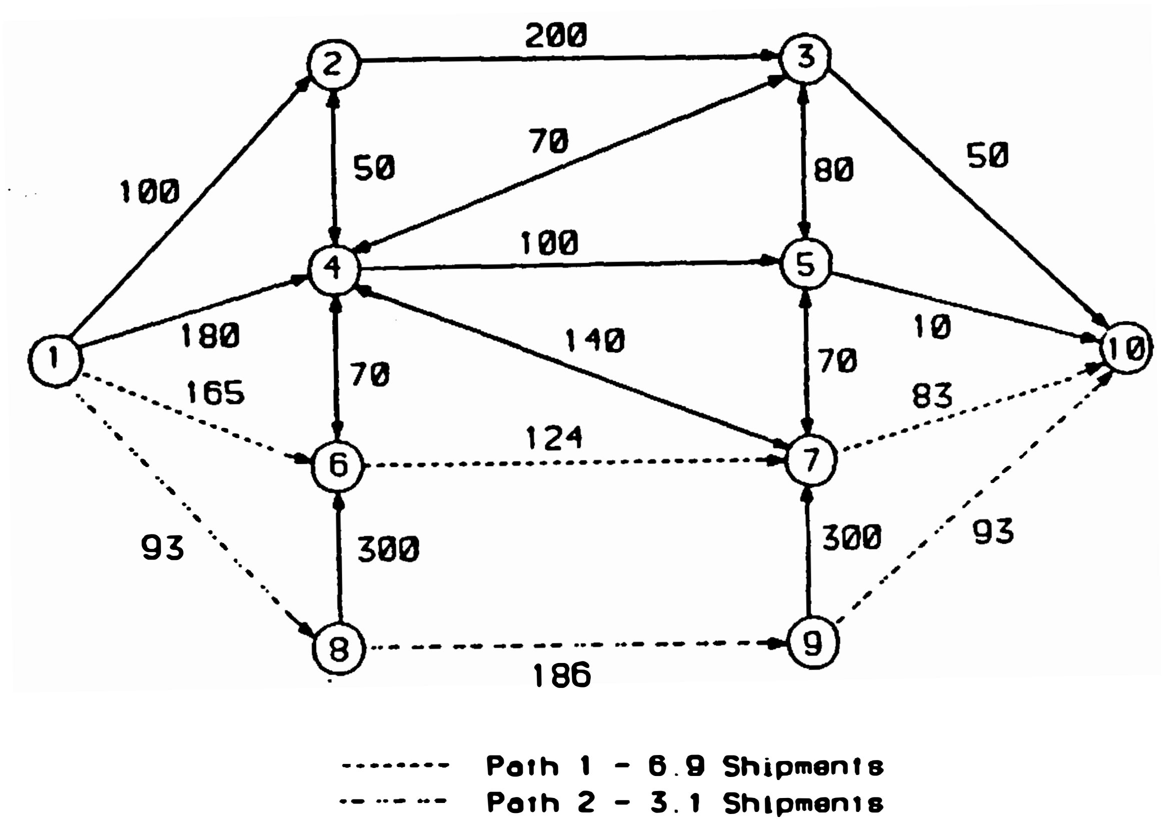


Figure 2.3 Risk Factors - 2 Paths.

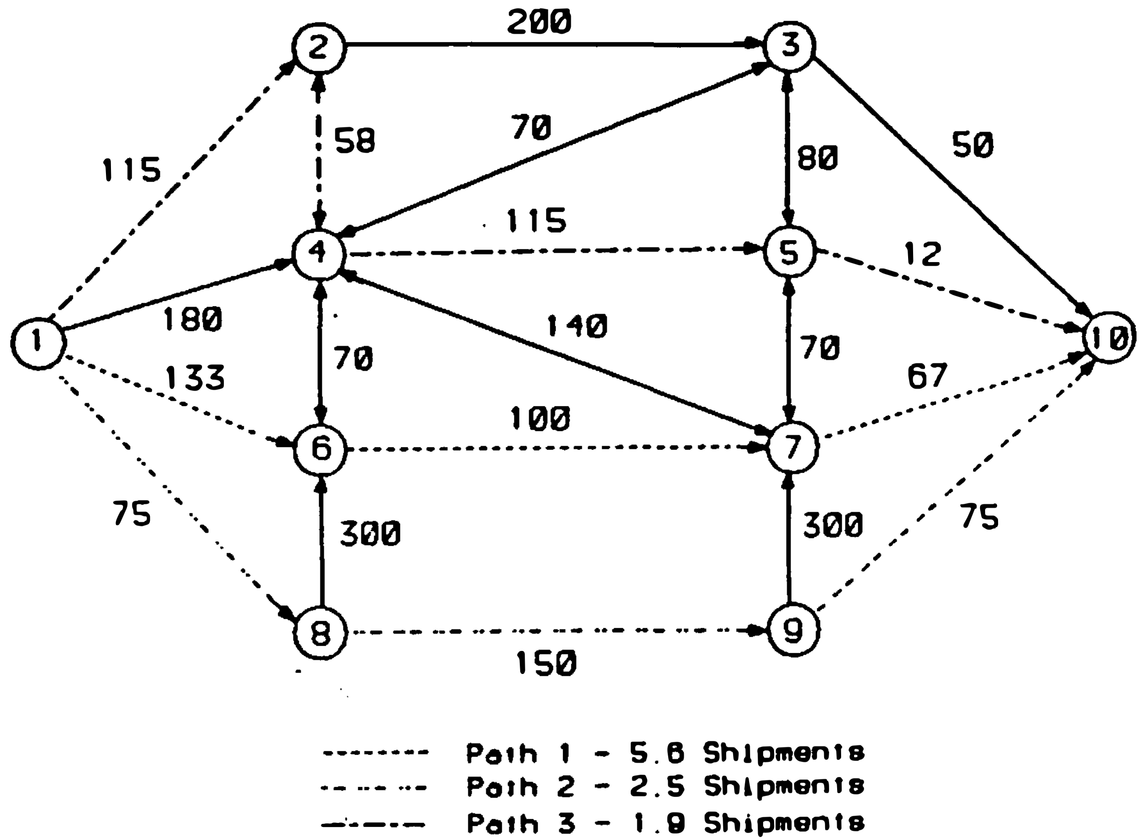


Figure 2.4 Risk Factors - 3 Paths.

iteration splits the routes among four paths and the path risk value is reduced to 254 (Figure 2.5 and Table 2.2). The result is an equilibrium of risk on the traversed highway routes of the network. The risk value for all routes is the same number and no additional route would have a lower value.

The total risk for all of society can also be calculated (Table 2.2). This value is obtained by multiplying the risk factor value for the paths by the number of paths at each iteration, as in equation (2.19). The first path gives the lowest MTTRM value since this is the minimum risk path. As the number of paths increases, the overall exposure rate grows larger. The first iteration generates a MTTRM value of 540. The second iteration increases this value to 744. The three paths generated have a total risk factor of 900. The last iteration of four routes increases the total societal risk factor to 1,016.

The results of the sample problem show that there is usually an inverse relationship between the total risk factor for society and that for the individual path. In the example network, if the Minimum Total Transport Risk Model is run, the total risk factor will be 540 for individuals along the traversed path. If the Equilibrium

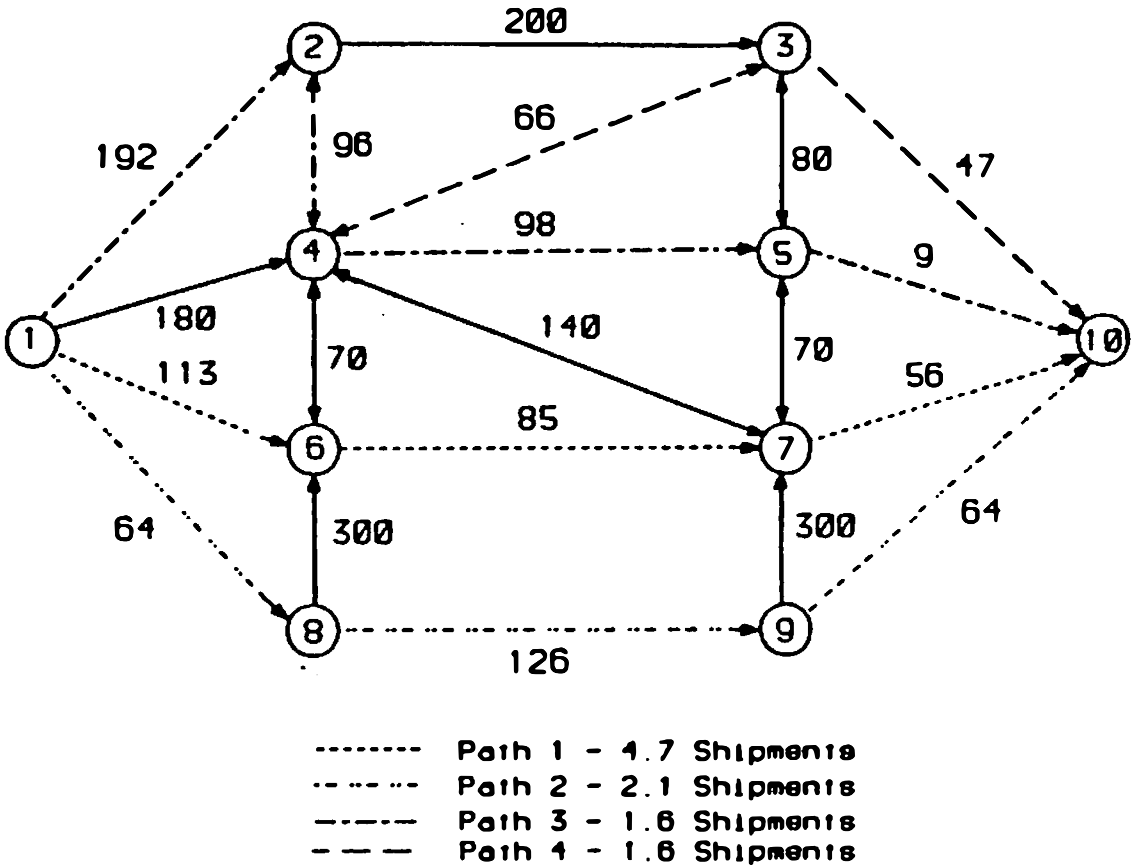


Figure 2.5 Risk Factors - 4 Paths.

Risk Transport Model is used and four paths are chosen, the risk factor for individuals along the initially traversed highway paths is reduced by 53 percent, but the risk to society will be increased by 87 percent.

The curve in Figure 2.6 provides information on the trade off between societal safety and individual path safety. The slope of the curve gives an indication of the degree of difference between the two risk factor measures. The steeper the slope, the greater the difference between path risk and societal risk. There is a major trade off between sending all shipments on a path and splitting them between two paths. The decrease in efficiency when the shipments are split into two paths may be offset by the 30 percent reduction in path risk. But, if the trade off between two and three paths or three and four paths is considered, the differences become rather small because the curve is flatter. The increases in societal risk may be too great to justify the decrease in path risk.

Risk and Distance

The risk factors generated by the MTTRM and ETRM also can be compared with a more commonly used shortest path model, like HIGHWAY (Joy and Johnson, 1983). If only distance is minimized over the same sample network used

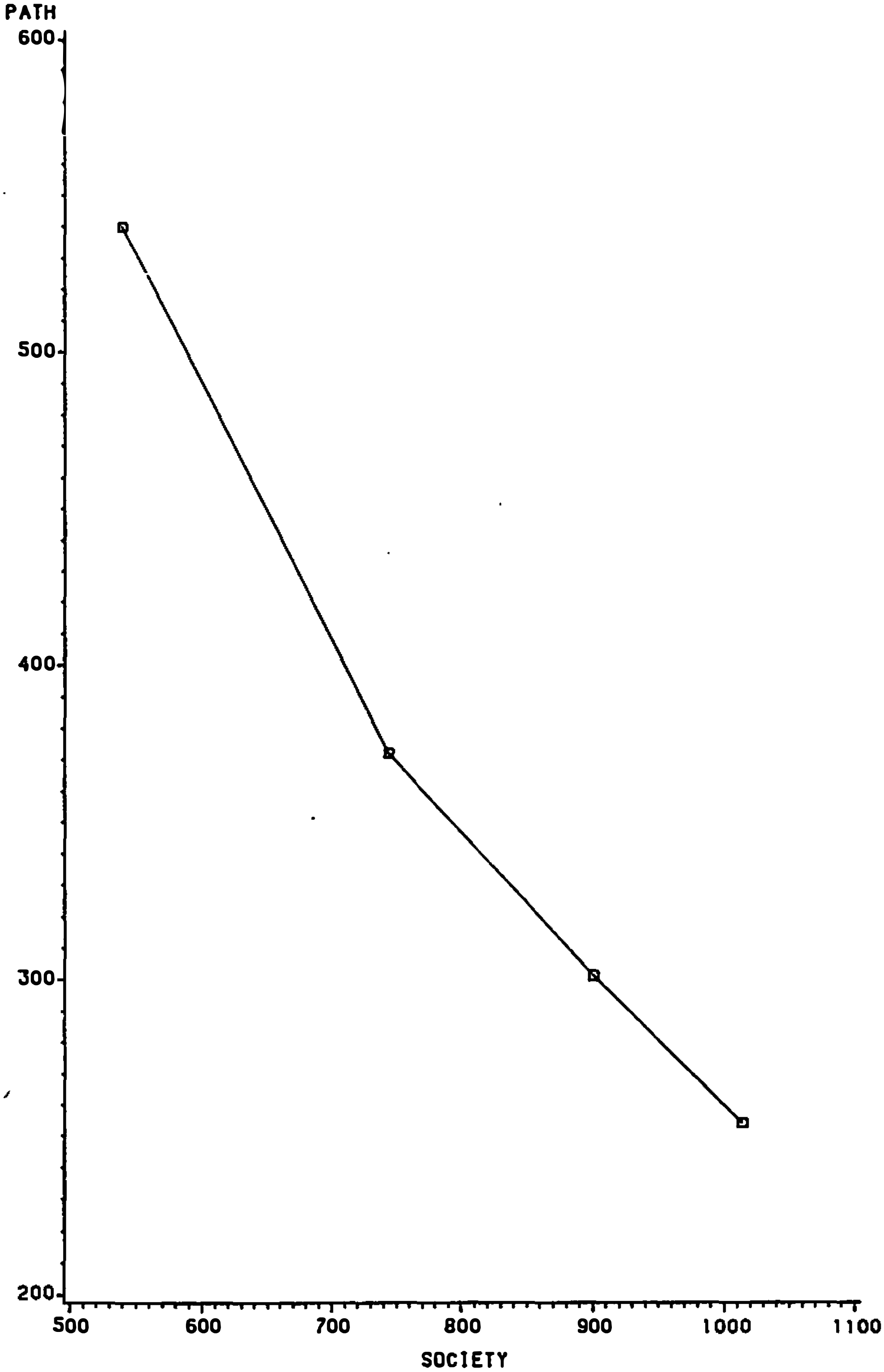


Figure 2.6 Risk Values for a Sample Problem.

before (Figure 2.7), the risk factor along this minimum distance route can be compared with that of MTTRM and ETRM risk factor. A risk value of 700 is obtained along the 55 mile path (1-4-5-7-9-10) when a shortest path algorithm is run for distance. This is much higher that that of the models which have the minimization of risk as one of their major objectives. The initial minimum risk path covers a distance of 220 miles, but only has a risk value of 90. There is, in this case, a trade off between distance and risk. A 75 percent reduction in mileage results in an 678 percent increase in risk.

Conclusion

Equity and efficiency can only be maximized at the same time when the population is uniformly distributed and has equal access to transportation (Morrill, 1974). In reality, it is impossible to maximize efficiency and equity at the same time because these uniform conditions do not exist (Mumphrey and Wolpert, p. 1973). When the range of solutions between the most efficient path and the most equitable set of paths is compared, policy makers can better understand the logical alternatives which are available. They can compare the risk to society with the risk to people living along each individual highway segment and choose a path or set of paths which will satisfy the

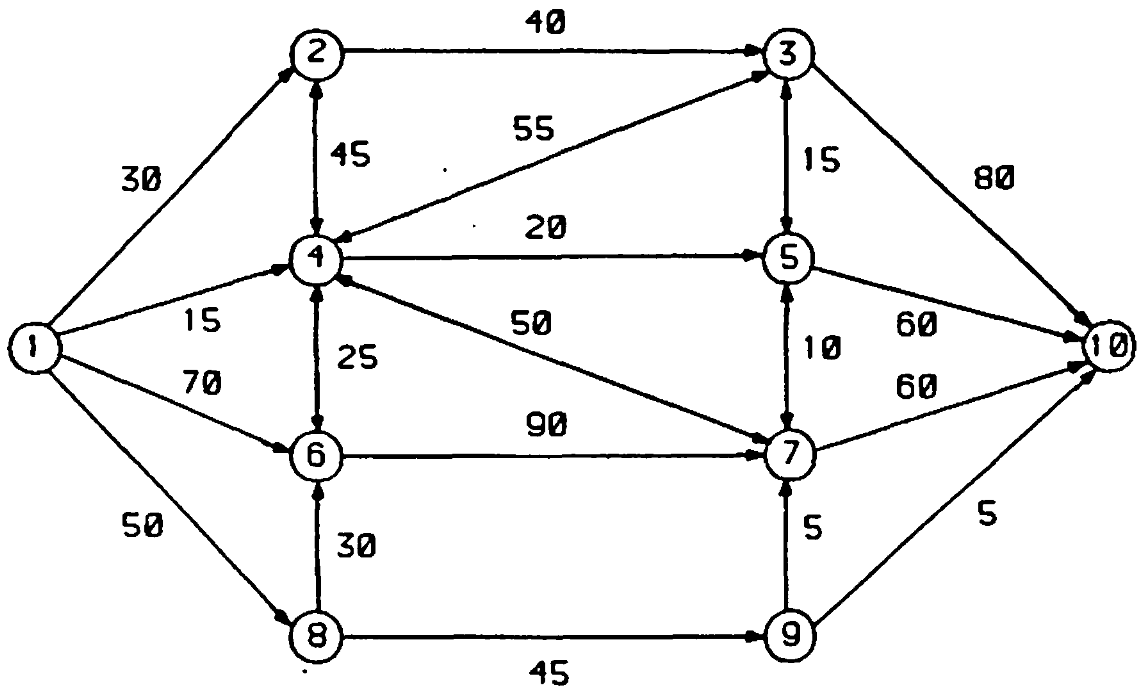


Figure 2.7 Distance.

efficiency and equity constraints that are placed on shipping the spent fuel.

Figure 2.6 (p. 62) and Table 2.2 (p. 56) provide a logical means by which the efficiency and equity of risk in shipping spent fuel can be evaluated. They give government officials at each level a gauge to measure risk. Central authorities such as DOE, DOT, NRC, and commercial freight haulers will strive for an efficient minimum cost or minimum risk shipment pattern for the movement of spent fuel. Thus, this group would advocate a one or two path scenario. By contrast, state and local officials may like to see a more dispersed pattern of shipments which would minimize risk at their local level. These officials would prefer a three or four path solution be implemented. The models give these different groups an opportunity to evaluate the cost and risk potential along a number routes. They provide a mechanism to reach a compromise on the routing of spent fuel.

The robustness of the MTTRM and ETRM provides a greater range of options for policy makers than they have had in the past. They can compare path and societal risk for a number of different routes and the economic consequences of these various options. The next chapter implements the two models by showing a number of minimum

risk and cost paths over which spent fuel would move between an individual reactor and a repository.

CHAPTER 3

THE APPLICATION OF THE MTTRM AND ETRM TO A SINGLE REACTOR AND REPOSITORY

The first application of the MTTRM and ETRM is for paths between a single reactor and a repository. This case represents the routing decisions which would be made if each individual reactor based its shipping decisions solely on the risk generated by its own trucks. No shipments from other reactors are considered, so there is no competition for links among different reactors.

Data Requirements

Data on the characteristics of the network and the flow of spent fuel over it are necessary to model the risk calculations for the network. The data needed to implement the model includes population density, highway mileage, vehicle speed, traffic count, and accident rates. This wide variety of data is not available at any one source. It had to be collected from the publications and computer files of various government and private sources. Much of the data was obtained from Oak Ridge National Laboratory. Other sources include Sandia National Laboratory and the Department of Transportation in Washington, D. C. Incident

free transport risk and the probabilities of damage to population and property resulting from an accident are calculated using these data. Once these values are found, the models can be implemented.

Network

A directed network of 137 nodes and 406 links was created for this research to simulate the shipment of spent fuel from the reactors to the repository sites (Figure 3.1). This network is composed mostly of interstate highways. Noninterstate segments are included in the network to connect reactor and repository locations to the interstate system.

Four locations are designated as sink points in the network. Three of these sites are the candidate repository sites for spent fuel in the Western United States: Deaf Smith County, Texas, Yucca Mountain, Nevada, and Hanford, Washington. The fourth site is DOE's candidate site for a monitored retrievable storage (MRS) facility for spent fuel, located near Oak Ridge, Tennessee (Figure 1.2, p. 8).

Ten reactors are selected as source points for spent fuel shipments in the United States (Figure 3.2). The Spent Fuel Logistics Model at Pacific Northwest Laboratory predicts that these ten reactors will generate

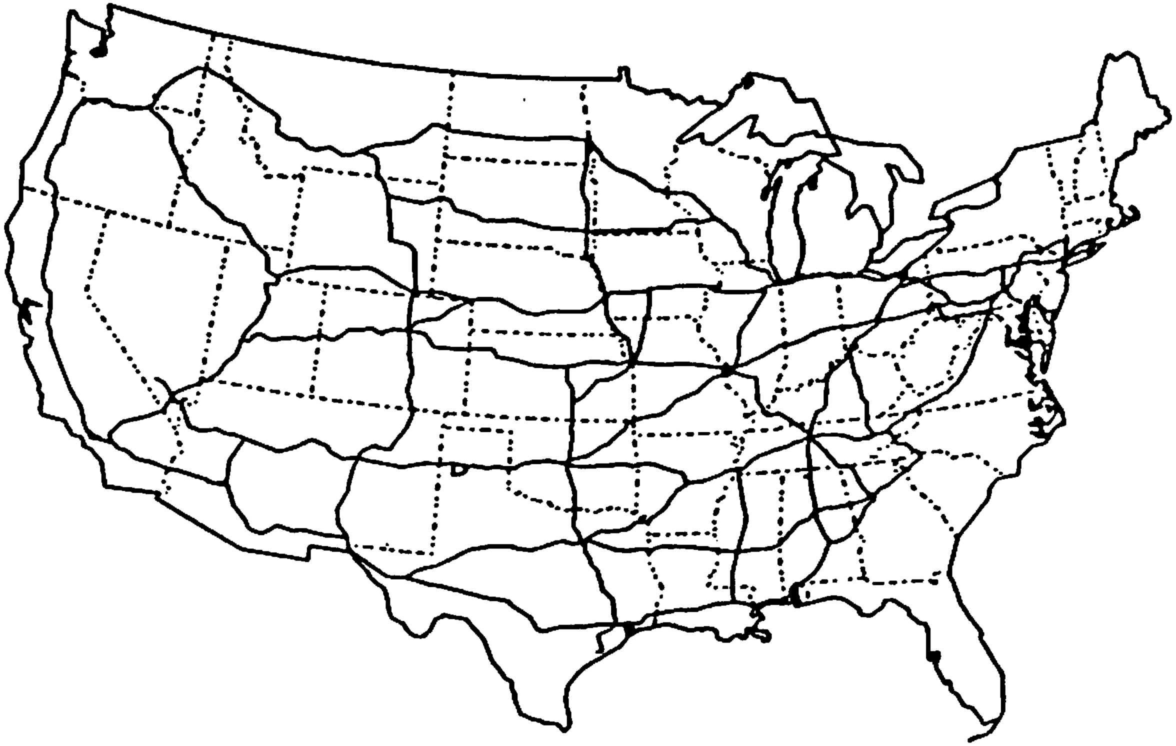


Figure 3.1 Network for the Transportation of Spent Fuel.

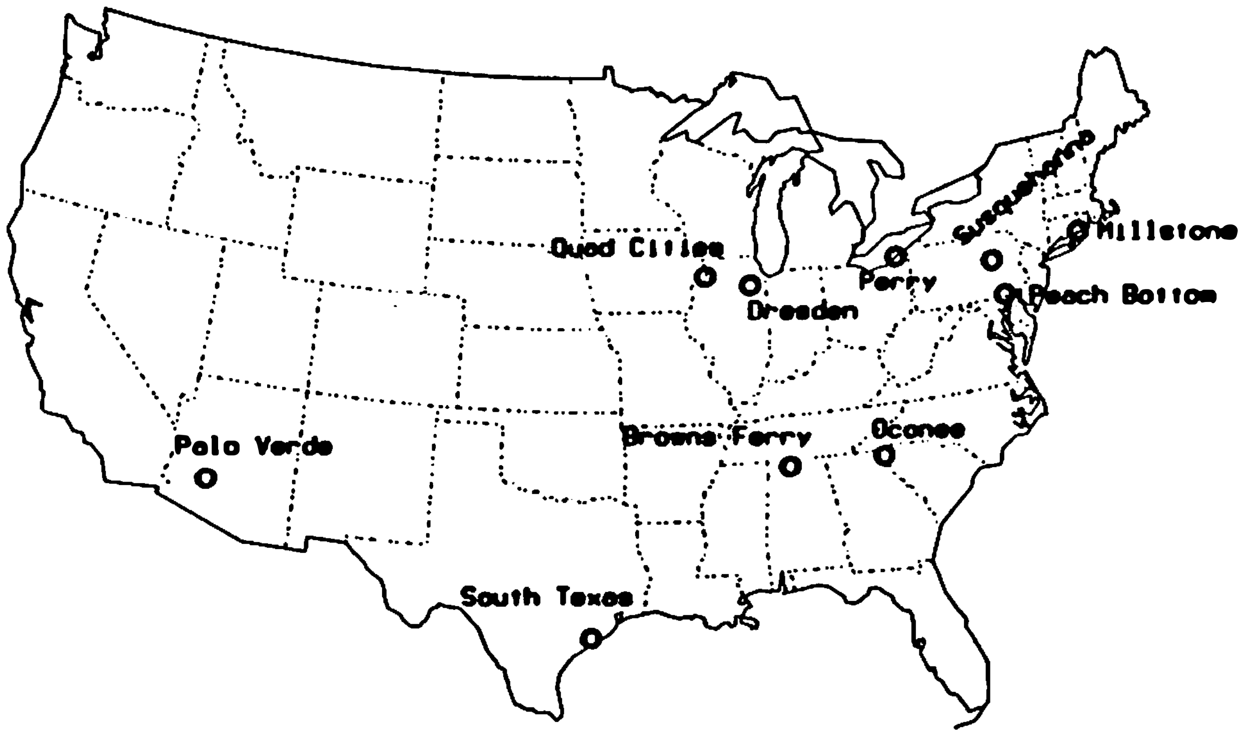


Figure 3.2 Reactors.

approximately twenty-five percent of the spent fuel in the nation between 1998 and 2025 (Table 3.1).

Average Population Density

The average population density along each link is estimated from the 1980 Census of Population. When a link is located within a Standard Metropolitan Statistical Area (SMSA), the average population density for the county through which it passes is used. In rural regions, the average population density for the state is used.

Link Distance

The distance between nodes is estimated with the use of a road atlas. A node is placed at the intersection of two or more links and at the source and sink points.

Speed

The average speed of vehicles on the highway is obtained from Federal Highway Administration's Highway Statistics (1983). The speeds are divided into four categories: urban and rural interstate, and urban and rural noninterstate highways.

Table 3.1

Reactor Sites on the Network

Reactor	State	Annual Number of Shipments
Browns Ferry	Alabama	218
Perry	Ohio	208
Peach Bottom	Pennsylvania	169
Susquehanna	Pennsylvania	159
Millstone	Connecticut	153
Palo Verde	Arizona	147
Dresden	Illinois	144
Oconee	South Carolina	131
Quad Cities	Illinois	127
South Texas	Texas	126

Traffic Count

The average traffic count is obtained from the vehicle miles traveled and road mileage tables in the Highway Statistics (1983). Once these two sets of data are known, the following equation generates the traffic count for rural and urban interstate and noninterstate highways:

$$t_s = \frac{m_s}{h_s}, \tag{3.1}$$

where:

m_s = vehicle miles traveled in state s,

h_s = highway miles in state s,

t_s = traffic count in state s.

Accident Rate

The accident rate for each state is calculated from mileage on the routes taken by radioactive materials through states from January 1982 to July 1984. The routes for these radioactive materials shipments are obtained from a DOT data base (USDOT, 1984). The mileages along these routes are then estimated. The number of accidents over

this same period of time is obtained from two sources: Waste Technology Services Division of Westinghouse Electric Corporation (1985) and the Materials Transportation Bureau of the DOT (1985). Even though these two data bases have information on radioactive materials accidents over the same period of time, they do not coincide. The number, location, and time of accidents differs somewhat in the two data sets. It was necessary to merge the two data bases by cross-checking the accident data by time, place, and material. Corrections on some erroneous or incorrect data which had been put into these files were also made. Therefore, the resulting data base which combines the information from these two sources should be a more accurate reflection of accident rates for radioactive materials truck transportation in the United States. The ratio of the number of accidents and miles traveled gives a rate of radioactive materials accidents per mile for each state. That is,

$$a_s = \frac{g_s}{b_s}, \qquad (3.2)$$

where:

a_s = accident rate per mile in state s,

g_s = number of radioactive material accidents in state s,

b_s = mileage traveled by radioactive materials in state s.

Some states have no accidents during this period of time. When this is the case, a weighted average of the contiguous states is used to estimate an accident rate for that state. That is:

$$a_s = \frac{\sum_c a_{sc} b_{sc}}{\sum_c b_{sc}}, \qquad (3.3)$$

where:

a_{sc} = accident rate for radioactive material transport in state c which is contiguous to state s,

b_{sc} = mileage traveled by radioactive materials in each state c which is contiguous to state s.

The combination of equations (3.2) and (3.3) gives accident rates for all the states through which the network passes (Figure 3.3). These rates are used to calculate the risk values for population and property which result from an accident.

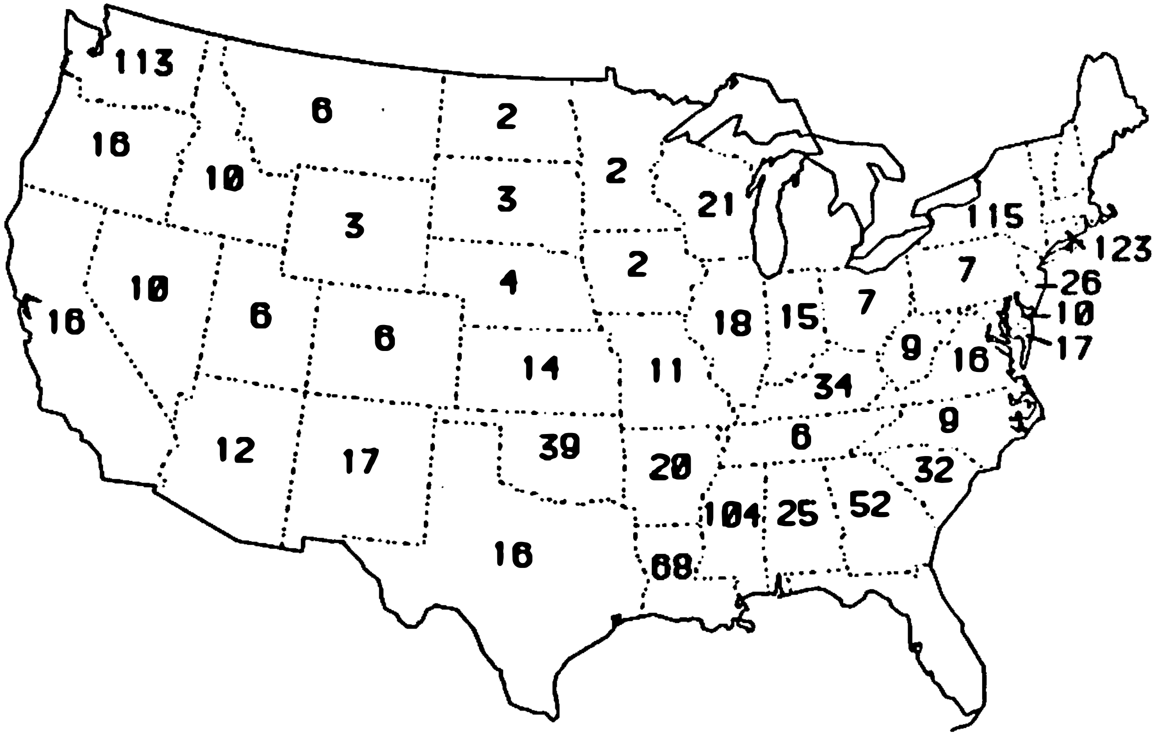


Figure 3.3 State Radioactive Materials Accident Rates (Accidents per 100,000 Miles).

Transportation Cost

The transportation cost to each repository is taken from a study by Wilmont et al. (1983). The variable cost for each repository reflects the difference in freight rates in various parts of the country.

Comparison of Beta Values

Three individual components make up the MTTRM and ETRM objective functions: incident free transport risk, the expected consequences of an accident on the population, and the expected consequences of an accident on property. These risk components contribute in various degrees to the overall risk of the shipments. The introduction of the beta values gives the models more flexibility because it provides the people planning the routing with the option of weighting the different types of risk. In the following examples, each individual risk value is multiplied by a whole number while the other risk values are held at 0 to determine the routing influence of each of the risk factors. Different beta values result in various routing patterns. The three sets of beta values which are used here are only meant to show some of the possible routes which could be generated by using these models.

Because the expected risk values due to accidents are so low for spent fuel transportation, the incident free exposure risk value exerts the most influence over routing if all beta values are equal. The risk values for incident free transport are greater than accident risk because there is a degree of assured risk from exposure to radiation when spent fuel is moved. Since this is the dominant risk factor, the influence of the incident free transport risk factors is determined by multiplying this rate by 1 and setting the accident rate beta values to 0 (Table 3.2).

Most of the probabilities of a radioactive materials accident along each segment of the highway network range from 10^{-9} to 10^{-12}. The low value of the accident factor is due to the extremely small expected probability of a radioactive materials accident. While the probability of a spent fuel transportation accident is very low, the consequences of such an accident are substantial. The personal injury and loss of life and property could be great.

The expected accident risk factors were multiplied by a beta factor of 10^{11} to increase their influence to a level similar to that of incident free transport risk (Table 3.2). The beta factor could be raised even more, if one had greater concerns about accident safety.

Table 3.2

BETA VALUES USED FOR EACH EQUATION

	Beta 1	Beta 2	Beta 3
Incident Free Transport Risk Equation	1	0	0
Probability of Risk to the Population Equation	0	10^{11}	0
Probability of Risk to Property Equation	0	0	10^{11}

Comparison of Path and Societal Risk

Three reactors in widely dispersed parts of the United States are selected for use in demonstrating the models: Millstone, Connecticut, Oconee, South Carolina, and Palo Verde, Arizona. Paths to the Hanford, Washington candidate permanent repository site for incident free transport risk, expected accident consequences on the population, and expected accident effects on property are computed from each reactor (Figure 3.4). One origin, Millstone, Connecticut, is used to illustrate the major model characteristics in this chapter. For a more detailed examination of each of the three cases, see Appendix C.

Incident Free Transport Risk

Incident free transport risk results from the movement of radioactive material without an accident. Since there is no accident considered in this case, the beta value for incident free transport risk is 1. This means that the population near the spent fuel shipment is certain to receive some radiation as the truck passes.

The major influences on path selection for incident free transport risk are population density along each link, length of the highway segment, number of vehicles on the highway, and the vehicle speeds. The MTTRM and the initial

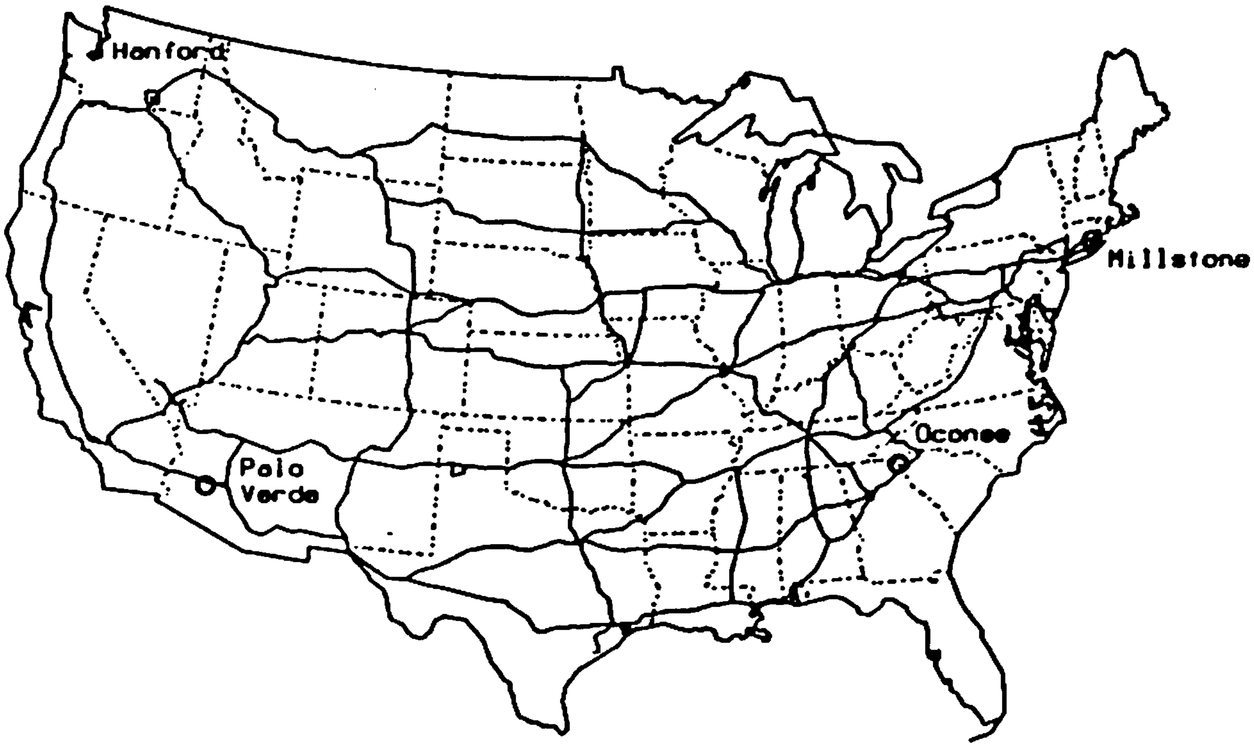


Figure 3.4 Single Reactors and the Hanford Repository.

iterations of the ETRM avoid densely populated urban areas, but eventually, as the risk factor increases on these less populated links, the paths shift to the urban centers. Such is the case with the paths from the Millstone reactor to the Hanford candidate repository site (Figure 3.5). The first two runs (the MTTRM and the ETRM for K = 2) assign spent fuel shipment paths north of New York City, but the third run goes directly through the urban center. The first three iterations also avoid Chicago, but the fourth run assigns some shipments through the city.

The initial societal and path risk values are the same in the MTTRM. At each of the next iterations of the ETRM, the values along the individual paths are decreased by distributing shipments over a larger number of paths. The addition of a second path provides the largest decrease in path risk. The drop in path risk is rapid for the first few iterations, but as more paths are traversed, the rate of decrease declines (Figure 3.6). The decrease in the path risk values by disbursement of shipments initially leads to an increase in societal risk because longer distances are being traveled by the spent fuel shipments (Figure 3.7). But at some point, the decrease in path risk values may be greater than the increase in the number of paths multiplied by the path risk value. This occurs when:

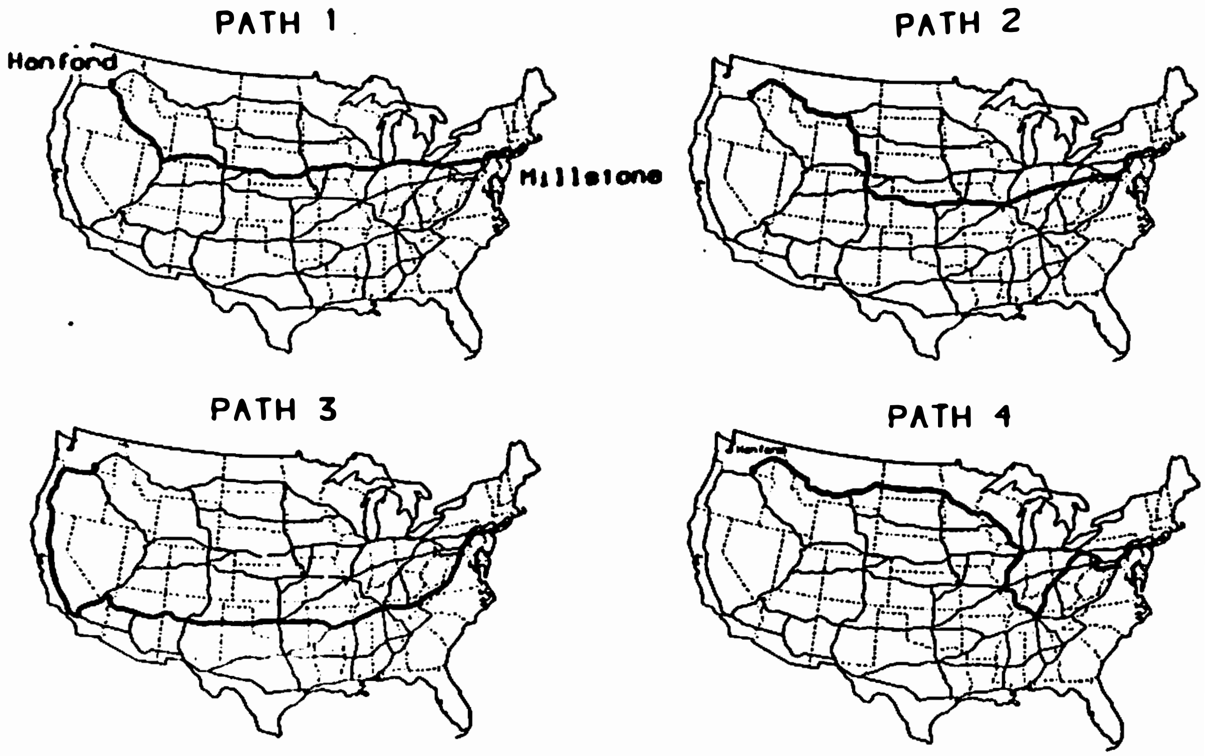
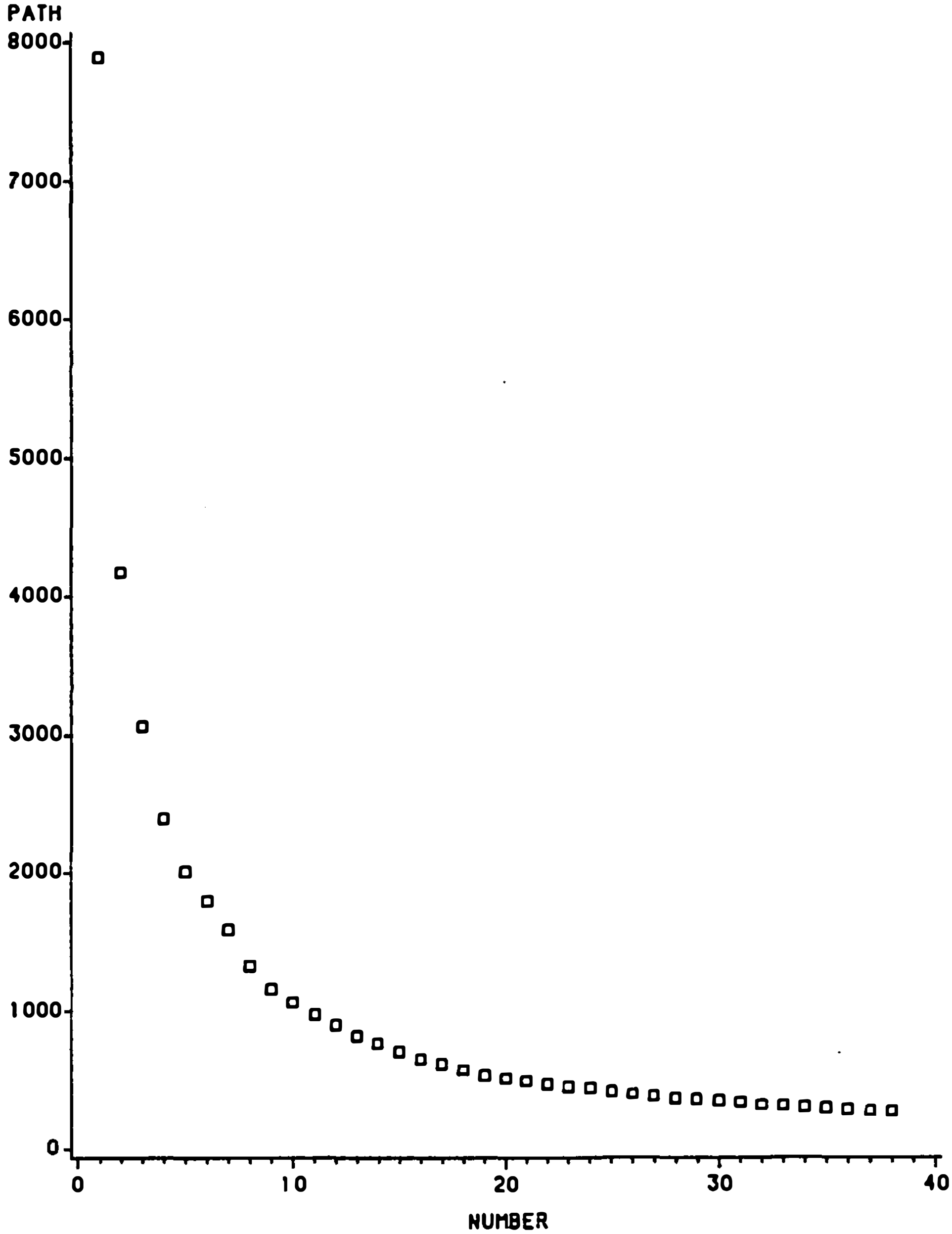
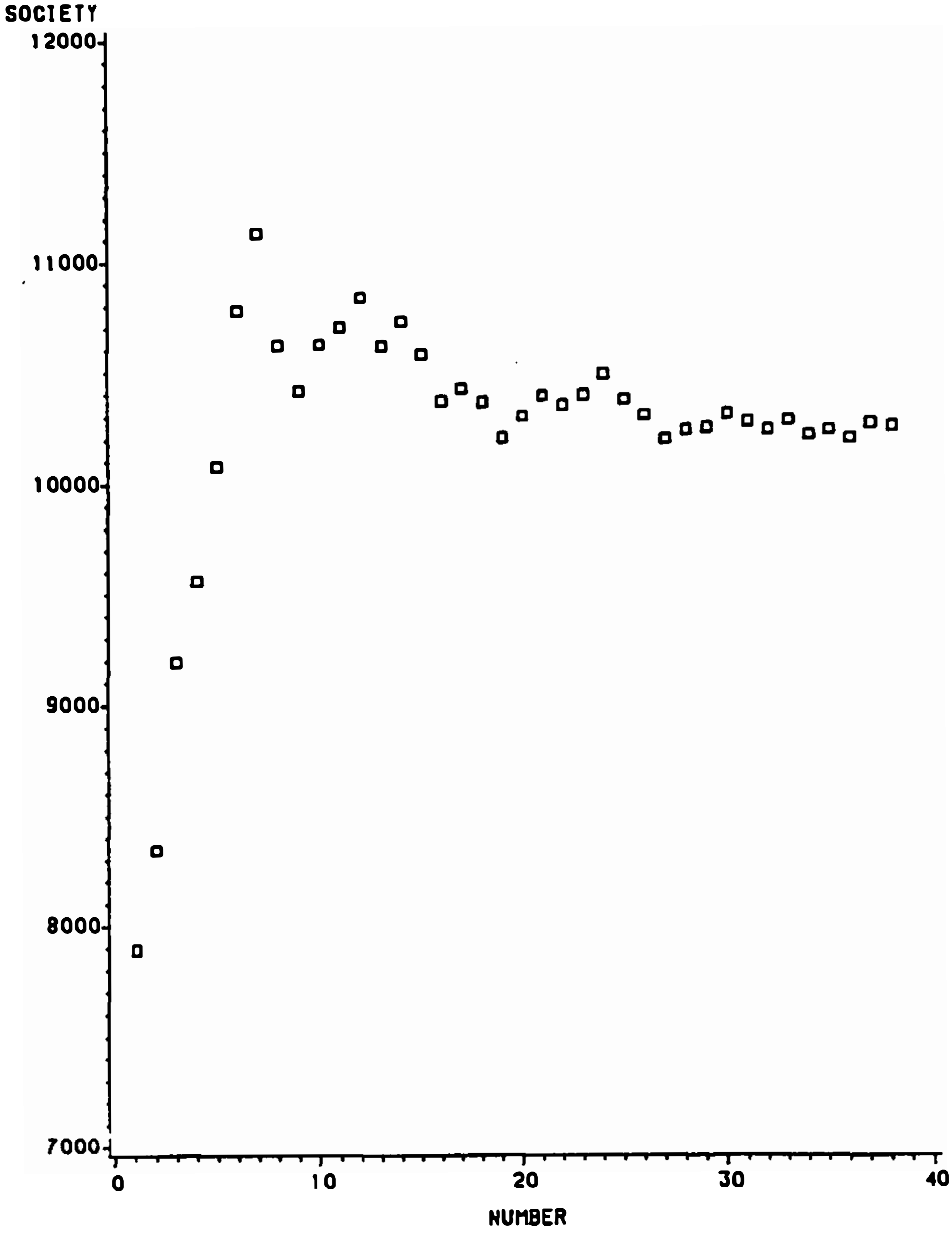


Figure 3.5 Four Paths Between Millstone Power Plant and Hanford Repository Which Minimizes Incident Free Transportation Risk.



RISK IS MEASURED IN PMR

Figure 3.6 Millstone Power Plant to Hanford Repository
Incident Free Transport Risk
Path Risk vs. Number of Paths.



RISK IS MEASURED IN PMR

Figure 3.7 Millstone Power Plant to Hanford Repository
Incident Free Transport Risk
Societal Risk vs. Number of Paths.

$$P_a Z_a < (P_a - 1) Z_{a-1} , \qquad (3.5)$$

where:

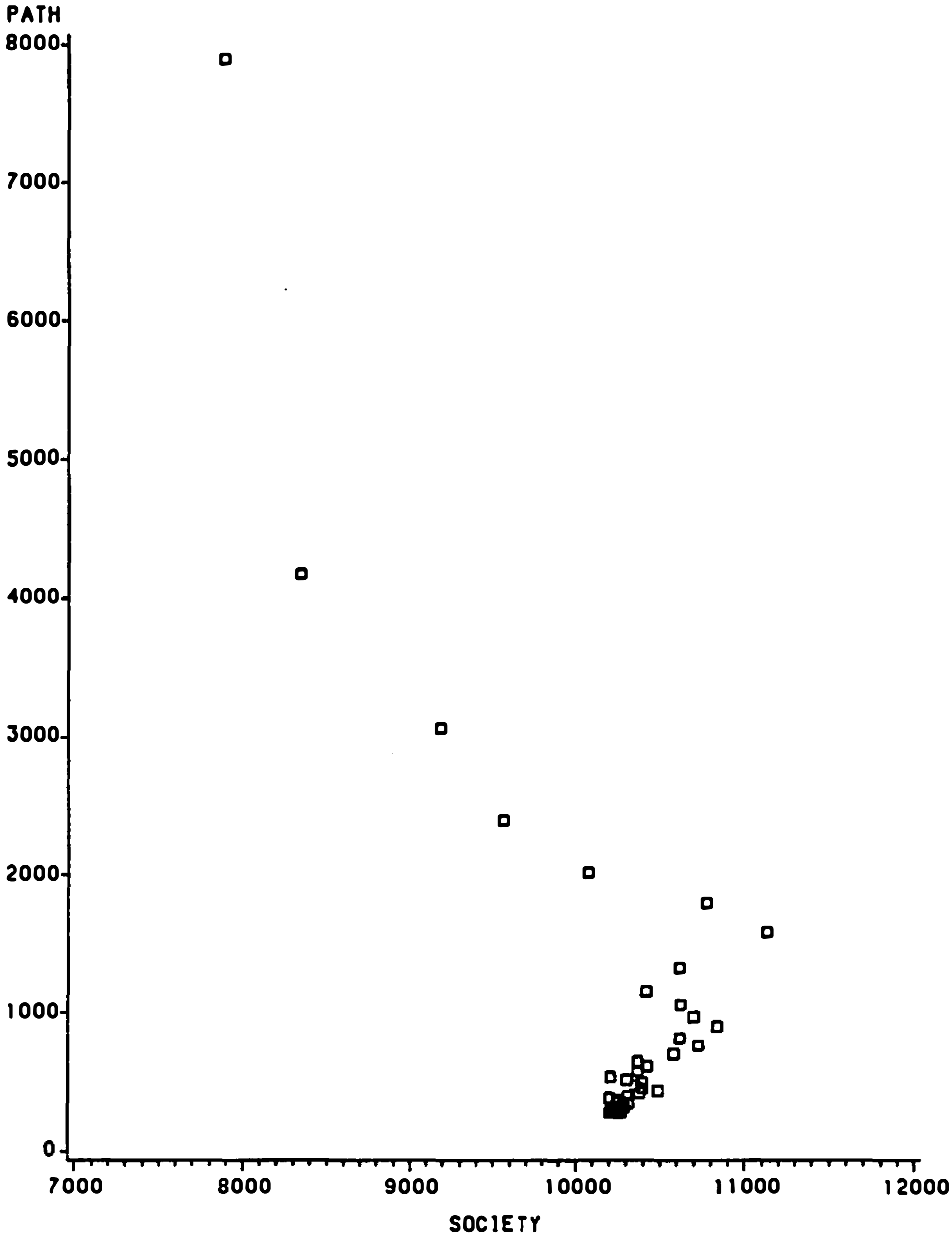
P_a = Number of traversed paths in the network at iteration a,

Z_a = Path risk value at iteration a,

Z_{a-1} = Path risk value at iteration a-1.

At this point, path risk values and societal risk values both decrease (Figure 3.8).

Each iteration also brings a redistribution of shipments along all the traversed paths. This change in the flow of shipments along each path allows the model to balance the risk value for that route. The choices for routes between the reactor and repository are rather restricted as the shipments begin and end their journey. In the middle section of the highway network, there are a great many alternative paths which can be taken. As the paths become increasingly dispersed, the risk values in the initially traversed states decline, while the risk values in the states which were originally unaffected by the routing increase (Figures 3.9 and 3.10). There is more than a 60 percent reduction in risk for several of the Great Plains and Rocky Mountain states when the first and



RISK IS MEASURED IN PMR

Figure 3.8 Millstone Power Plant to Hanford Repository
Incident Free Transport Risk
Path Risk vs. Societal Risk.

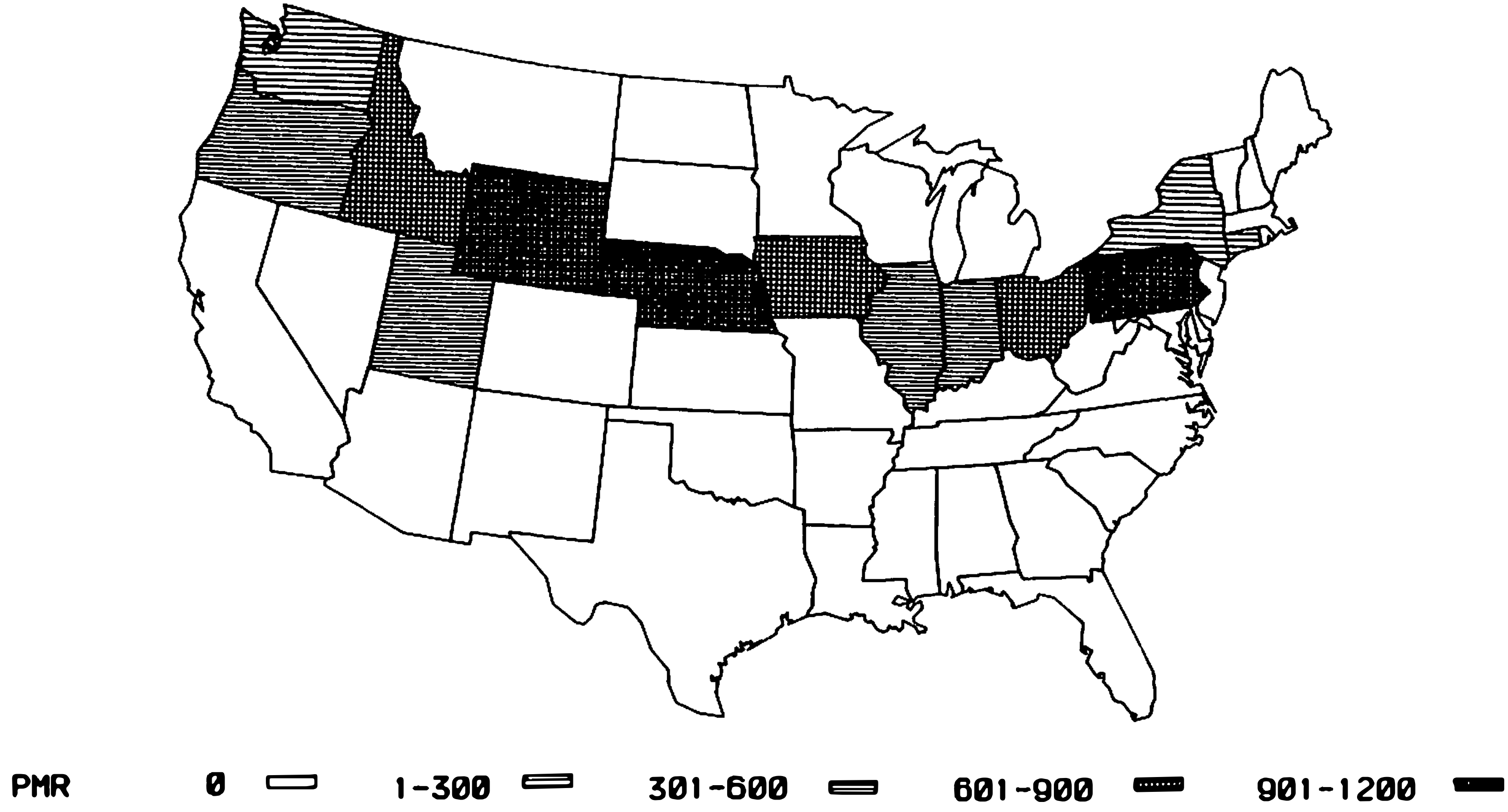


Figure 3.9 State Risk for Incident Free Transportation From Millstone Power Plant to Hanford Repository for the MTTRM Solution.

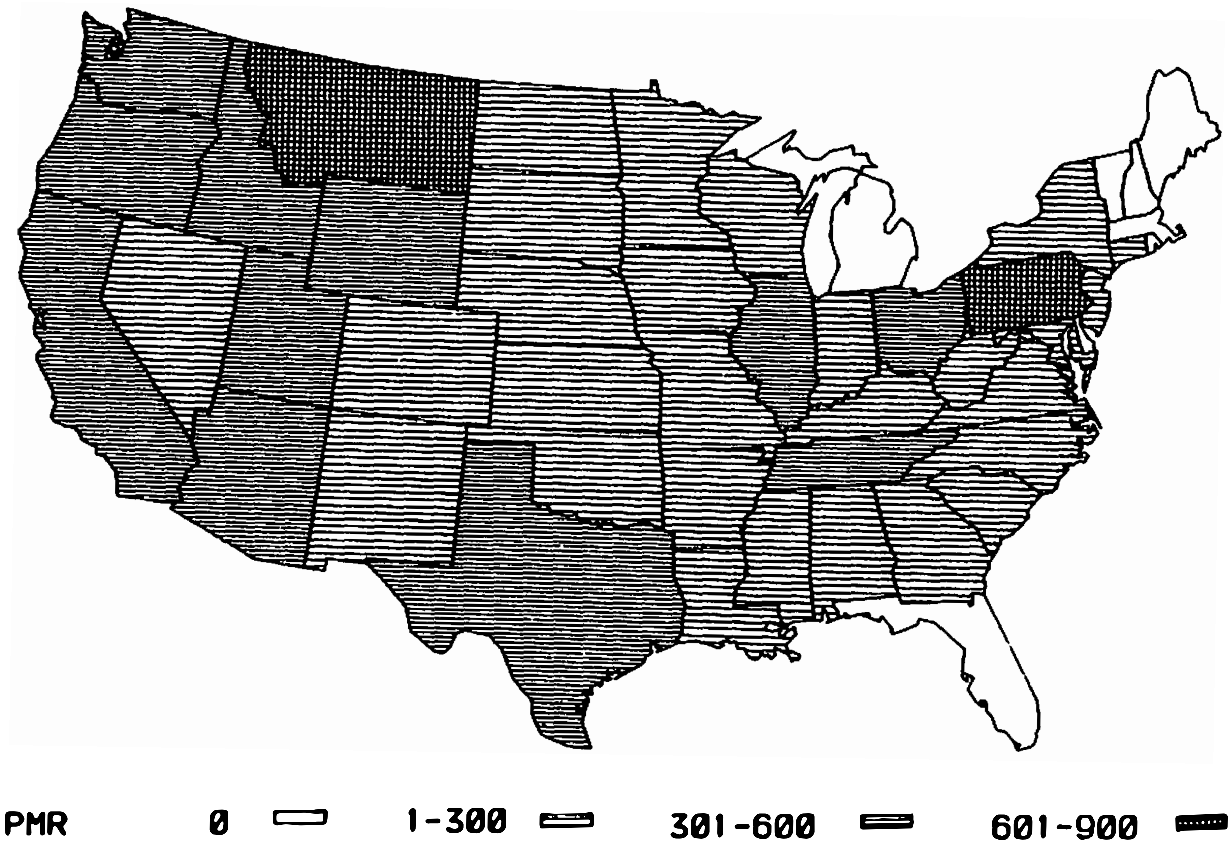


Figure 3.10 State Risk for Incident Free Transportation from Millstone Power Plant to Hanford Repository for the ETRM, Maximum Equity Solution.

last runs are compared for the Millstone to Hanford case (Figure 3.11).

This generalization does not apply to states where the reactor and repository are located. If there is more than one path in the state, then the risk value for this state will increase because a higher risk path will be used for some of the shipments in the state. This occurs in Washington when the maximum number of paths are used to reduce path risk. The original route for spent fuel only travels sixty-two miles in a rural part of the state. The second, higher risk route covers 200 miles and passes through the major urban center of Spokane. This second route is used on one-third of the shipments into Hanford.

If there is only one path in the state where the reactor or repository is located, then the risk value will remain the same. This result occurs because there are no alternate higher risk paths over which to send the spent fuel. This happens in Connecticut when the spent fuel is shipped from Millstone to Hanford.

Expected Accident Risk to the Population

The variables which are of primary concern when trying to minimize the potential accident risk to the population are the accident rate and the population density along each

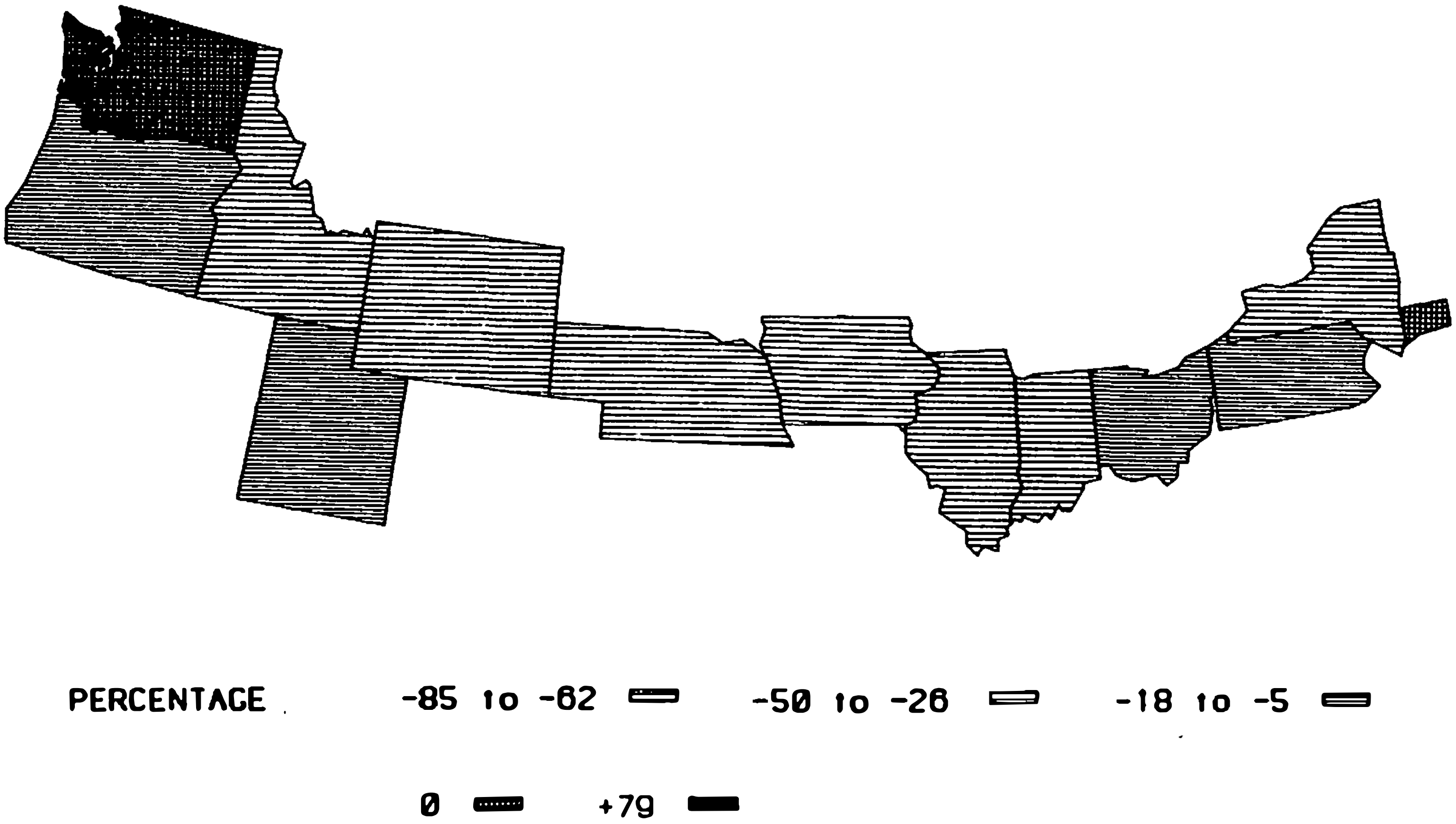


Figure 3.11 Percentage Change in Risk from the MTTRM to the ETRM, Maximum Equity Solution for Initially Traversed States Between Millstone Power Plant and Hanford Repository.

highway segment. The MTTRM and the first few iterations of the ETRM avoid states with high accident rates and highly populated links. Accident rates, rather than distance, are the major factors influencing path choice. As a result, if only the accident risk is considered, the paths which are generated tend to be more circuitous than those produced with the incident free transport risk values. The least risk path between Millstone nuclear power plant and the Hanford candidate repository site illustrates this point. The route generated by the MTTRM avoids New York City and the heavily populated areas of northern Ohio, Indiana, and Illinois by traveling south of this region. In the Great Plains region, the path shifts to the north through South Dakota to avoid the relatively high accident rate states of Nebraska and Kansas (Figure 3.12).

Expected Accident Risk to Property

Accident risk to property is represented in terms of projected property damage and decontamination costs. The cost varies according to the type of area through which the highway runs. For instance, the land values and clean up costs would be much higher for an accident in an urban center than they would be in a forest or desert area.

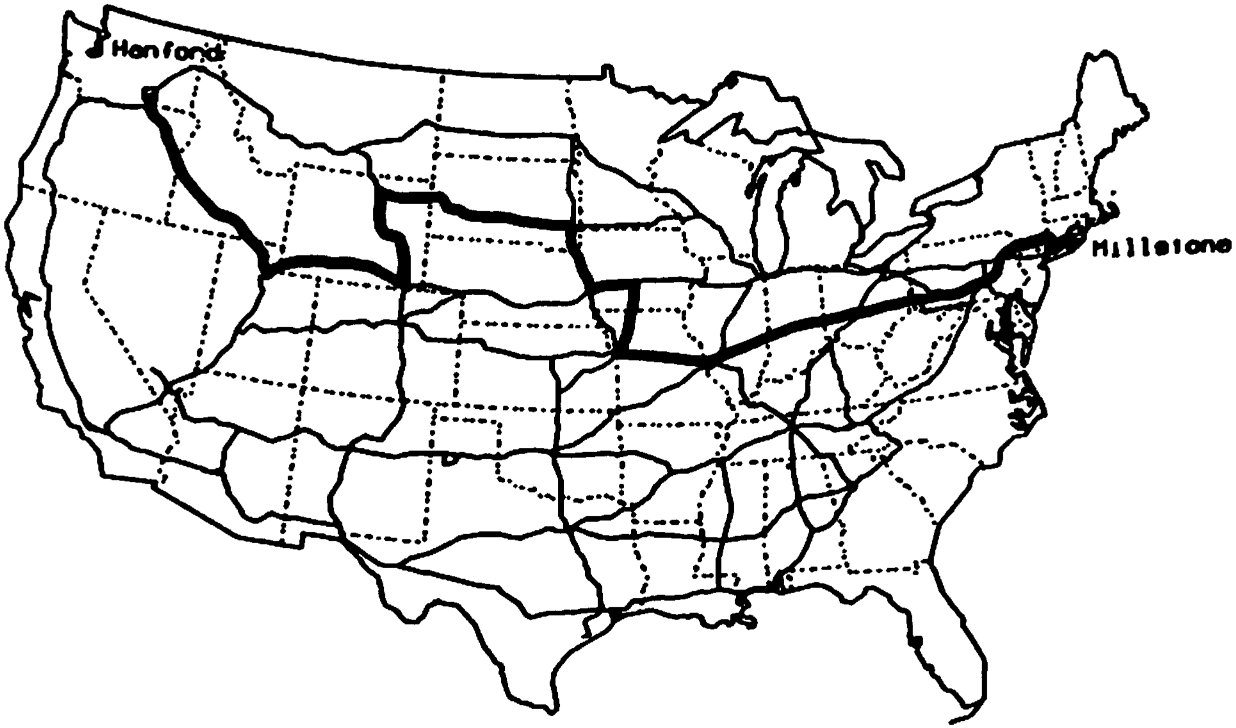


Figure 3.12 First Minimum Risk Path Between Millstone Power Plant and Hanford Repository for Expected Accident Risk to the Population.

The incident free transport risk and potential accident risk to the population are measured in person milirems (pmr). The potential accident risk to property is measured in pmr dollars. The reasoning behind this measure is that the greater the accident rate and property value along the link, the more it will cost if an accident occurs.

The MTTRM and the first few iterations of the ETRM avoid links with high property values and high accident rate states. The first Millstone to Hanford run totally bypasses the highly urbanized Great Lakes states by traveling through Virginia and Tennessee before it turns in a northwesterly direction. In the West, the path winds its way through the states which have the lowest accident rates (Figure 3.13).

Comparison of Risk and Transport Cost

The minimum risk path does not usually coincide with the minimum cost path. As a result, there is a trade off between risk and cost. The model can find the least cost path and a series of minimum risk paths. The risk and cost of each of these paths can be determined so that transport planners may evaluate the various shipment patterns.

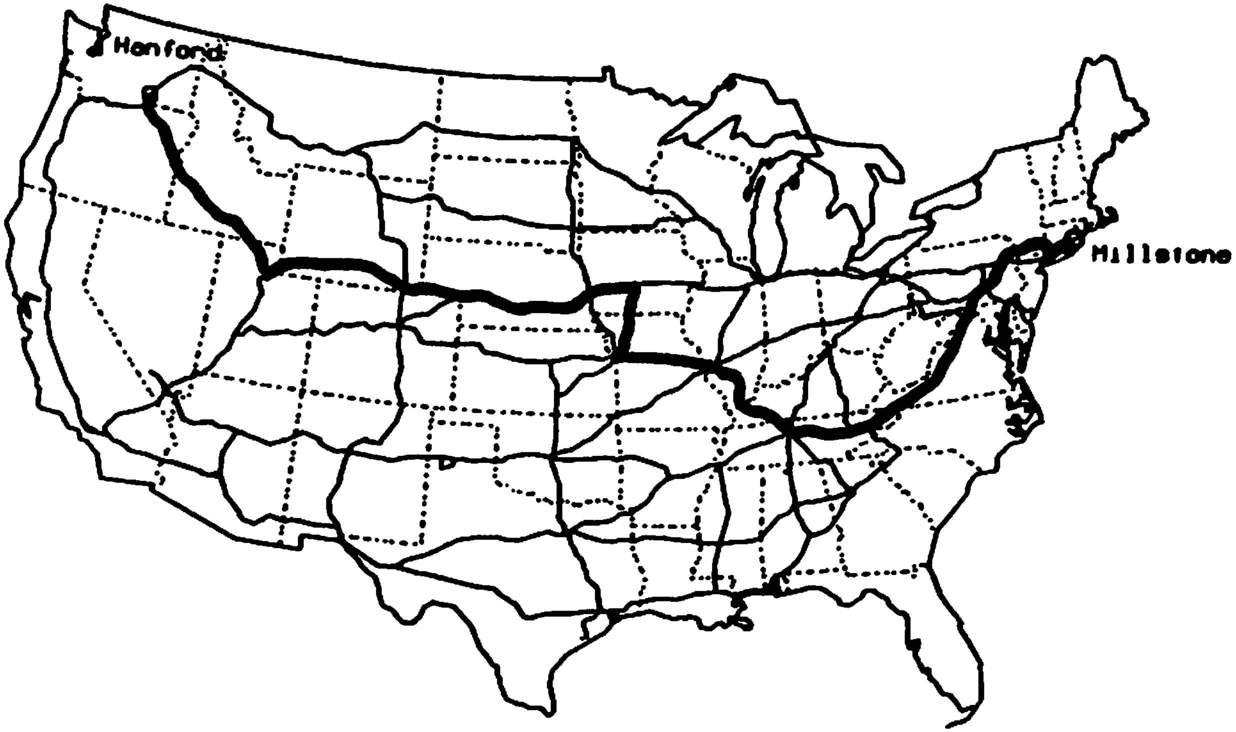


Figure 3.13 First Minimum Risk Path Between Millstone Power Plant and Hanford Repository for Expected Accident Risk to Property.

The cost of the shipments initially rises for the first few iterations (Figure 3.14). At the same time, the path risk values are falling sharply and societal risk values are increasing (Figure 3.8, p. 88). After the large initial changes, the path variations become minor and the shipping costs stabilize.

Transport planners can chart the risk of the various number of paths and the transport cost for each of these shipments. If a budget constraint exists, the ETRM can generate a series of minimum risk paths which do not exceed the budget constraint. The set of minimum risk paths which fall within the budget limitations can then be used. The introduction of a budget constraint into the ETRM can be accomplished by adding the constraint:

$$\sum_{ji \in N} m^{f} d_{ji} x_{ji} \leqslant B \quad \text{,for all b,} \qquad (3.6)$$

where:

m^f = shipment cost per mile for repository f,

B = total budget for shipping spent fuel from all reactors b to repository f.

to the MTTRM and ETRM.

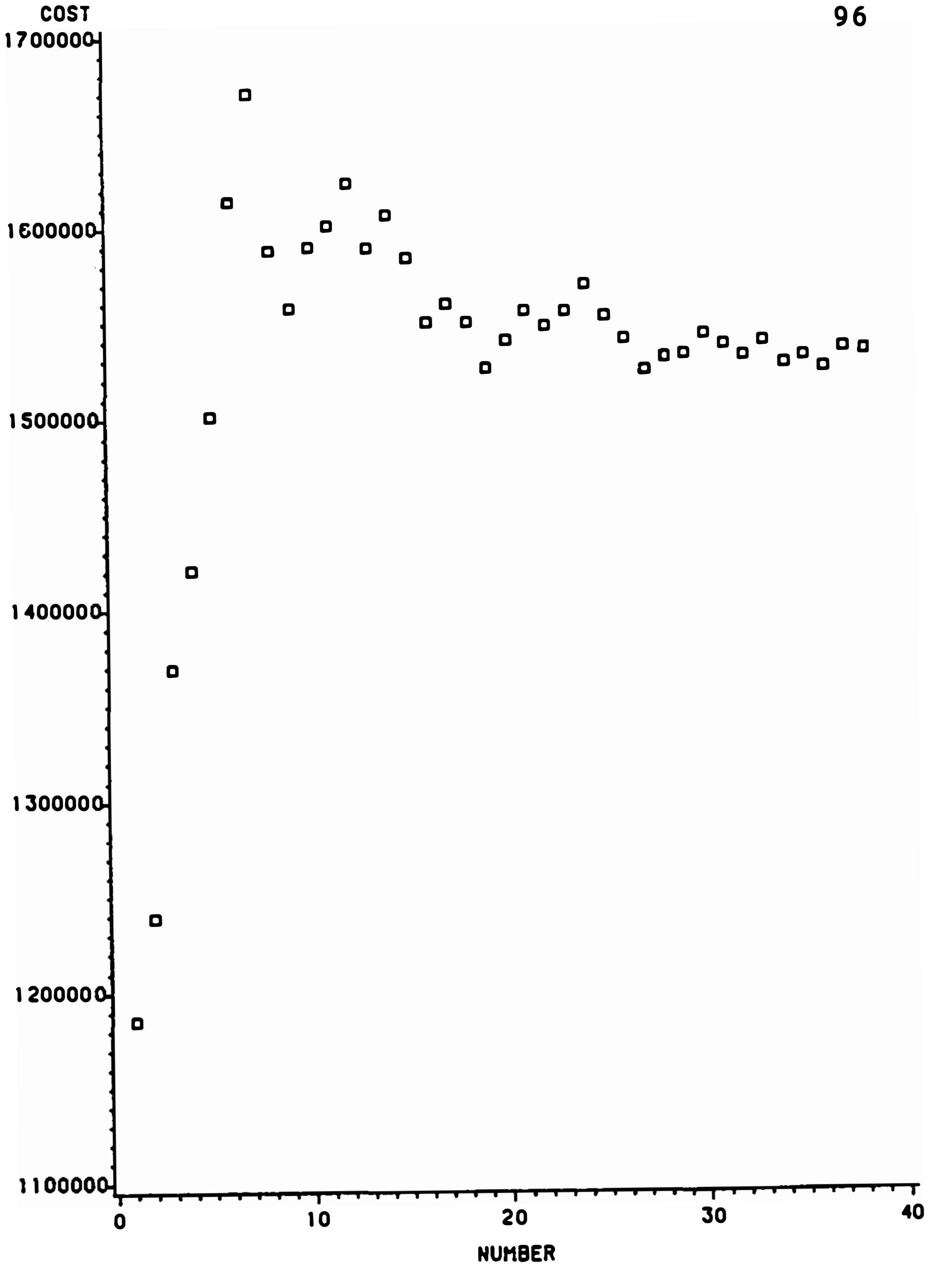


Figure 3.14 Millstone Power Plant to Hanford Repository
Incident Free Transport Risk
Total Cost vs. Number of Paths.

A comparison can be made between the cost and path risk for shipments from Millstone to Hanford. Using the minimum cost path as a base, the cost of moving 153 shipments of spent fuel annually increases by 2.4 percent and the path risk drops by 1.1 percent when the cargo is taken by the initial minimum risk path. If the paths are split into two routes, the shipping cost only increases by 6.6 percent, but the path risk falls by 48 percent (Figure 3.15).

Conclusion

This chapter presents the MTTRM and ETRM in an example using a single reactor and repository. The data which are used in the example are briefly discussed. The role of the beta values and their influence on the final results of the models is explained. The degree of importance of each risk factor can be determined by the size of the beta value.

The trade offs between path and societal risk for incident free transport and expected accident occurrences are examined. As the rate of path risk declines, the risk to society increases. The first few paths give reasonable solutions which can realistically be used by shippers. As the iterations of the model continue, the paths which are generated become much longer and beyond the realm of

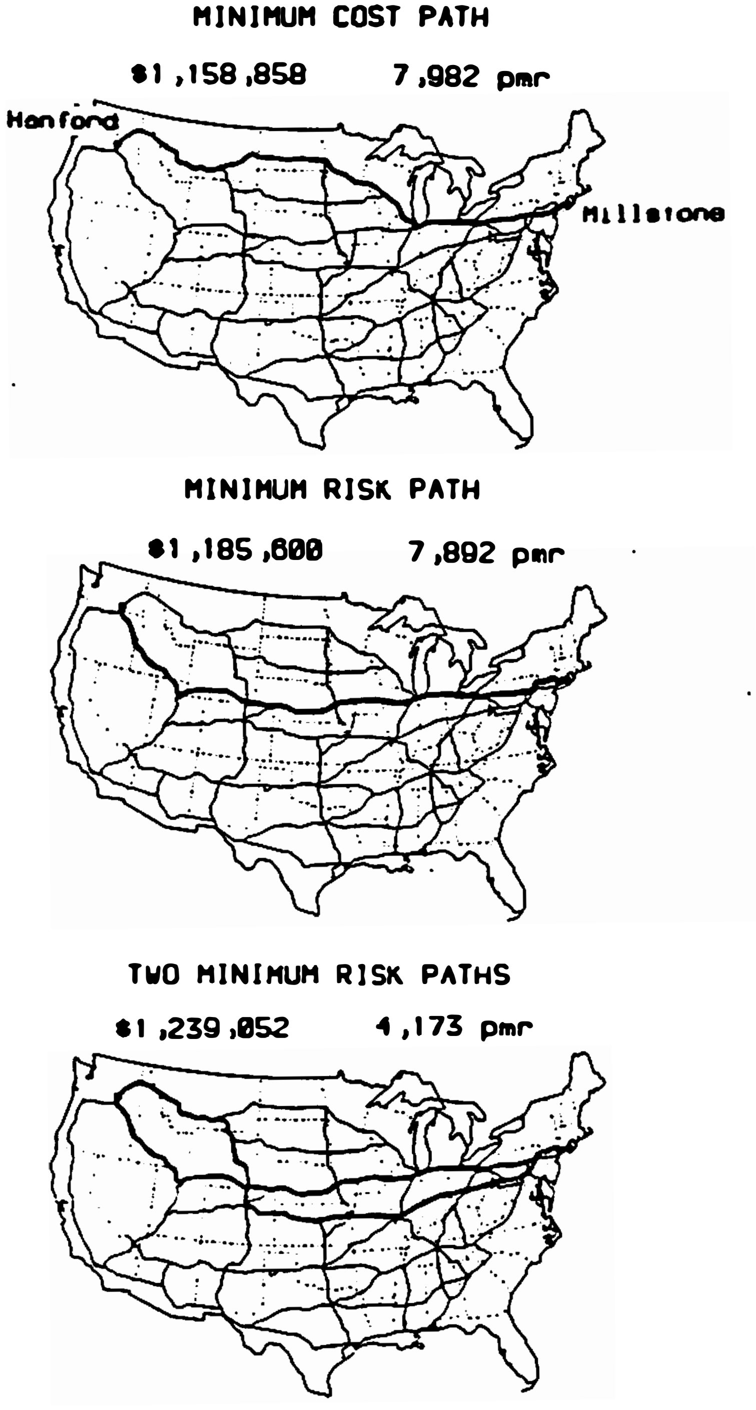


Figure 3.15 Minimum Risk and Minimum Cost Paths Between Millstone Power Plant and Hanford Repository for Incident Free Transport

feasibility for a shipper to profitably travel. Therefore, the first three to four iterations of the ETRM usually provide all the routes which can be reasonably used. These first few model iterations also provide the greatest decrease in path risk and the largest increase in societal risk.

A comparison is also made between risk and cost. The cost of shipping the spent fuel increases quite rapidly as the first few path shipments are split along different routes. At some point, the changes in the route pattern become very minor and the cost of shipping stops rising.

A budget constraint can be introduced into the models. When a budget constraint is incorporated into the ETRM, this provides a means of finding the set of routes which will minimize path risk within a specific fiscal limitation.

CHAPTER 4

THE APPLICATION OF THE MTTRM AND ETRM TO SEVERAL REACTORS AND A SINGLE REPOSITORY

Introduction

In reality, more than one reactor will be shipping spent fuel to a repository site at the same time. This will result in even greater risk of radiation exposure on the nation's highways. If only shortest path routes are used, the levels of exposure and risk will be particularly high for a few Western corridor states near the final repository site. For example, if the Hanford site is chosen, North Dakota, Nebraska, Wyoming, Montana, Idaho, and Washington will have the majority of trips pass through them (Figure 4.1). Even the MTTRM will generate this tree structure shipment pattern (Figure 4.2). As the shipments move toward the repository, they will gradually filter onto one or two major paths. As a result of this accumulation of shipments on these key paths, the people in these Western states along the highways being used for shipping will experience a relatively high level of risk.

A more equitable distribution of risk can be achieved by the ETRM. The use of the ETRM assumes that there will be cooperation, perhaps imposed by the government, among

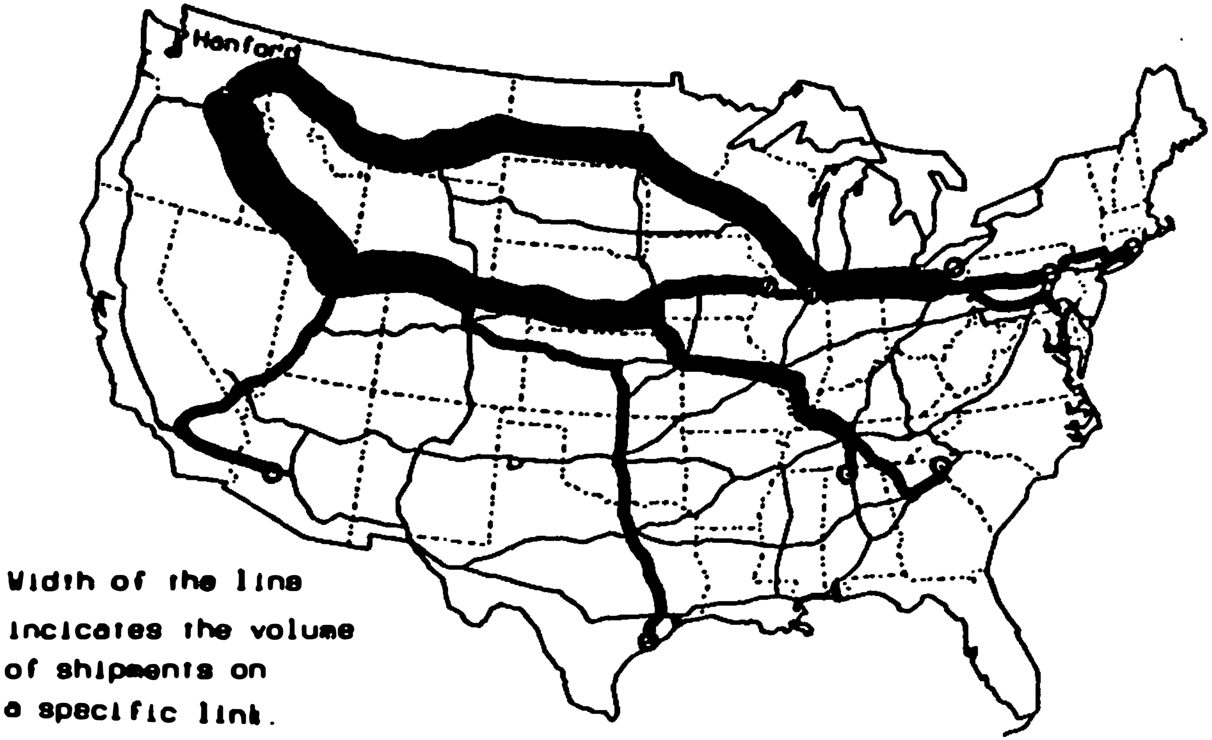


Figure 4.1 Minimum Cost Paths from Ten Reactors to Hanford Repository.

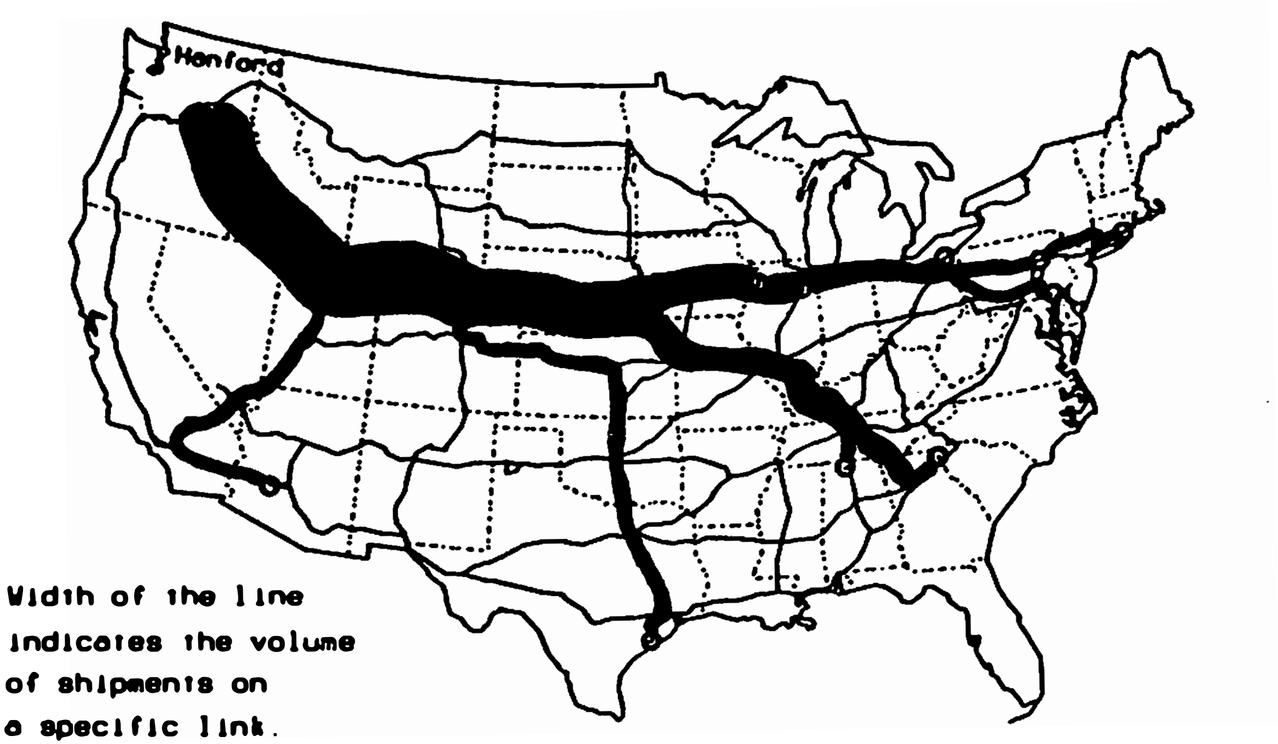


Figure 4.2 MTTRM Paths from Ten Reactors to Hanford Repository Which Minimize Incident Free Transportation Risk.

shippers of spent fuel from each reactor to a repository. This cooperation is in the form of shifting shipment patterns when the risk on a highway segment increases. Each shipper is assumed to know the flow pattern of spent fuel moving from all reactors to a repository. These trucking firms adjust their shipment patterns in a manner which will equalize the risk values over the set of paths from that reactor. Thus, there is competition for links, but there is also cooperation to reduce the risk value on the paths traversed by trucks from each reactor.

The incident free transport risk, expected accident risk to the population, and expected accident risk to property are each isolated for the multiple reactor routing case by using the same beta values that were employed in the single case examples in the previous chapter (Table 3.2, p. 80). Since the basic behavior of the models is considered in detail in Chapter 3 and Appendix C, a more general discussion of path and societal risk and cost for all reactors will be included in this chapter. A set of maps for each type of risk and the minimum cost paths is found in Appendix D. The final section of the chapter is devoted to a discussion of repository and MRS siting based on risk and cost factors.

Comparison of Path Risk and Societal Risk

As in the single reactor examples, the multiple reactor runs of the MTTRM avoid urban areas. The MTTRM paths generated from the Northeastern reactors to Hanford for incident free transport risk avoid Chicago (Figure 4.2). This is due to the high population density and property values in that area. The ETRM increases risk on these rural least risk links and forces some of the shipments to urban areas.

Figure 4.3 demonstrates this point with a series of maps showing the links over which shipments move using the MTTRM and the first three iterations of the ETRM. At the third iteration of the ETRM, all but three of the major links in the network have been traversed by at least one shipment. Thus, as the number of reactors shipping spent fuel increases, more of the network experiences spent fuel shipments.

The same path-societal risk relationship for multiple reactors holds as it did for a single reactor to a repository. That is, the initial iterations of the ETRM provide the greatest reduction in path risk and the greatest increase in societal risk (Figure 4.4). The only difference is that the risk values are much greater for both paths and society when multiple reactors are being

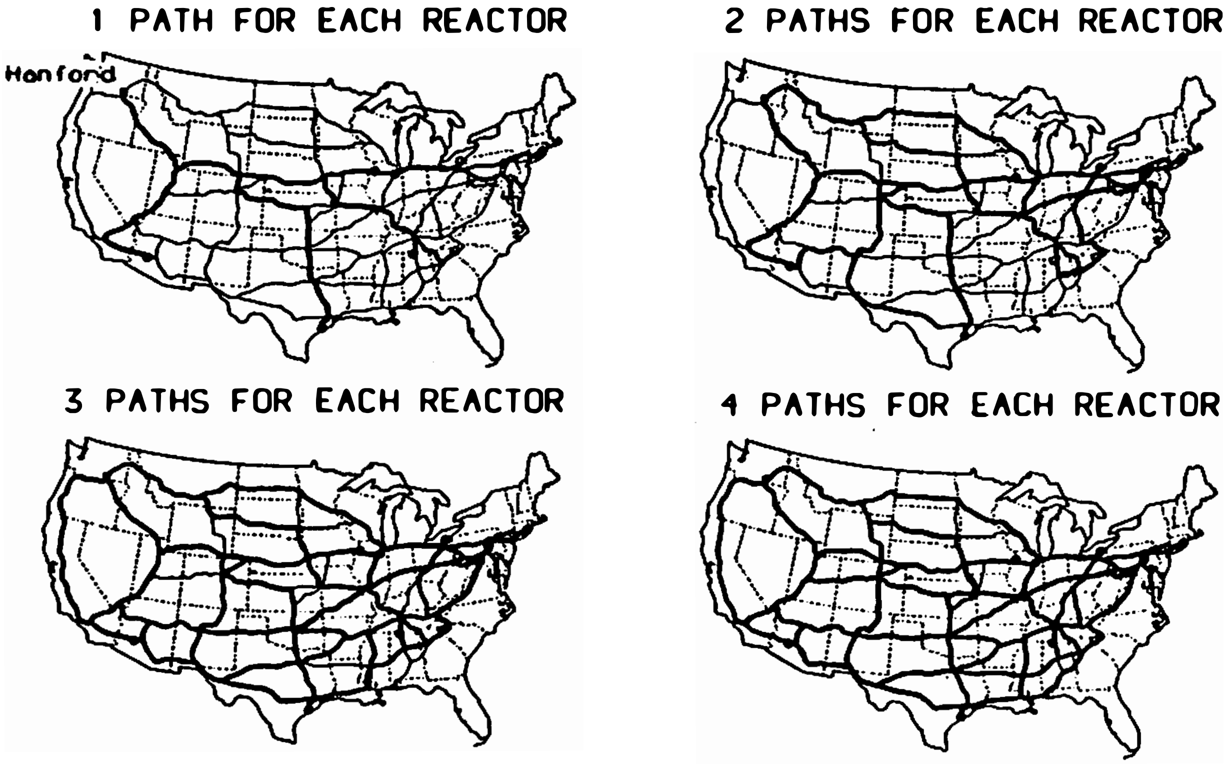
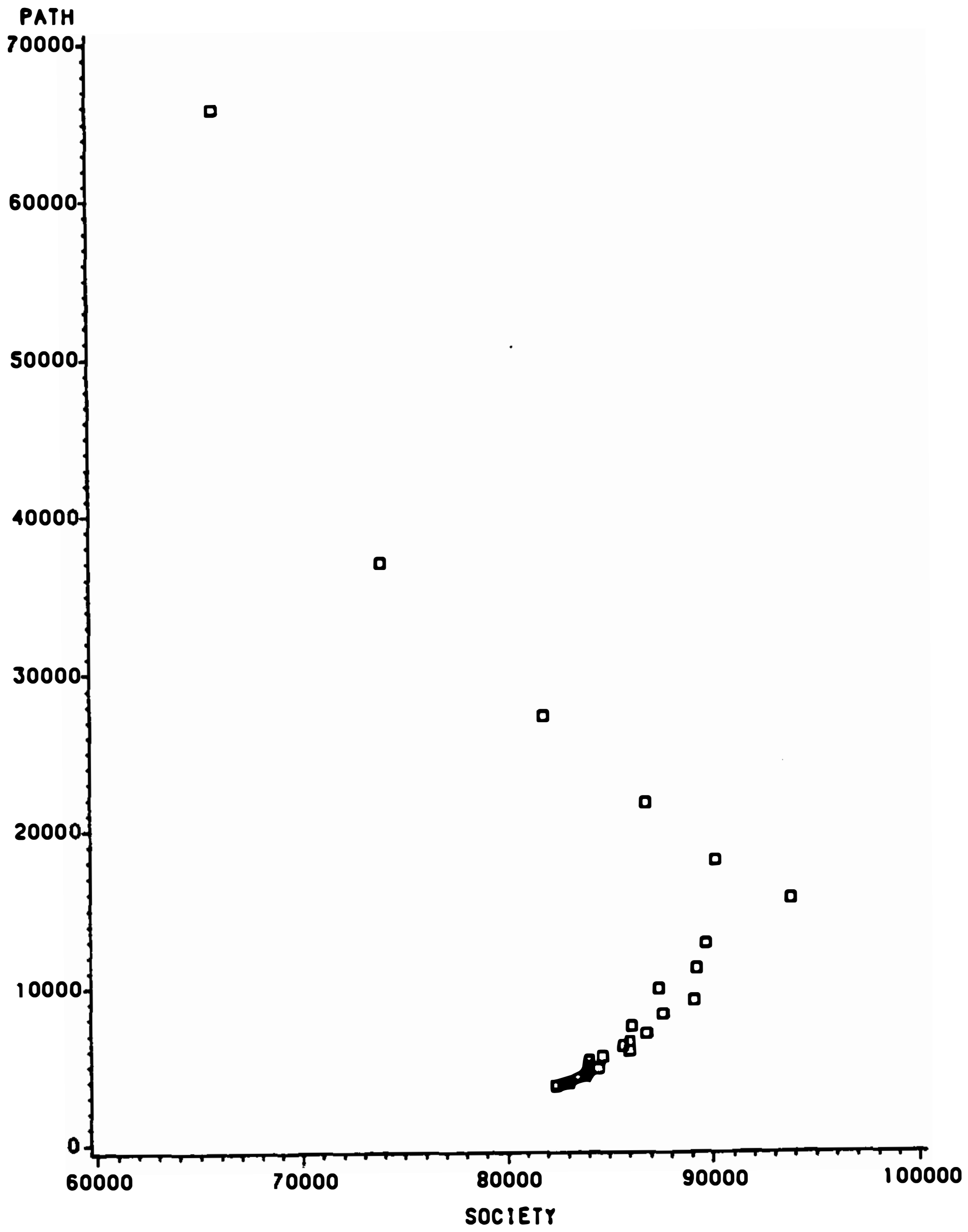


Figure 4.3 Four Paths from Ten Reactors to Hanford Repository Which Minimize Incident Free Transport Risk.



RISK IS MEASURED IN PMR

Figure 4.4 Path Risk vs. Societal Risk Between Ten Reactors and Hanford Repository for Incident Free Transport Risk.

considered. Usually, after six iterations, the decrease in path risk becomes minimal and the societal risk also begins to slowly decline.

When ten reactors are considered, the distribution of risk from the MTTRM is much greater than the single reactor case (Figure 4.5). States with high risk values on the MTTRM do experience substantial reductions in risk with the initial iterations of the ETRM, but states which initially have very low risk or no risk, see an increase in their risk (Figure 4.6). This is what would be expected in any move toward more equity.

Comparison of Risk and Transport Cost

The cost of shipping the spent fuel rises sharply during the initial iterations of the ETRM because each reactor is dispersing its shipments over a wider range of paths on the network (Figure 4.7). Once the major alternative paths are selected, the increase in path cost stabilizes because the later path changes are made by altering just a few links on the initial routes generated by the ETRM. When these alternate links result in shorter path lengths, the shipment costs actually decline.

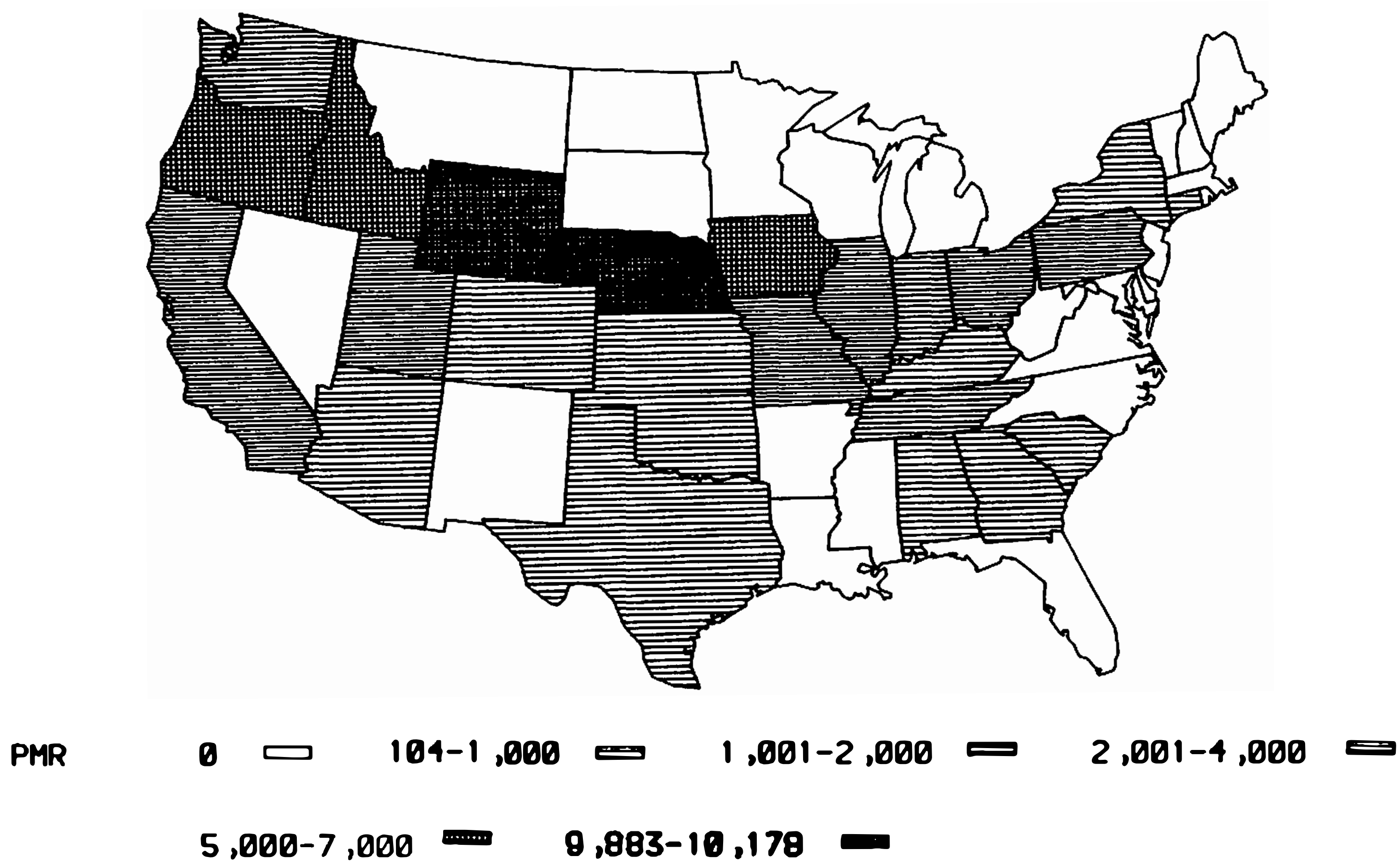


Figure 4.5 State Risk for Incident Free Transportation from Ten Reactors to Hanford Repository for the MTTRM Solution.

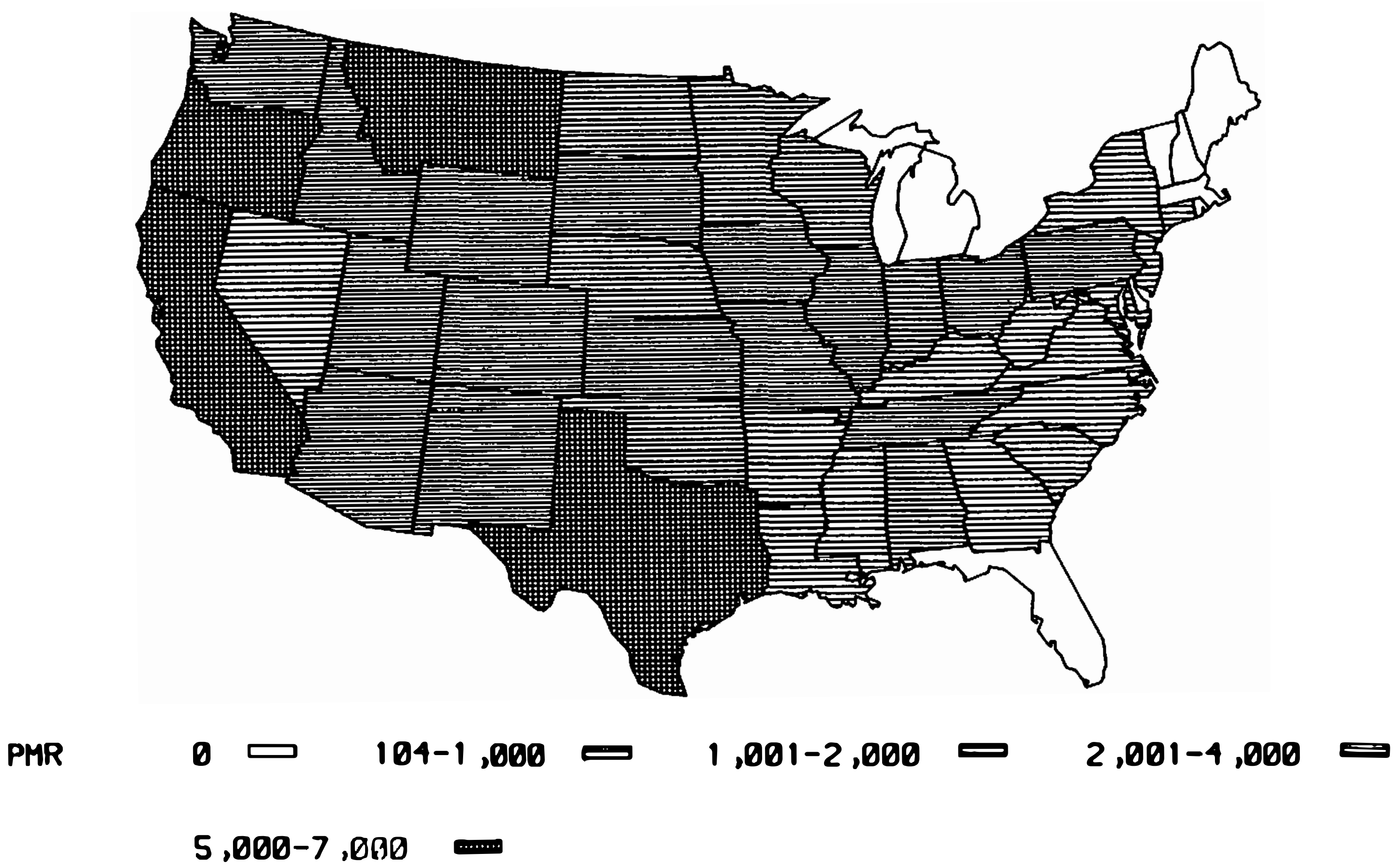


Figure 4.6 State Risk for Incident Free Transportation from Ten Reactors to Hanford Repository for the ETRM, Maximum Equity Solution.

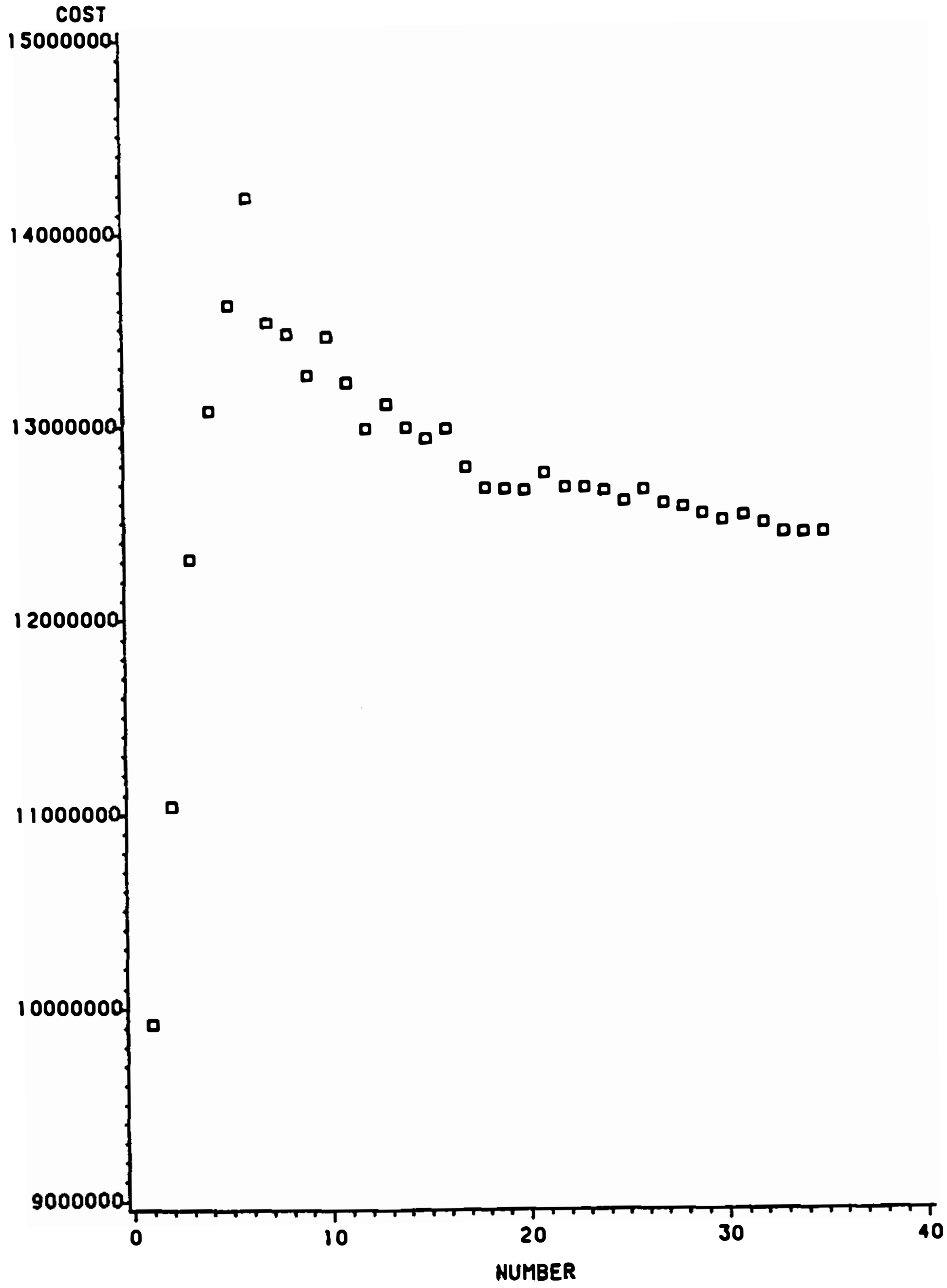


Figure 4.7 Total Cost vs. Number of Paths Between Ten Reactors and Hanford Repository for Incident Free Transport Risk.

The reactors which are nearest to the repository generate fewer routes than those which are farther away. For instance, when incident free transport risk to Hanford is considered, Palo Verde nuclear power plant in Arizona only has a maximum of seven paths, while Millstone nuclear power plant in Connecticut generates thirty-two paths. The final cost for moving each shipment from Palo Verde to Hanford is $5,516, while the cost for Millstone is $9,357. Thus, the per shipment cost from reactors which are nearer the repositories is less than those farther away.

Evaluation of Repository and MRS Siting Based on Risk and Transport Cost

The MTTRM is used to compare the cost and risk of shipping spent fuel from the ten reactors to the potential storage sites in this section. The cost figures are derived from average shipment cost for each mile multiplied by the total shipment mileage. The risk values are obtained by summing the risk on each link of the path which is traversed by spent fuel shipments.

The MRS Option

In each case, the cost and risk value is lowest for the MRS site (Tables 4.1 to 4.3). This result is certainly

Table 4.1

INCIDENT FREE TRANSPORT RISK

	Annual Cost ($)	Annual Risk (PMR)
MRS	3,623,759	22,671
Deaf Smith	5,773,980	35,649
Yucca Mountain	8,516,675	55,677
Hanford	9,918,491	65,863

Table 4.2

EXPECTED ACCIDENT RISK TO POPULATION

	Annual Cost ($)	Annual Risk (PMR)
MRS	3,958,735	15,100
Deaf Smith	9,097,477	17,909
Yucca Mountain	10,789,323	17,014
Hanford	11,996,918	19,306

Table 4.3

EXPECTED ACCIDENT RISK TO PROPERTY

	Annual Cost ($)	Annual Risk (PMR-$)
MRS	3,362,276	141,729,152
Deaf Smith	7,409,528	196,820,768
Yucca Mountain	9,944,219	174,341,840
Hanford	11,356,322	177,219,392

reasonable considering the locational relationships between the reactors and repositories (Figure 4.8). Most of the reactors are located in the Eastern half of the United States. The MRS is the only storage facility in this region. The Deaf Smith, Yucca Mountain, and Hanford sites are progressively further west and thus are located greater distances from the main concentration of reactors.

It is important to remember that DOE's current plans are to have the MRS site act only as a repackaging and temporary storage facility. The spent fuel will eventually be shipped to one of the three candidate permanent repository sites in the West by unit train. Therefore, the current risk factors for the MRS will have an additional transport risk added to them.

The determination of the cost and risk for the shipment of spent fuel from the MRS to a final repository is beyond the scope of this current research because of the need to calculate cost and risk of moving the spent fuel by rail. But this is an important issue which should be considered before an investment is made in constructing an MRS facility in Tennessee.

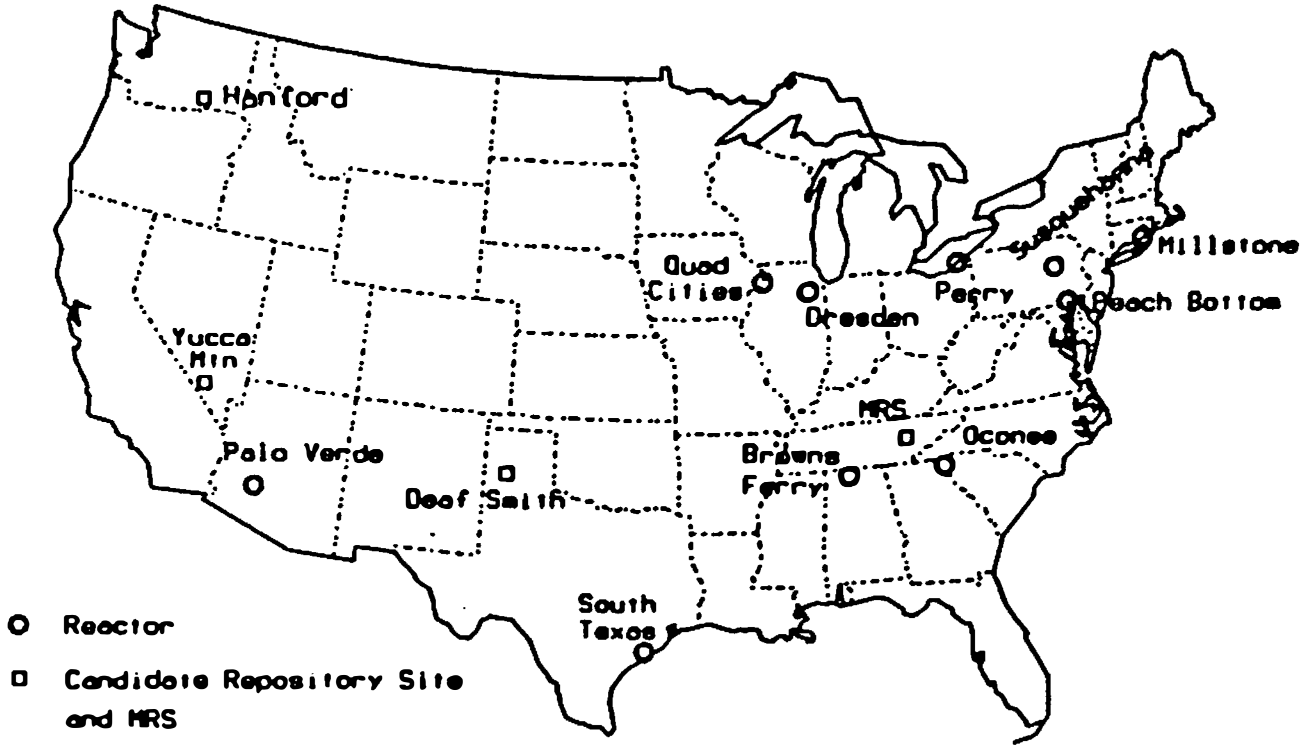


Figure 4.8 Candidate Repository Sites and Reactors.

The Direct Shipments to a Repository Option

If the alternative of shipping directly to the permanent repository is considered, then the Deaf Smith, Texas location is the least cost site, but the risk values vary considerably for the three candidate permanent repository sites. Deaf Smith has the lowest incident free transport risk (Table 4.1). One of the main factors in this type of risk is distance. Since the Deaf Smith site is the closest of the three candidate repositories to most of the reactors, the incident free transport risk is lower for this location (Figure 4.9).

The expected accident risk to the population is lowest for the Yucca Mountain, Nevada site. Most of the shipments to Yucca Mountain from the Northeastern reactors travel through the upper Great Plains and Rocky Mountain states (Figure 4.10). These states have rather low population densities and accident rates (Figure 3.4 p. 82). By contrast, the routes from the Northeastern reactors to the Deaf Smith site pass through the Southeast, where population density and accident rates are higher (Figures 3.4, p. 82 and 4.11).

The two important factors determining expected accident risk to property are accident rates and property values along each link. Since the Great Lakes region is

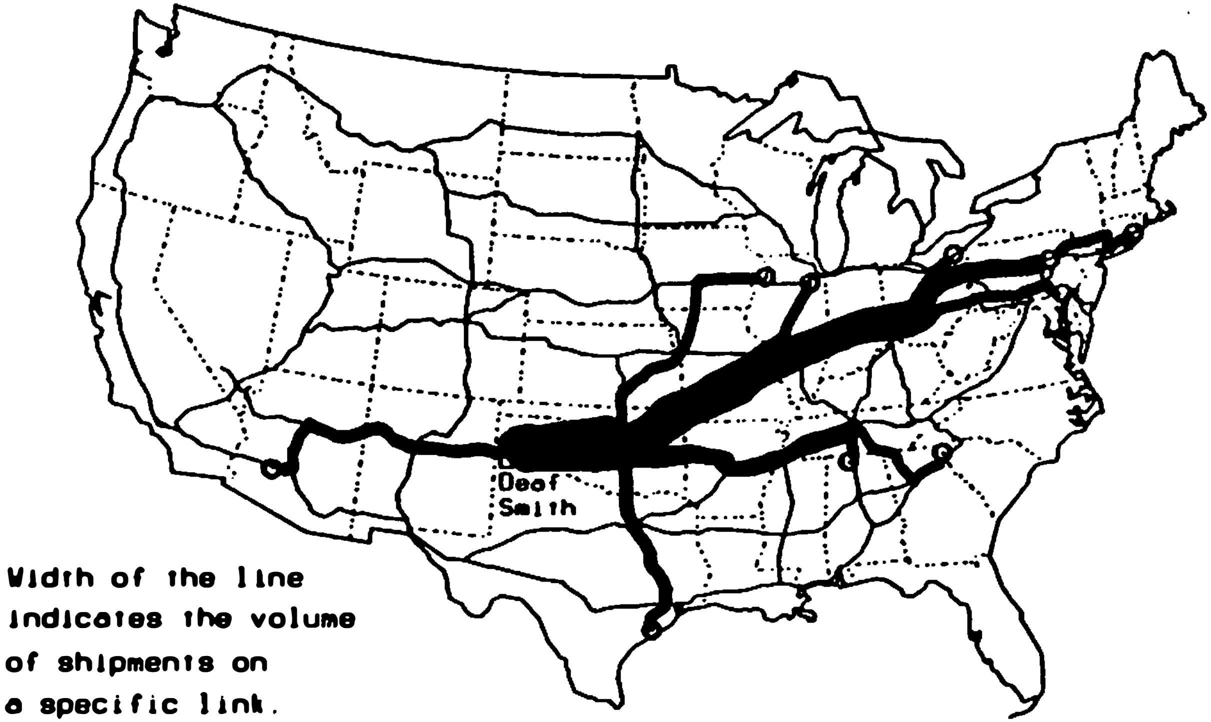


Figure 4.9 MTTRM Paths from Ten Reactors to Deaf Smith Repository Which Minimize Incident Free Transportation Risk.

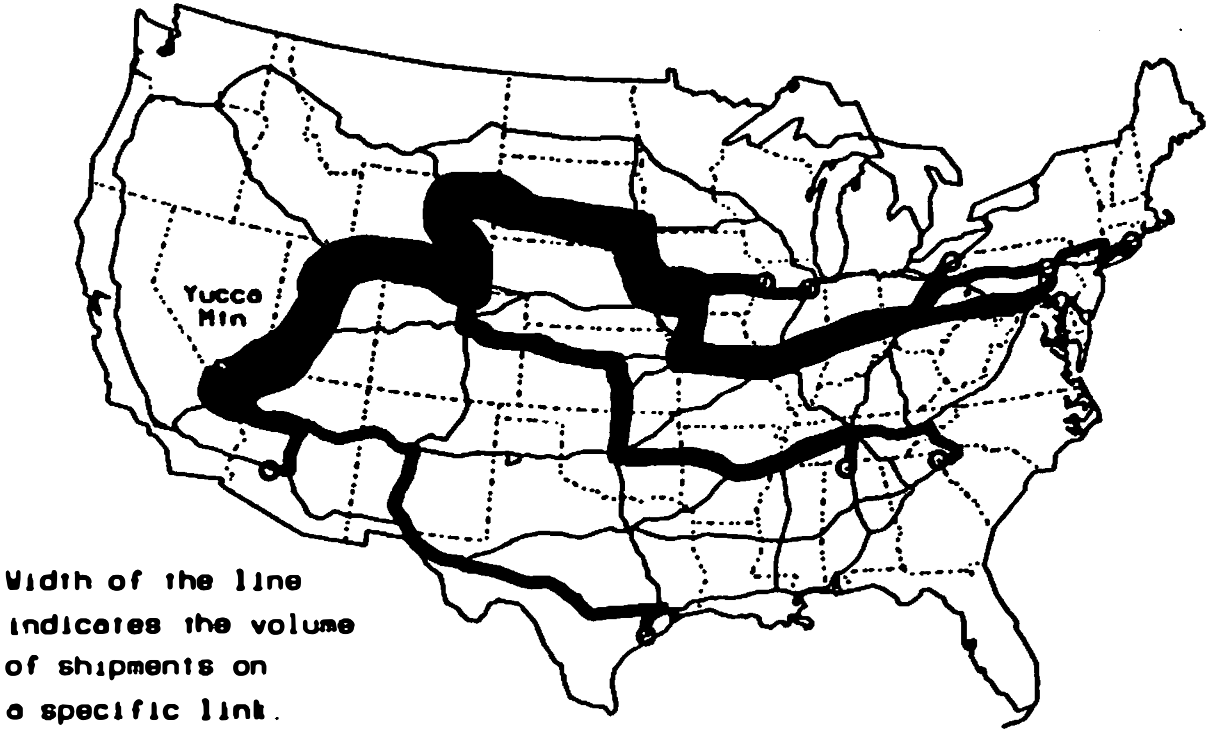


Figure 4.10 MTTRM Paths from Ten Reactors to Yucca Mountain Repository Which Minimize Expected Accident Risk to the Population.

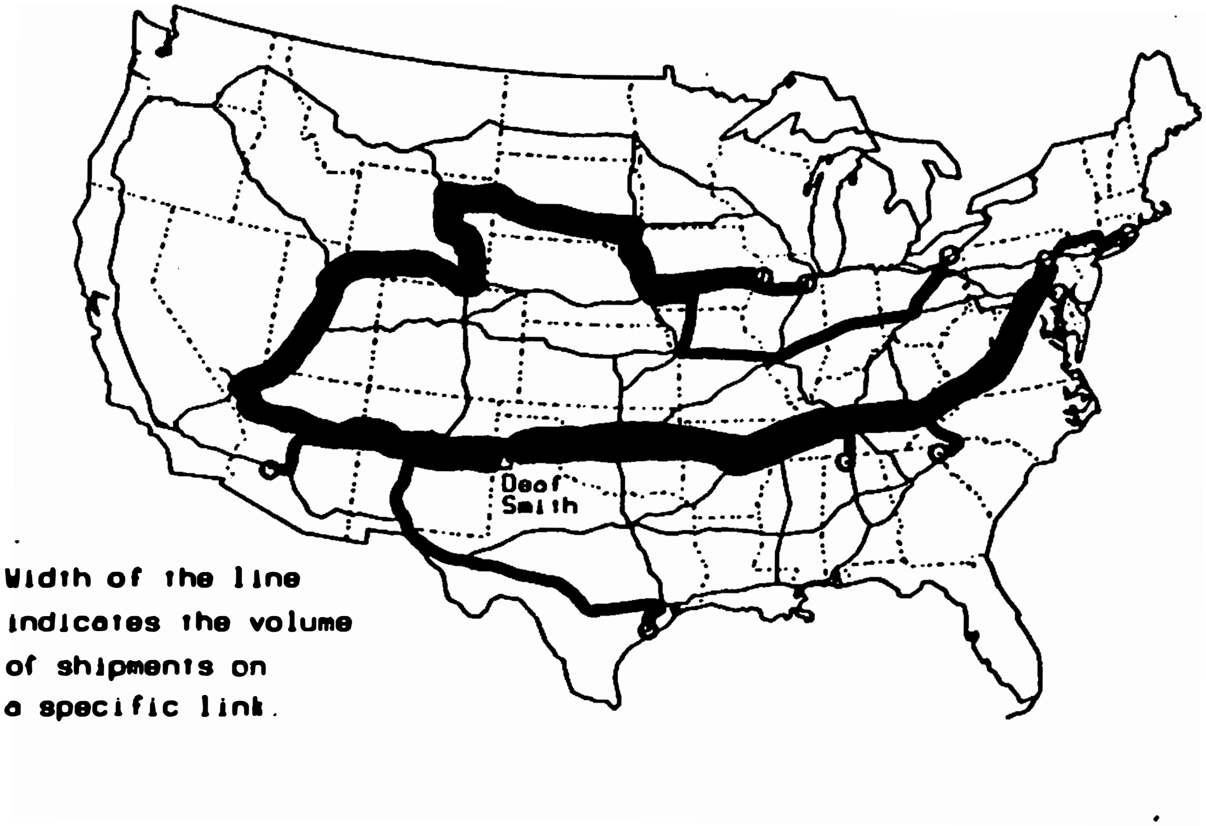


Figure 4.11 MTTRM Paths from Ten Reactors to Deaf Smith Repository Which Minimize Expected Accident Risk to the Population.

very urbanized, the property values along the highways in this area are high. This causes the shipments from the Northeast to avoid this part of the United States. They shift to the more rural Southeastern states. The shipments to Hanford and Yucca Mountain then move through the Great Plains and Rocky Mountain states where accident rates are relatively low (Figures 4.12 and 4.13). The shipments to Deaf Smith must travel through several high accident rate states such as Arkansas and Oklahoma (Figure 4.14). The results of these routing patterns show the risk for Yucca Mountain to be the lowest for the candidate sites. Hanford also has a relatively low risk, while Deaf Smith has a much higher risk (Table 4.3).

In each of the three cases which are considered, either Deaf Smith or Yucca Mountain is shown to be the minimum transport risk site. Hanford is the highest risk and cost site for incident free transport risk and expected accident risk to the population. The Hanford site ranks second in terms of expected risk to property when only the permanent sites are considered. It also has the highest transport cost in this category. If similar results are found using all of the reactors which are projected to ship spent fuel in the near future, then the Hanford site would

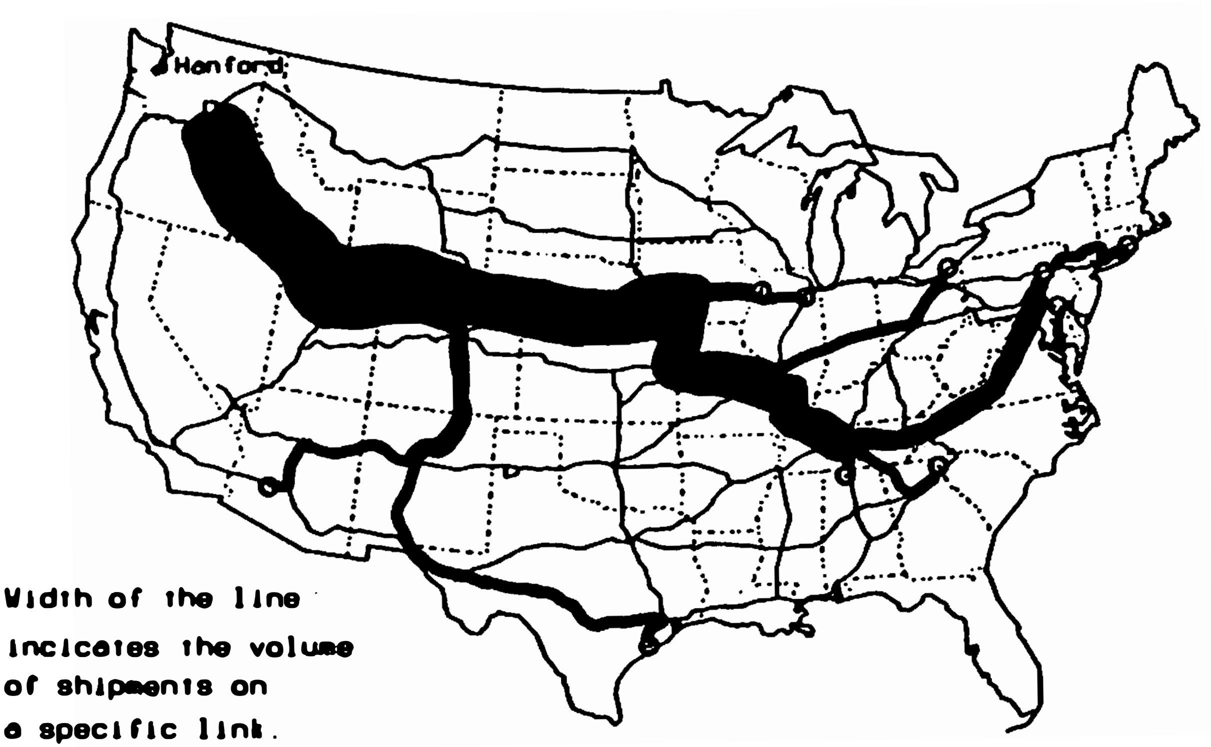


Figure 4.12 MTTRM Paths from Ten Reactors to Hanford Repository Which Minimize Expected Accident Risk to Property.

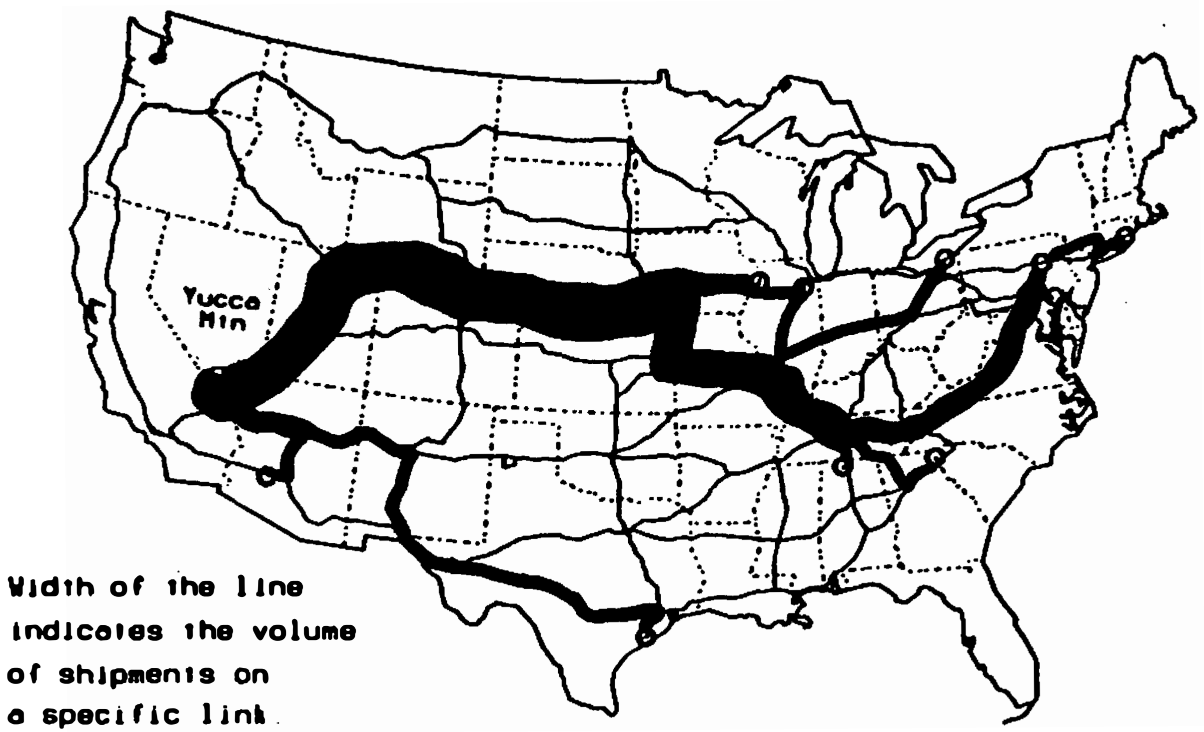


Figure 4.13 MTTRM Paths from Ten Reactors to Yucca Mountain Repository Which Minimize Expected Accident to Property.

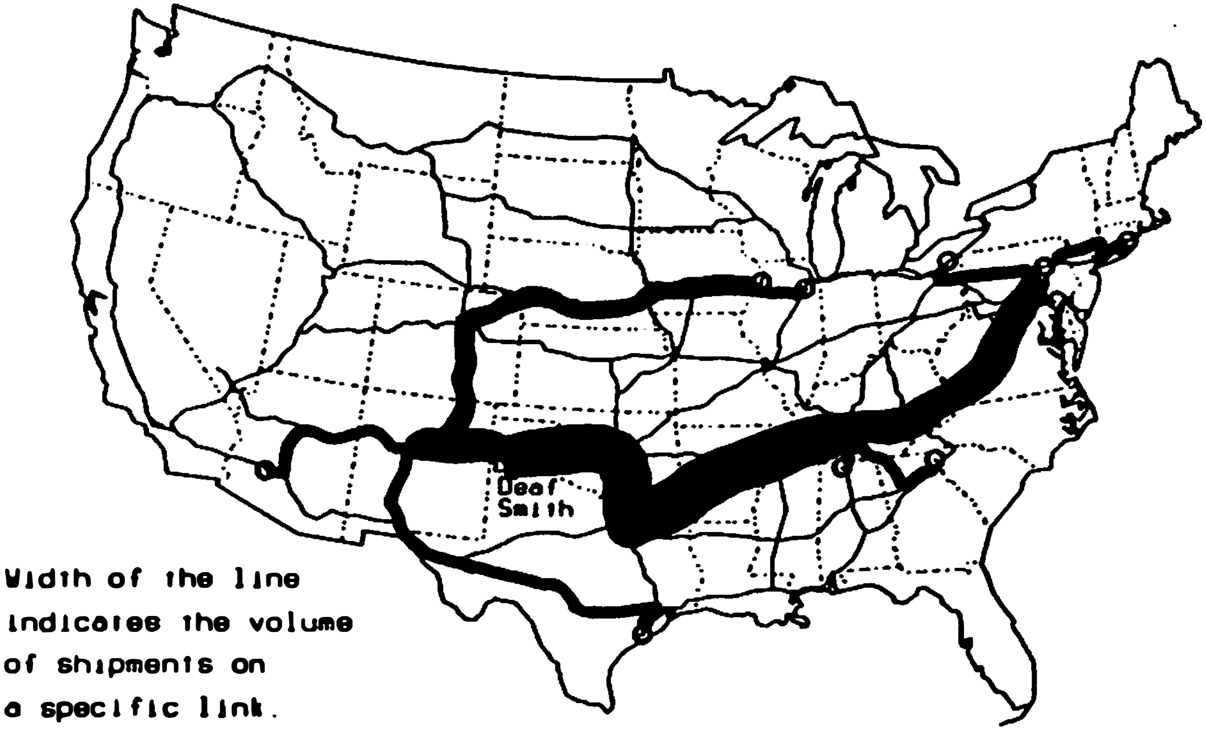


Figure 4.14 MTTRM Paths from Ten Reactors to Deaf Smith Repository Which Minimize Expected Accident Risk to Property.

rank as the least desirable location in terms of transport risk and cost.

Conclusion

This chapter focuses on using the MTTRM and ETRM to represent flows of spent fuel from several reactors to each of the prospective repository sites and the MRS. The same basic relationships between path risk and societal risk which are found with single reactors and repository shipments hold in the multiple reactor case. Initially, path risk decreases as societal risk and shipment costs rise sharply. After most of the major alternative routes have been taken, the decrease in path risk becomes minimal. The societal risk also begins to gradually decline and shipment costs stabilize.

Incident free transport risk, expected accident risk to the population, and expected accident risk to property are each used to compare cost and risk of shipping spent fuel to the four storage sites from the ten reactors. The comparison of transporting spent fuel from the ten reactors to the four proposed spent fuel storage facilities shows that the MRS site in Tennessee is the location which minimizes cost and risk. If the spent fuel is eventually transferred from the MRS to one of the permanent storage

sites in the West, the additional cost and risk of this move will need to be considered.

When the ten reactors ship directly to the candidate repository sites, Deaf Smith always emerges as the minimum cost location, but the risk factor varies. The Deaf Smith site has the minimum incident free transport risk. Yucca Mountain is the site with the minimum expected accident risk to population and property.

CHAPTER 5

SUMMARY AND CONCLUSIONS

Summary of Research

The primary objective of this study is to develop two models which will provide policy makers the tools to better evaluate the risk and cost of transporting spent fuel. This is accomplished by the development of the Minimum Total Transport Risk Model which minimizes all of society's risk and the Equilibrium Transport Risk Model which minimizes path risk. The former optimizes efficiency; the latter equity.

Three types of risk are considered in both models. Incident free transport risk incorporates the length of the highway segments, population density along the highway, traffic volume on the highway with the spent fuel, and speed of the traffic into its calculations. The expected accident risk to the population considers the radioactive materials accident rate for each state, the probability that various amounts of the cask contents will be released, and the population density along each segment of highway which would be exposed in case of an accident. The expected accident risk to property also takes into account the variable state accident rates and release

probabilities, along with the cost of the accident to property owners in the vicinity. Each of these types of risk is associated with a weight parameter, which enables planners to emphasize each type of risk in their analysis.

To study the effects of each type of risk on the routing pattern of the models, three different sets of beta values are used. Paths, costs, and risk values associated with each type of risk are then generated. If the models are applied to evaluate the actual shipment of spent fuel, some combination of the three types of risk would be used. It would be up to the discretion of the transport planners to determine the beta values applicable to their particular situation.

The MTTRM finds paths which minimize risk for all of society. The major problem with this efficient minimum societal risk solution is that it places a heavy burden of risk on those people along the few routes chosen. At the same time, the people along the rest of the network may be receiving the benefits of the nuclear power in the form of electricity without having to experience any of the risk.

The ETRM addresses this situation by spreading the risk over a number of paths on the network. Each path which is generated has the same minimum risk as the other paths from any one reactor. The result is a series of minimum risk paths from each reactor to a repository.

As the risk value on individual paths decreases, the overall societal risk value rises. This occurs because the increased number of trips results in more shipment miles through the network. For the network used in this study, most of the major alternative paths are chosen by the sixth iteration. The small changes in routing patterns after this may actually decrease the number of shipment miles. This results in declining path and societal risk values in the later iterations of the ETRM.

The ETRM terminates when path patterns repeat themselves. At this point, no further reduction in path value may occur. The practical value of the model is usually found in the first two or three iterations. Beyond this point, the paths that are generated follow routes which may be too long to be considered practical by any shipper. Thus, even though the ETRM achieves a very low path risk value at the end of its calculations, the loss in efficiency may be unacceptable. The more reasonable

solution may be a suboptimal path risk value which can be obtained with acceptable levels of cost and societal risk.

The length of the trip is reflected in its cost. The least cost trip does not usually follow the same path as the minimum risk path. As a result, there is normally a trade off between risk and cost. During the first few iterations of the ETRM, the cost rises rapidly with each path which is added. This rapid increase in cost stabilizes when the changes in the path structure diminish to minor variations of one or two links in a path.

The final section evaluates the locational relationships of the spent fuel storage sites, based on transportation cost and risk. The MRS facility is the least cost and risk location for the ten reactors which are used in the study. This result is not surprising since over eighty percent of the operating reactors in the United States are located east of the Mississippi River and the MRS is the only one of the facilities studied which is found in this region. There will be additional risk and cost associated with the MRS in the future because the DOE plans to move the spent fuel stored there to one of the permanent sites which are now being considered in the Western United States. Any study determining the

feasibility of building the MRS should keep this additional cost and risk in mind.

If the direct reactor-repository shipment option is considered, then the focus turns to the three candidate repository sites in the West. The cost of shipping spent fuel from each reactor to the repository is a function of the volume of spent fuel at the reactor and the distance it must be transported. Since most of the older reactors are in the East, they tend to have the largest amounts of stored spent fuel and the farthest distances to travel. This fact means that as the location of the candidate repository site moves farther west, the cost of shipping rises. This is borne out in the analysis which shows that shipping costs from the Eastern reactors escalate from Deaf Smith to Yucca Mountain to Hanford.

Since distance is one of the primary factors in the calculation of incident free transport risk, Deaf Smith is the least risk location when this type of risk is considered. Many of the Southeastern and South Central states through which spent fuel shipments would move to Deaf Smith have higher than average accident rates. Most of the Great Plains and Rocky Mountain states have low accident rates, low population densities, and few major metropolitan areas. As a result of this difference, the

expected accident risk to the population and property is least for the Yucca Mountain site. These results of course are based on a specific set of beta weights. A change in the beta weights could alter the numerical results presented here. However, the locational relationships should stay the same. Deaf Smith would continue to be the least cost location. Any combination of beta weights would still result in the choice of Deaf Smith or Yucca Mountain as the safest repository location when transport risk is considered because they are the minimum risk sites when each type of risk is individually used in the models.

Policy Implications

This is one of the first attempts to introduce risk into the routing process as a precondition to determine the most appropriate path or set of paths for the shipment of spent fuel. Previous models have found the shortest path and then evaluated its risk (Joy and Johnson, 1983). The MTTRM and the ETRM provide a more explicit method for considering risk in the routing question than the previously limited shortest path models. Since risk is a primary consideration, these models explicitly address a major public concern.

There are a limited number of routes which can be taken from the Eastern United States to the three permanent candidate repository sites in the West. Currently, there are only seven interstate highways which serve as major east-west corridors (I94, I90, I80, I70, I40, I20, and I10). Even with this limited number of routes the combination of paths which can be taken between the Eastern reactors and Western repositories is enormous. One of the runs of the ETRM generated over eighty different paths between Millstone nuclear power plant in Connecticut and the Hanford candidate repository site in Washington. The only way to compare these alternative paths is by some logical means of measure of risk and cost. The MTTRM and ETRM provide this means of measure.

The MTTRM and ETRM give the policy makers at different levels of a government a means by which to judge the cost and risk of various routing alternatives. Each iteration generates a different risk value for society and people along the chosen paths. These risk and cost values can be considered by decision makers at the local, state, and national level to determine which set of paths will be the best compromise solution.

An example of this policy application can be seen in the case of shipping spent fuel from Millstone to Hanford (Figure 5.1). The MTTRM path runs through Iowa and Nebraska. These two states experience high levels of exposure on this minimum risk run of 809 and 1,190 pmr, respectively. When two paths are generated, the risk in Iowa and Nebraska drop to 428 and 629 pmr, respectively, while the risk in their neighboring states of Missouri is 322 pmr and Kansas is 535 pmr. By using these models, state officials, DOE, and NRC should be able to assess the trade offs in risk and determine how the routing should take place. Clearly, each model will have its own proponents. Indeed, if the trade off between equity and efficiency is studied, each level of equity may have different sets of advocates.

Future Research

There are a number of possibilities for expanding the scope of the research into shipping spent fuel using the MTTRM and ETRM. Some of these steps can be accomplished with relative ease, while others will require considerable time and effort.

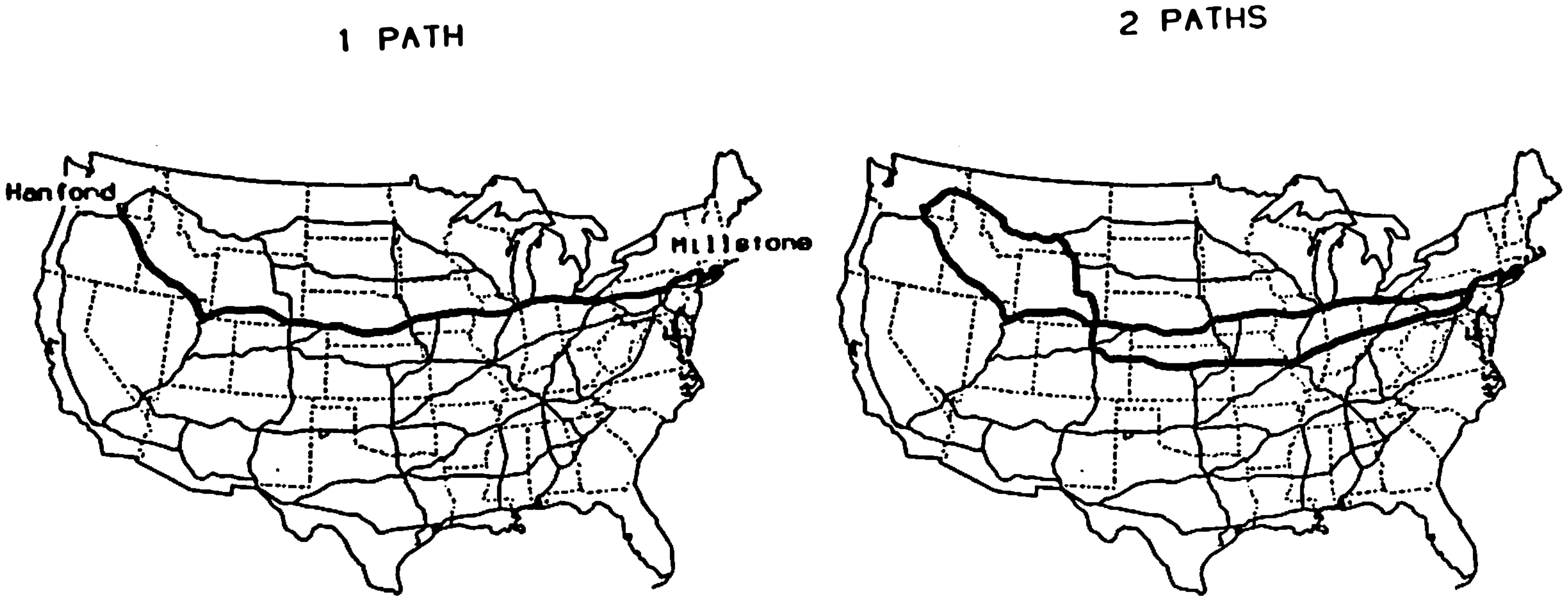


Figure 5.1 Two Path State Risk Options.

Risk Units

A primary concern for the models to be implemented is that of the risk units. Currently, the incident free transport risk and expected accident risk to the population are measured in person milirems. The expected accident risk to property is measured in person milirem dollars. The current research has avoided the problem of combining these different units by treating each of them as a separate case.

If these three types of risk are combined, then the units associated with each of them would need to be eliminated or changed to the same form. The beta weights can be used to accomplish this task.

The beta weights can be used to eliminate the risk units by simply multiplying them by the inverse of the units associated with a particular type of risk. This will result in a unitless risk figure which can be used only for ordinal comparisons.

The beta weights can also be used to convert the risk units to some common form. This can be accomplished by determining the number of deaths or cancers associated with each level of exposure in person milirems. The cost of these deaths and cancers can then be determined and

combined with the economic losses to property in the form of lost production and decontamination costs.

Link Deletions

One of the easiest and most practical steps which can be taken to improve the usefulness of the models is to incorporate the ability to delete certain links from the network. If there is concern about specific links in the highway which have too high a population density living along them or a very high accident rate or some link contains a feature such as a bridge or tunnel which policy makers and safety experts feel should be avoided by spent fuel shippers all together, a constraint can be added to the models which will remove these links. For example, a requirement which stipulates that spent fuel cannot be transported along a segment of highway whose population density is more than a minimum level, can be represented by the constraint:

$$x_{ji} = 0, \quad \text{for every } j,i \in g, \tag{5.1}$$

where:

$$g = \{ j,i \mid p \geq p^{*} \},$$

p^{*} = minimum population density along link ji.

If (5.1) is added to the MTTRM and ETRM, the flows along the designated link ji would be eliminated.

A similar constraint (5.1) could be used for legislative restrictions on the movement of spent fuel over links ji. The definitions of g and p^{*} would need only change to:

$$g = \{ j,i \mid p = p^{*} \},$$

p^{*} = legal restriction which prohibits the movement of spent fuel over link ji.

This type of constraint can be incorporated in the MTTRM and ETRM to reflect DOT, NRC, state, and local restrictions on certain links.

MRS Risk and Cost Calculations

The risk and cost figures for the MRS have an additional component which has not been considered in this research. The spent fuel will eventually be shipped from the MRS to a permanent repository site by unit train. Therefore, the cost and risk for this transfer should be

added to the original values for the movement from the reactors to the MRS.

This risk should be a constant C_f for each candidate permanent repository site f. The question arises as to whether the risk of shipping spent fuel to the MRS and then shipping it to a permanent repository at a later date is less than the risk of shipping the spent fuel directly to a repository site. This can be represented by the equation:

$$R_m + C_f \begin{cases} \leq R_f & \text{, then MRS is transport risk effective,} \\ > R_f & \text{, then MRS is not transport risk effective,} \end{cases} \quad (5.2)$$

where:

R_m = risk value for shipping all spent fuel to the MRS,

C_f = constant representing the risk of shipping the spent fuel from the MRS to a permanent repository f by unit train,

R_f = risk value for shipping all spent fuel to candidate permanent repository site f.

If the combined risk of shipping spent fuel from all the reactors to the MRS and the risk of forwarding it to a permanent repository is less than or equal to the risk of shipping the spent fuel directly to the permanent repository site, then it might be worthwhile to build the

MRS. On the other hand, if the shipping risk using the MRS as an interim storage facility is greater than the risk of moving the spent fuel directly to the permanent repository site, the justification for the MRS would be very questionable.

The same general relationship holds for the transport cost. The cost of building the MRS would need to be incorporated into C_f along with the transport cost of the unit train when this factor is considered.

Multiple Repositories

Eventually, DOE is planning to build a second repository in the Eastern United States. This Eastern repository will begin taking spent fuel as the Western repository reaches capacity. If DOE moves its construction time schedule forward to build the two repositories simultaneously, this would allow the reactors to have the option of shipping to two repositories. The transport cost and risk should be reduced if this scenario occurs. Each reactor could ship to the repository which is determined to be the least risk or least cost path or series of paths from it. A determination could also be made on the savings in transport cost and risk to see if building two repositories at once would be feasible.

The MTTRM can be modified to solve this problem as follows:

$$Z = \min \sum_{f} \sum_{b} \sum_{j} \sum_{i \in N} c_{ji} \, x_{ji}^{bf} , \qquad (5.3)$$

s.t.

(2.12), (2.13), and

every reactor sends its shipments to the least cost or least risk repository f. (5.4)

where:

f = a repository.

The ETRM should be changed as follows:

$$Z' = \sum_{f} \sum_{b} D^{bf} = \sum_{f} \sum_{b} \min \sum_{ji \in P_a} (c_{ji}^{b} \, x_{ji}^{bf}), \qquad (5.5)$$

such that constraints (2.12), (2.13), (2.17), and (5.4) are satisfied.

If DOE decides to build each of the repositories the same size, then it will not be possible to minimize risk or cost in shipping from all reactors, but the construction cost using duplicate plans might be less expensive than building two reactors of different sizes. In this case, constraint (5.4) would be substituted with:

$$\sum_i \sum_b c_{if} x_{if}^b = C, \text{ for all } f, \tag{5.6}$$

where:

C = the number of shipments which each repository f can receive.

Changes Over Time

One last extension of the models might consider the element of time. As spent fuel ages, its degree of radioactive emissions decrease. Thus, it is much safer to ship fifteen year old spent fuel than it is to ship five year old spent fuel. Other factors such as population density, land values, accident rates, and the highway network may also change over time. A general representation of minimizing the ETRM shipment risk over time is:

$$\min \sum_t Z_t \alpha_t , \tag{5.7}$$

s.t.

(2.12), (2.13), and (2.17),

where:

Z_t = risk of shipping spent fuel from reactors to a repository during time period t,

α_t = adjustment factor for time period t.

The solution to this type of problem would involve dynamic programming techniques (Wagner, 1975).

Problems and Limitations

The results of any model are only as good as the quality of the data which are used. The MTTRM and ETRM models use a very gross level of data because of the large area over which the highway network of the United States extends. The population, land value, and accident rate units along each link are estimated at a high level of aggregation. Not all major highway segments are included either. If the models are to be applied to represent the risk and cost figures from all reactors to each of the repository sites, then a much finer level of detail should be used in the data base for population density, land use, and accident rates.

The areal units over which the change in risk is measured are much too large. The state units which are used may have several interstate highways running through them. When the shipments are dispersed over a number of paths, it is difficult to see the areal change in risk at the state level. The county level is much more appropriate

since it would reflect the change in risk for a single highway running through that area.

Few studies have been done on release probabilities of spent fuel in highway accidents. Once a final cask design is approved for shipping of spent fuel, extensive testing should be done on the container to determine the degree of leakage at each level of accident severity. When this determination has been made, new probability figures could be incorporated in the accident risk calculations for population and property.

The MTTRM and ETRM are single mode models. Much of the spent fuel will be shipped by rail. This factor of exclusive highway use, limits the models scope of operation to those reactors without rail access and those with rail connections who still plan to use trucks for shipping spent fuel. It also leaves the question of the additional risk and cost of the unit train which should be incorporated into the MRS calculations.

There is no present way to use these two models with rail traffic because it would require a different routing algorithm. Rail routing algorithms usually maximize the distance over which one company hauls the shipment before it turns its cargo over to another company to complete the trip. A shortest path algorithm is used between the source

and the sink, but at each intersection where two different rail systems interconnect, there is a penalty function for that transfer (Peterson, 1983). Adapting the MTTRM and ETRM to this type of algorithm must await further research.

Final Remarks

Despite these limitations, the basic structure of the models is valid. That is, incorporating risk, probabilities of accidents, and questions of equity and efficiency into the routing decision process are steps forward. The insights gained into the relationships between equity and efficiency will likely hold even with further data refinements. Indeed, the development of tools for the analysis of equity and efficiency should aid decision makers in addressing one of the major issues of our time, the transportation of radioactive spent fuel.

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APPENDICES

APPENDIX A

STEPS IN THE EQUILIBRIUM TRANSPORT RISK MODEL

1. Calculate risk factors for each link using (2.10).

2. Calculate shortest path P_i through the network.

3. Split shipments along each path P_i so that the total risk factor Z for each path is equal (See Appendix B).

4. Multiply the number of shipments along each path by the risk factor for each individual link.

5. Repeat steps 2 to 4 until no new path is found.

6. Report the results.

APPENDIX B

TRIP ASSIGNMENT AND RISK FACTOR EQUILIBRIUM

Suppose the number of current shortest paths found is n, then:

$$\sum_{ji \in P_l} c_{ji} t_l = C . \qquad (B.1)$$

where:

P_l = The l-th path.

t_l = The number of trips on the l-th path.

C = Constant.

c_{ji} = Risk factor on link ji.

and

$$\sum_{l=1}^{n} t_l = T. \qquad (B.2)$$

Let:

$$a_l = \sum_{ji \in P_l} c_{ji} . \qquad (B.3)$$

then (B.1) and (B.2) can be written in the matrix form

$$A\ t = b. \qquad (B.4)$$

where:

$$A = \begin{bmatrix} 1 & 1 & 1 & . & . & . & 1 \\ 0 & a_2 & 0 & . & . & . & -a_n \\ . & 0 & a_3 & 0 & . & . & -a_n \\ . & . & . & . & . & . & . \\ a_1 & 0 & . & . & . & . & -a_n \end{bmatrix}$$

$$t = \begin{bmatrix} t_1 \\ . \\ . \\ . \\ t_n \end{bmatrix} \qquad b = \begin{bmatrix} T \\ 0 \\ . \\ . \\ . \\ 0 \end{bmatrix}$$

Equation (B.4) can be factored into a lower and upper triangular matrix (Burden, 1981).

$$L\ U\ t = b. \tag{B.5}$$

where:

L = The lower triangular matrix.

U = The upper triangular matrix.

$$L = \begin{bmatrix} 1 & & & & & & \\ 0 & 1 & & & & & \\ 0 & 0 & 1 & & & & \\ . & . & . & . & & & \\ . & . & . & . & . & & \\ a_1 & -\frac{a_1}{a_2} & \frac{a_1}{a_3} & . & . & {}_{i=1}^{n} & \frac{a_1}{a_i} \end{bmatrix} \quad (B.6)$$

$$U = \begin{bmatrix} 1 & 1 & 1 & . & . & . & 1 \\ & a_2 & 0 & . & . & . & -a_n \\ & & a_3 & 0 & . & . & -a_n \\ & & & . & . & . & . \\ & & & & . & . & . \\ & & & & & . & . \\ & & & & & & -a_n \end{bmatrix} \quad (B.7)$$

Let: $U\,t = y.$ (B.8)

Solve: $L\,y = b.$ (B.9)

Since L is a lower triangular matrix, it is easy to solve for y.

Since the values of y and the upper triangular matrix U are known, it is easy to solve for t.

To solve for t:

Let:

$$y_n = \frac{-a_1 T}{\dfrac{a_1}{\sum_i \dfrac{1}{a_i}}} . \qquad \text{(B.10)}$$

then

$$t_i = \frac{-y_n}{a_i}, \quad \text{for every } i, \quad i \neq 1. \qquad \text{(B.11)}$$

and

$$t_1 = T - \sum_{i=2}^{n} t_i . \qquad \text{(B.12)}$$

APPENDIX C

COMPARISON OF RISK AND COST FOR A SINGLE REACTOR - REPOSITORY CASE

Introduction

Three reactors are used to compare risk values for shipping spent fuel. Millstone, Oconee, and Palo Verde nuclear power plants send their respective annual flows of spent fuel to the Hanford candidate repository site (Figure C.1). These three reactors were selected because they are located in widely dispersed parts of the United States. Hanford was chosen because it is the most distant of the four alternative choices for transporting the spent fuel. The longer distances to Hanford provide more routing alternatives for the models.

The maps in this section, which compare path and societal risk, show the first four minimum risk paths. This provides a visual representation of the initial set of the most reasonable routes.

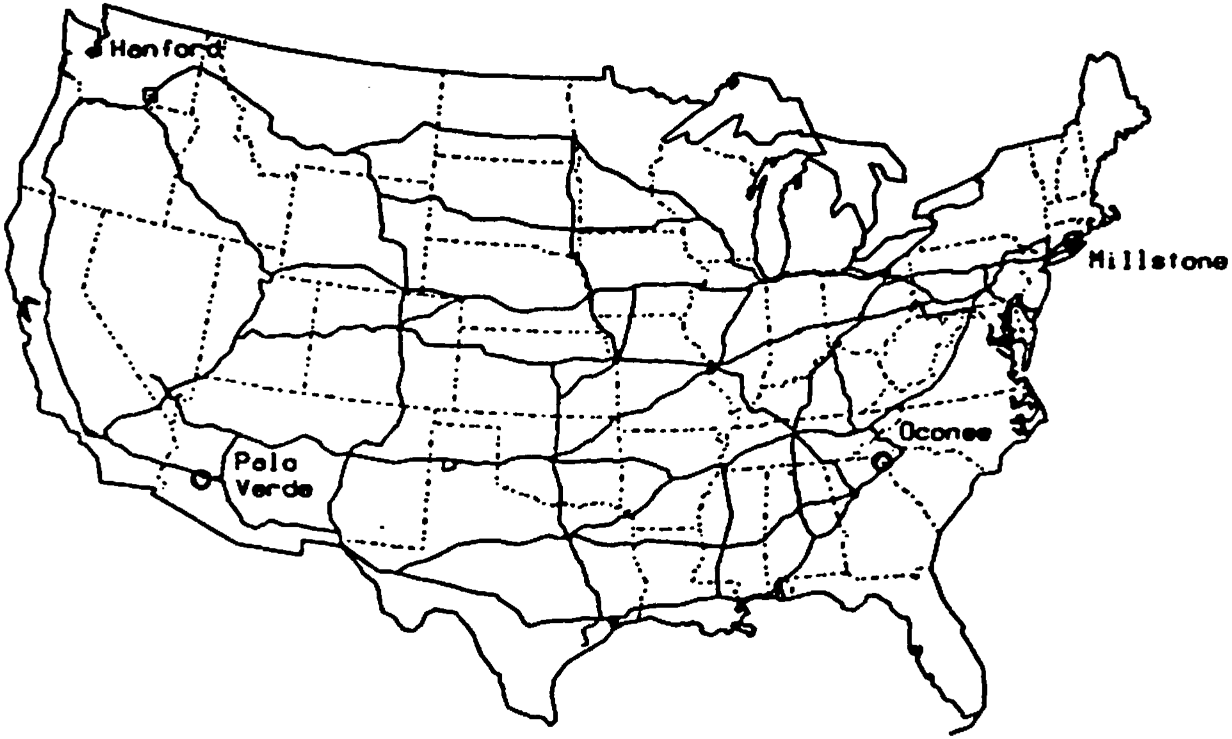


Figure C.1 Single Reactors and a Repository.

Comparison of Path and Societal Risk

Incident Free Risk Values

The comparison of incident free risk values between the three reactors reflects a number of differences in distance traveled, population density along the routes, amount of traffic on the highways, and number of shipments of spent fuel. When the three reactors are considered, the highest exposure rates in person milirems (pmr) are found in shipments from Millstone, Connecticut to Hanford, Washington. The initial path shows a risk value of 7,892 pmr of exposure. The first path goes through a number of densely populated areas in the Northeastern section of the United States such as the suburbs of New York City, Cleveland, and Chicago (Figure C.2). This tends to raise the population exposure rates to a higher level. The Millstone reactor is also the longest distance away from the repository. The first minimum risk path covers 2,969 miles. As the number of paths increases, the risk to path consistently declines, while the total societal risk increases until the eighth iteration (Figure C.3). After this point, the risk to individual paths slowly declines and the risk to society vacillates between 10,255 and 10,838 pmr. The final path risk value is 270 pmr for 38

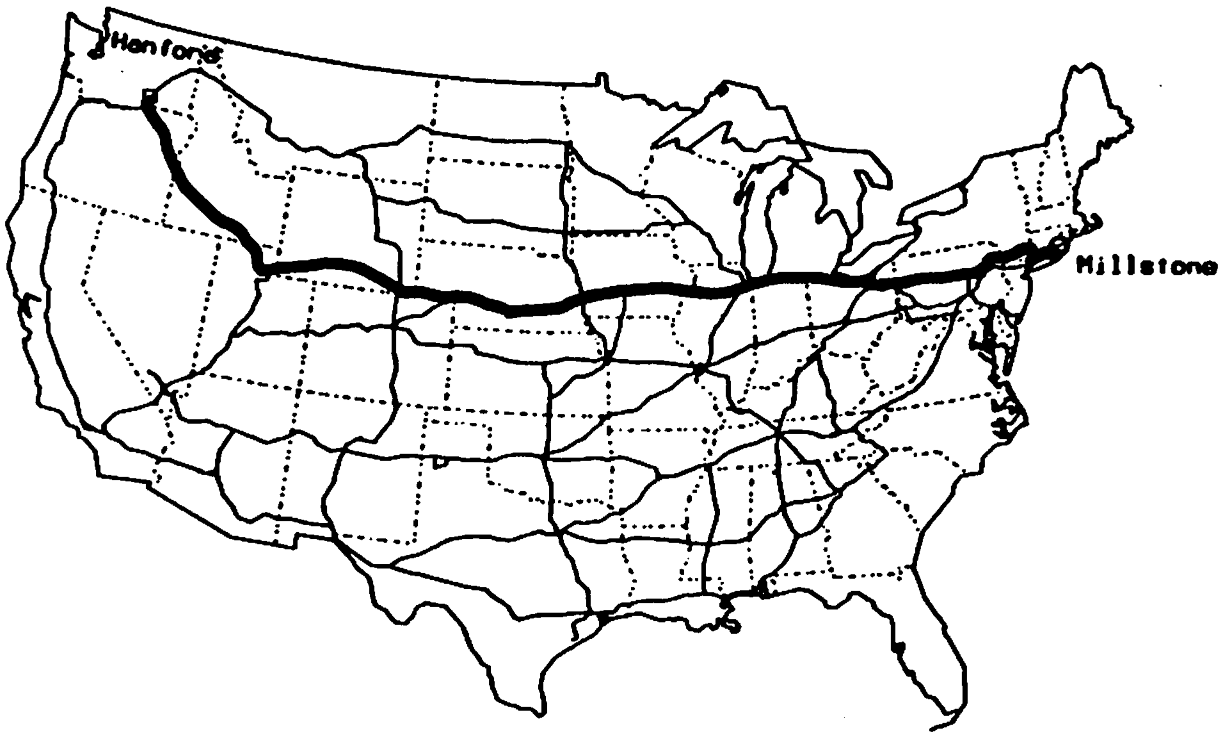
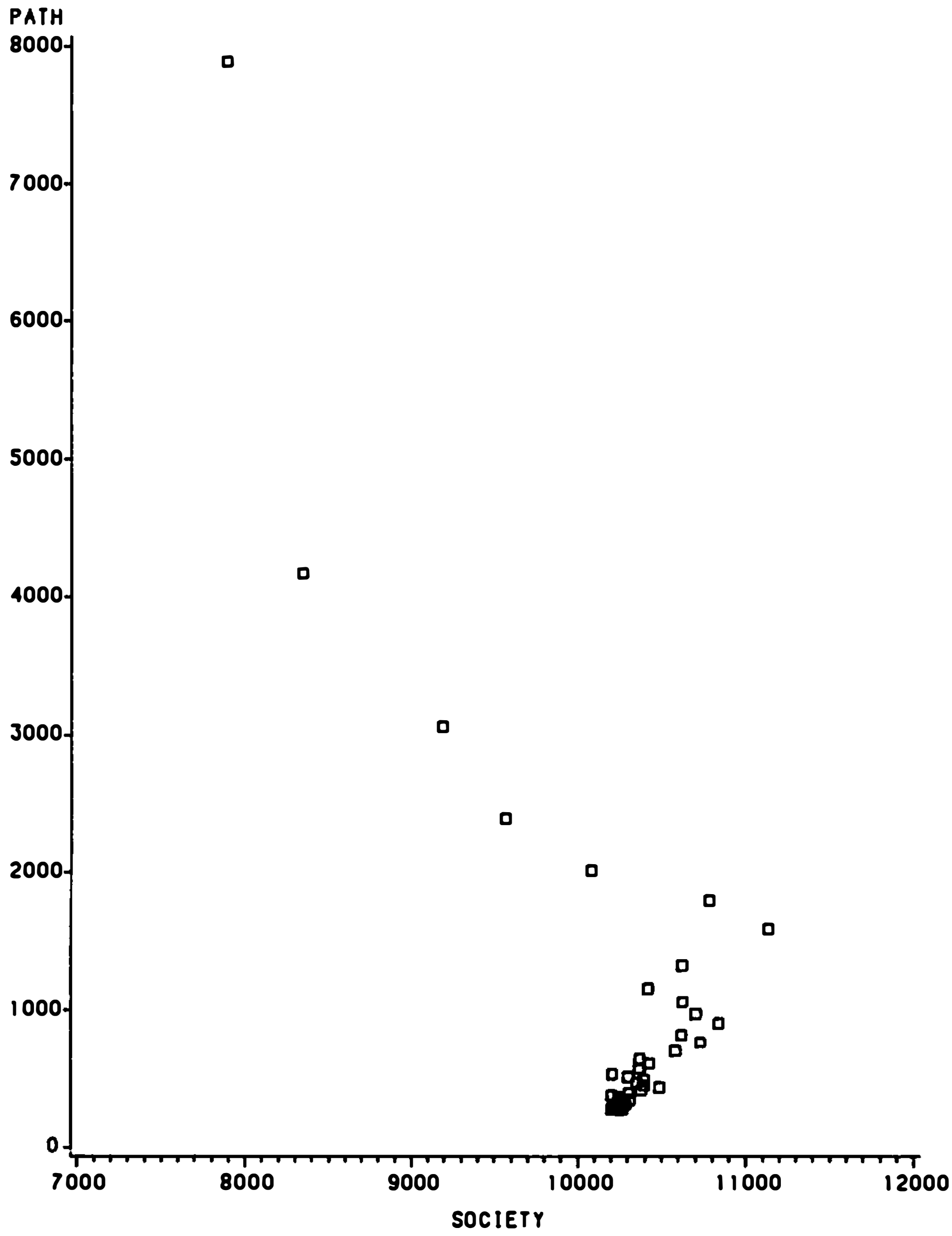


Figure C.2 First Minimum Risk Path Between Millstone Power Plant and Hanford Repository for Incident Free Transport Risk.



RISK IS MEASURED IN PMR

Figure C.3 Path Risk vs. Societal Risk Between Millstone Power Plant and Hanford Repository for Incident Free Transport Risk.

paths. The initial divisions in paths give the greatest reductions in path risk. For instance, the division into two paths cuts the risk value along those two paths nearly in half. After the fifth iteration, the decreases in path risk become relatively small.

The Oconee reactor shipments to Hanford using this same set of beta values have an initial risk value of 6,281 pmr. The path goes through a number of cities such as Atlanta, Georgia, Nashville, Tennessee, St. Louis, Missouri, Kansas City, Missouri, and Omaha, Nebraska (Figure C.4). The overall trip is shorter than the one from Millstone by 210 miles. The states in the Southeast through which these shipments pass have lower population densities than in the Northeast and there are fewer shipments from Oconee. These factors account for the lower risk values for shipping spent fuel between Oconee and Hanford.

The same basic pattern of path and societal risk values holds for the Oconee shipments. There is a large decrease in path risk in the first four iterations (Figure C.5). After that, there is a gradual decline in risk for people along paths. The increase to society continues for nine iterations to 8,095 pmr. It then oscillates between 7,877 and 8,101 pmr.

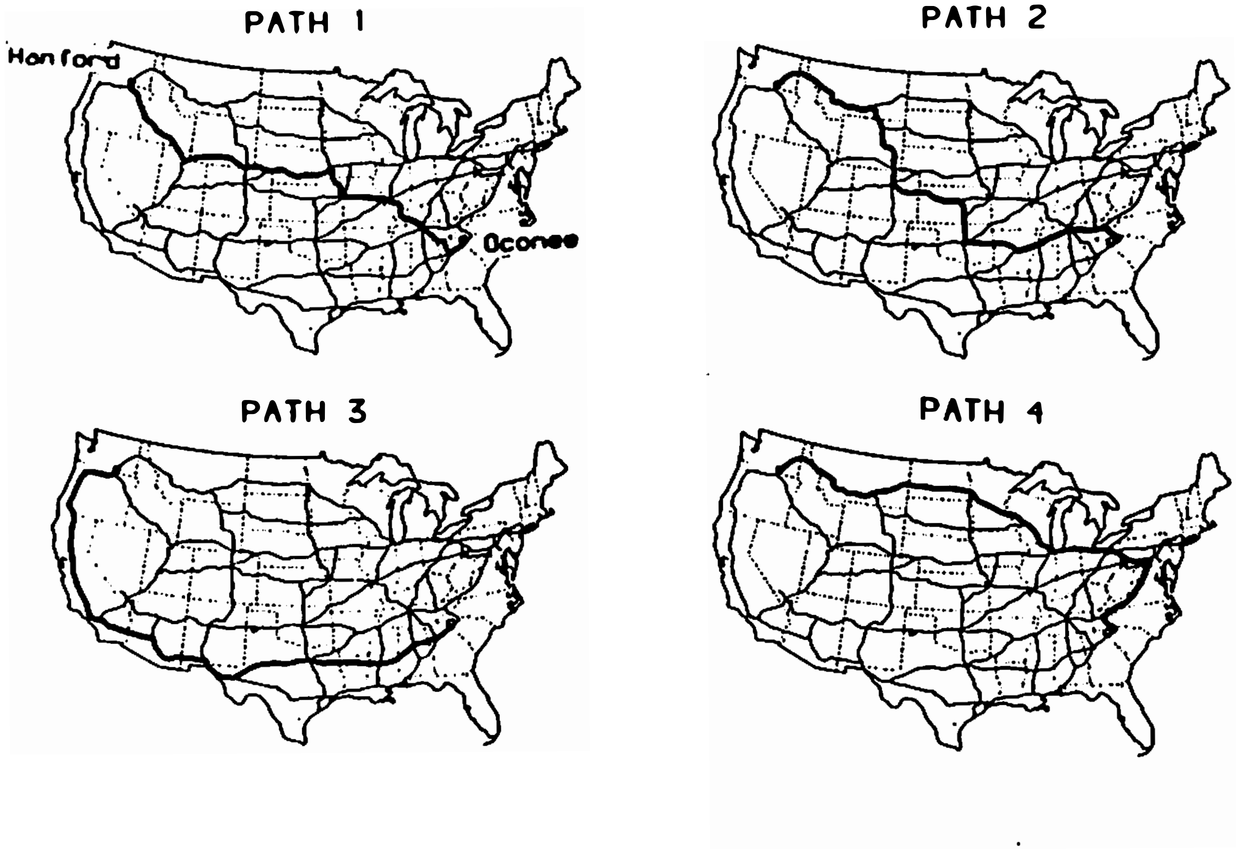


Figure C.4 Four Paths Between Oconee Power Plant and Hanford Repository Which Minimize Incident Free Transport Risk.

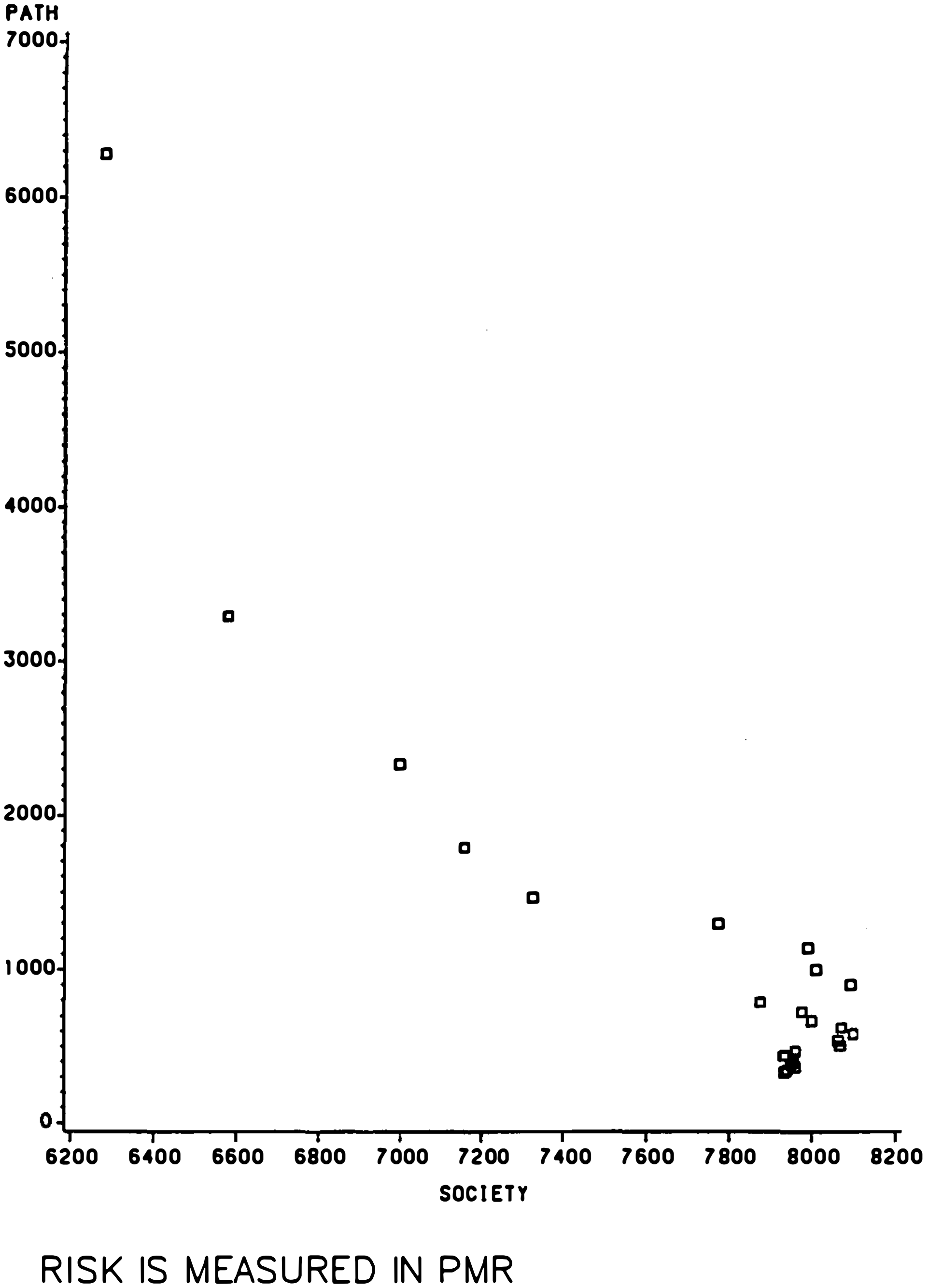


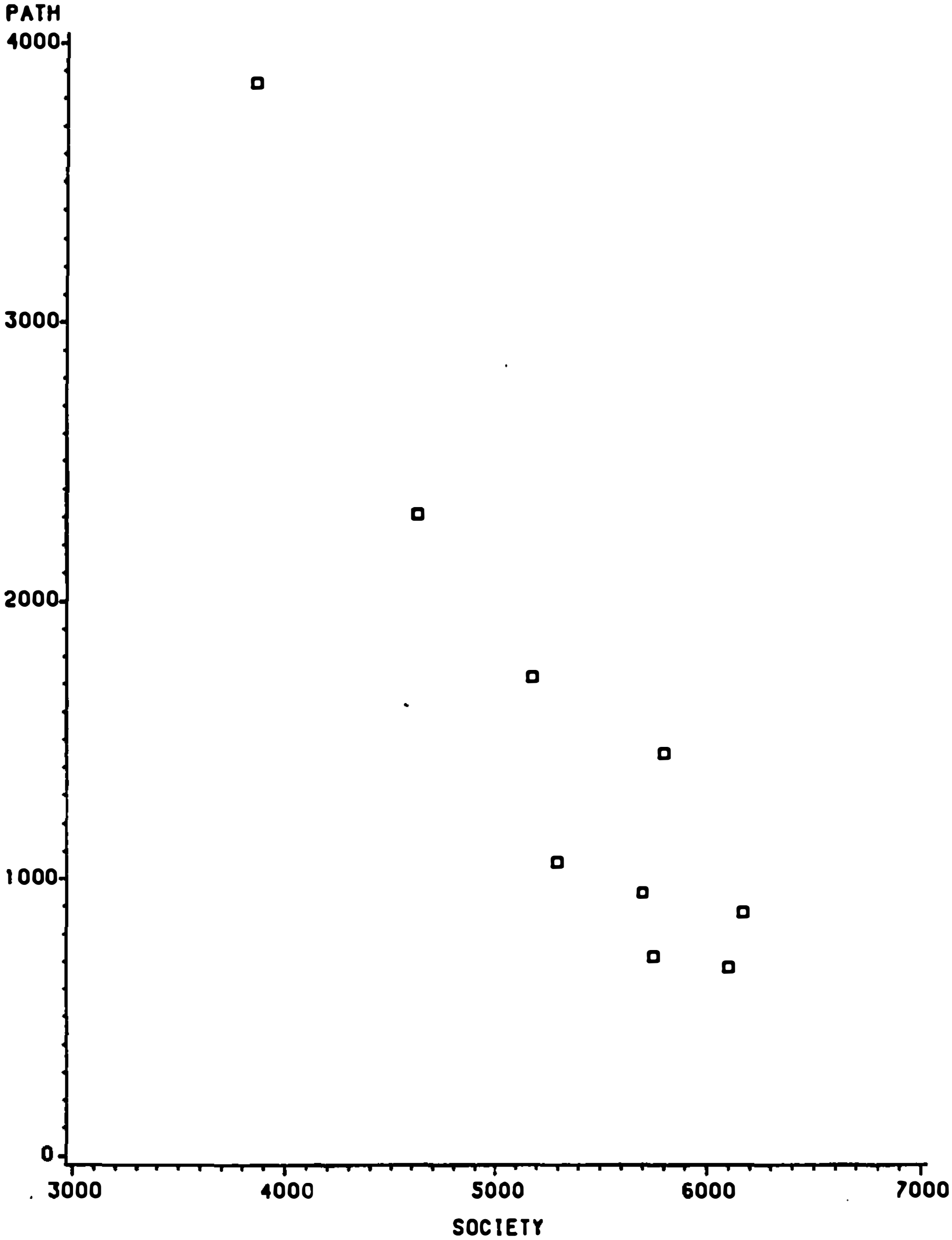
Figure C.5 Path Risk vs. Societal Risk Between Oconee Power Plant and Hanford Repository for Incident Free Transport Risk.

Palo Verde is the nearest of the three reactors which were chosen. It lies only 1,537 miles from Hanford by the initial least risk route. It's nearness and the relatively sparse population of the West contribute to the low initial risk factor of 3,862 pmr for the spent fuel shipments (Figure C.6). This value for path risk falls to a low of 678 pmr after eight iterations. The short distance and sparse network in the West leads to fewer alternative routes. Societal risk values gradually increase from 3,862 pmr to 5,801. Then, they begin to swing from a low of 5,294 to 6,168 pmr.

The initial minimum risk path taken by the shipments from Palo Verde to Hanford runs west into Southern California (Figure C.7). It then turns north through Nevada, Utah, Idaho, and Oregon.

Expected Accident Risk to the Population

For Millstone, there is a change in the relationship between path and societal risk and a major shift in routing pattern from the incident free transport risk. The increase in societal risk rises sharply from 9,850 to 16,341 pmr during the second iteration (Figure C.8). Then it drops back to between 12,714 and 14,437 pmr for the remainder of the iterations. Path values drop



RISK IS MEASURED IN PMR

Figure C.6 Path Risk vs. Societal Risk Between Palo Verde Power Plant and Hanford Repository for Incident Free Transport Risk.

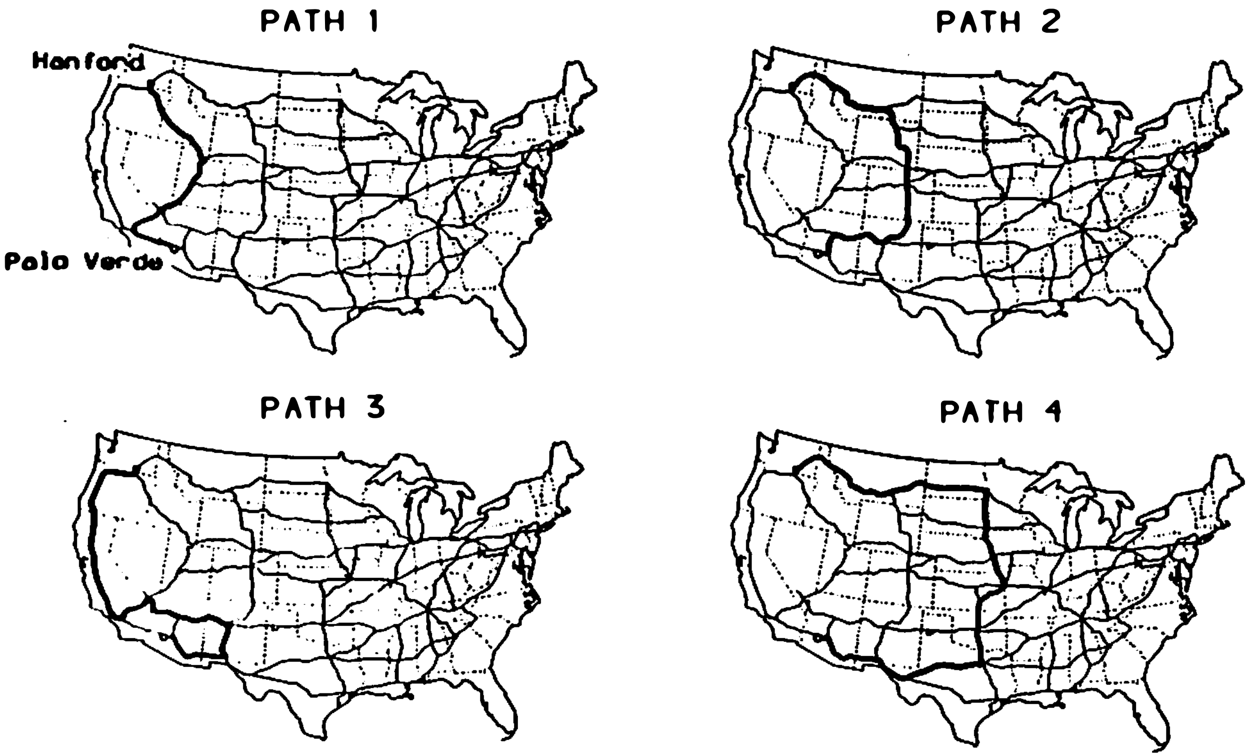
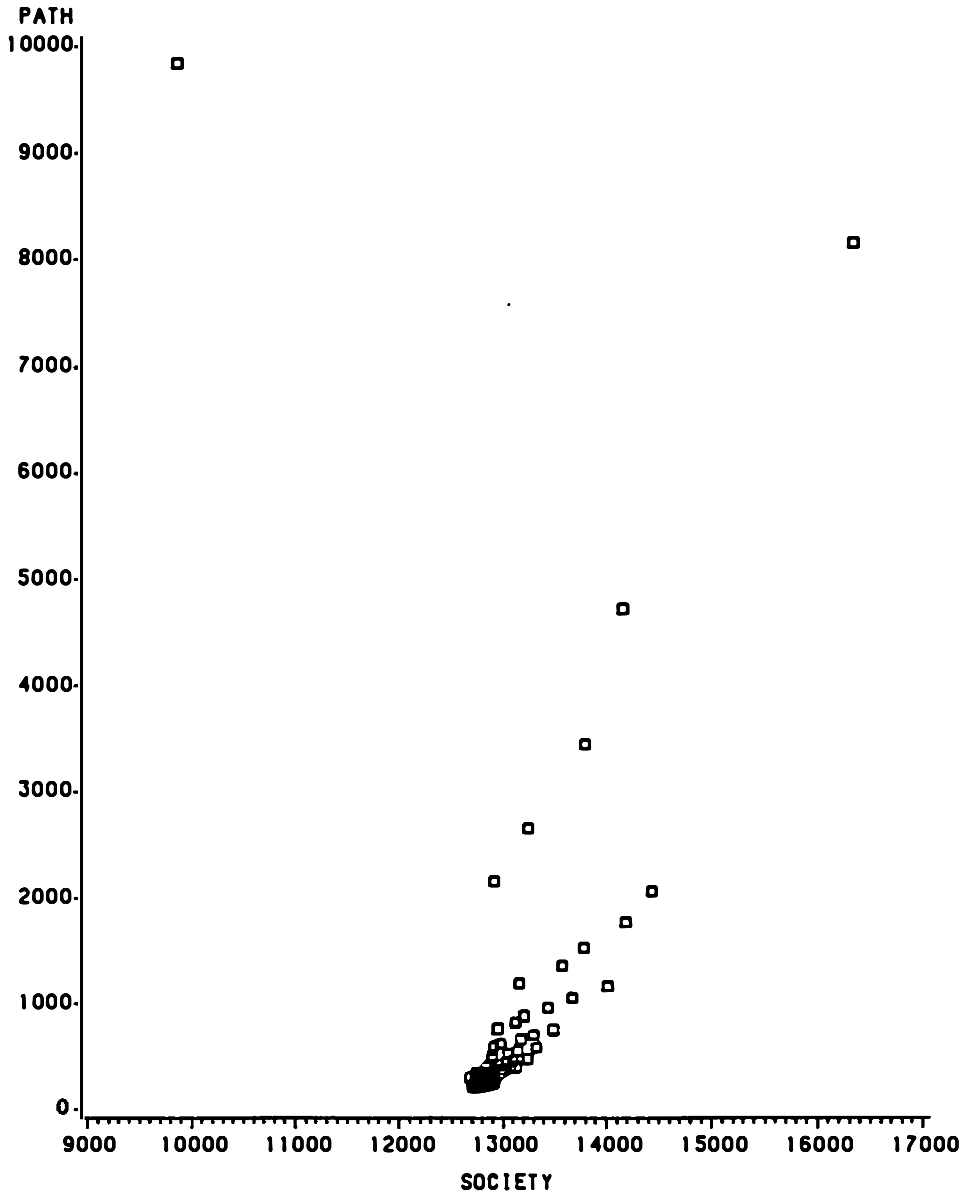


Figure C.7 Four Paths Between Palo Verde Power Plant and Hanford Repository Which Minimize Incident Free Transport Risk.



RISK IS MEASURED IN PMR

Figure C.8 Path vs. Societal Risk Between Millstone Power Plant and Hanford Repository for Expected Accident Risk to the Population.

substantially during the first six iterations, then reach a point of diminishing returns.

The route taken from Millstone by the initial shipment pursues a course just south of the initial incident free transport path. It moves through southern Pennsylvania, central Ohio, Indiana, Illinois, and Missouri (Figure C.9). It then turns north through South Dakota, thus avoiding the higher accident rate states of Kansas, Nebraska, and Oklahoma. From South Dakota, the route drops south through Wyoming, Utah, Idaho, and Oregon. Even though the trip would be much shorter through Montana, Idaho, and Washington, the minimum risk path avoids this route because of the high incidence of accidents in Washington.

There is an inverse relationship between path risk decrease and society's risk increase for the first seven iterations of the Oconee to Hanford run for minimizing accident risk to the population (Figure C.10). After this point, the characteristic agglomeration of societal and path risk occurs.

The path taken by the spent fuel from Oconee moves due east through Tennessee, Arkansas, and Oklahoma (Figure C.11). At this point it moves across the West seeking out states with the lowest accident rates.

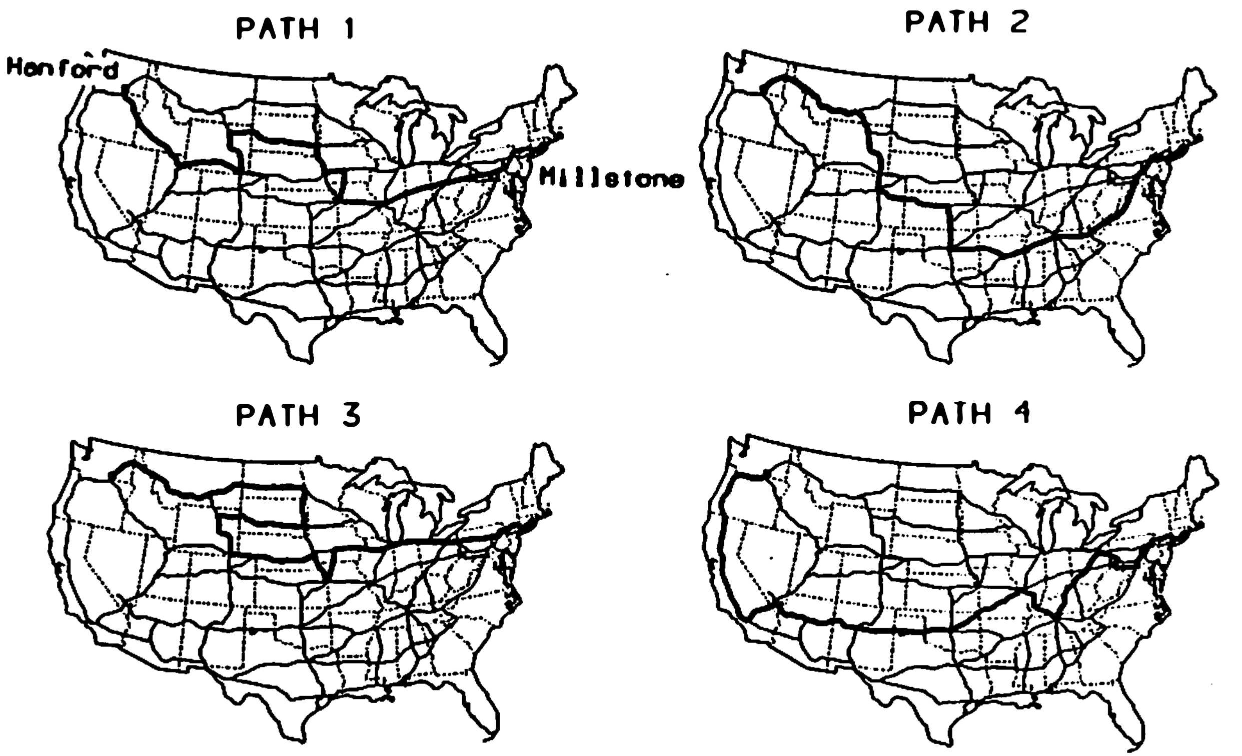
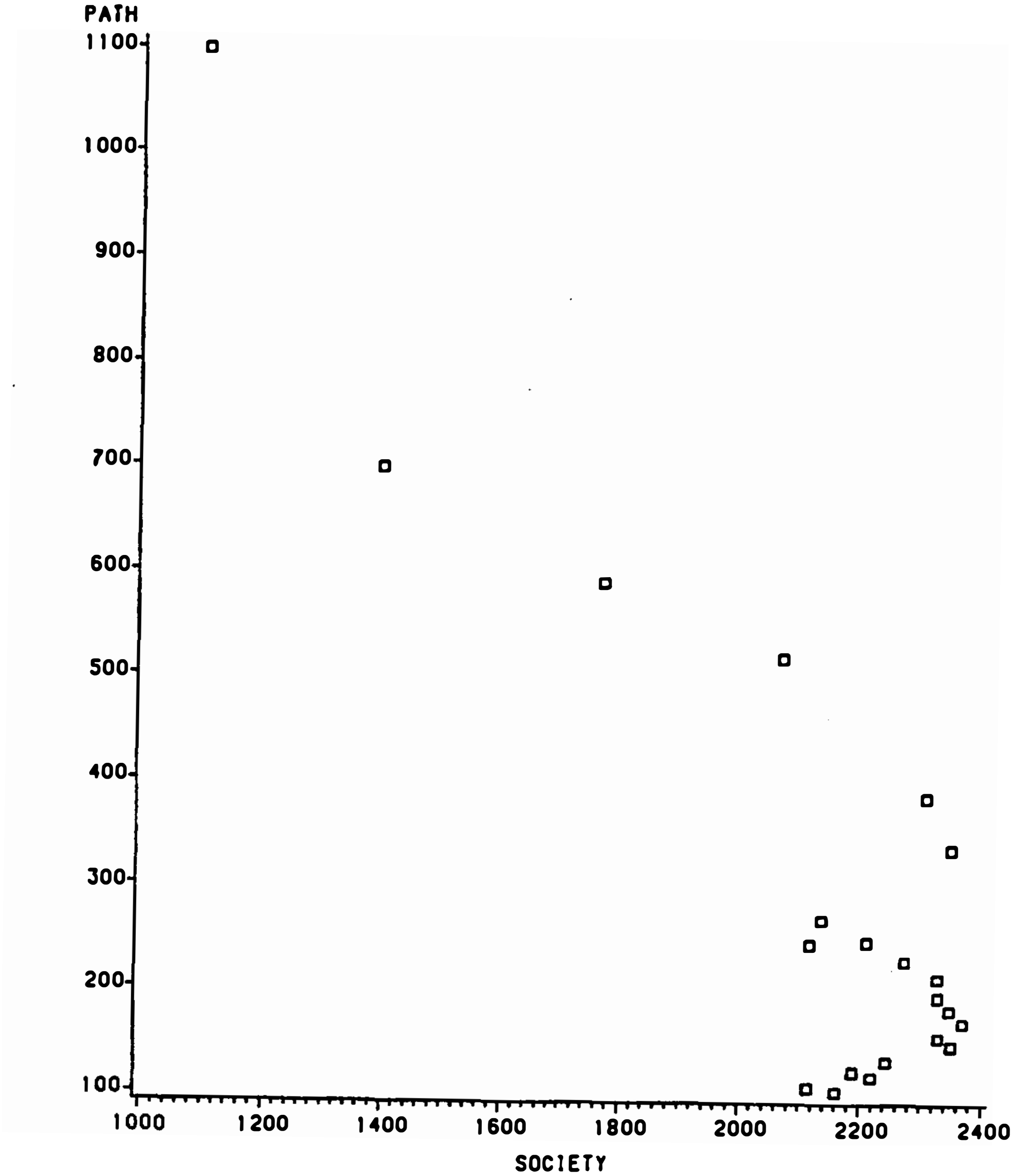


Figure C.9 Four Paths Between Millstone Power Plant and Hanford Repository Which Minimize Expected Accident Risk to the Population.



RISK IS MEASURED IN PMR

Figure C.10 Path Risk vs. Societal Risk Between Oconee Power Plant and Hanford Repository for Expected Accident Risk to the Population.

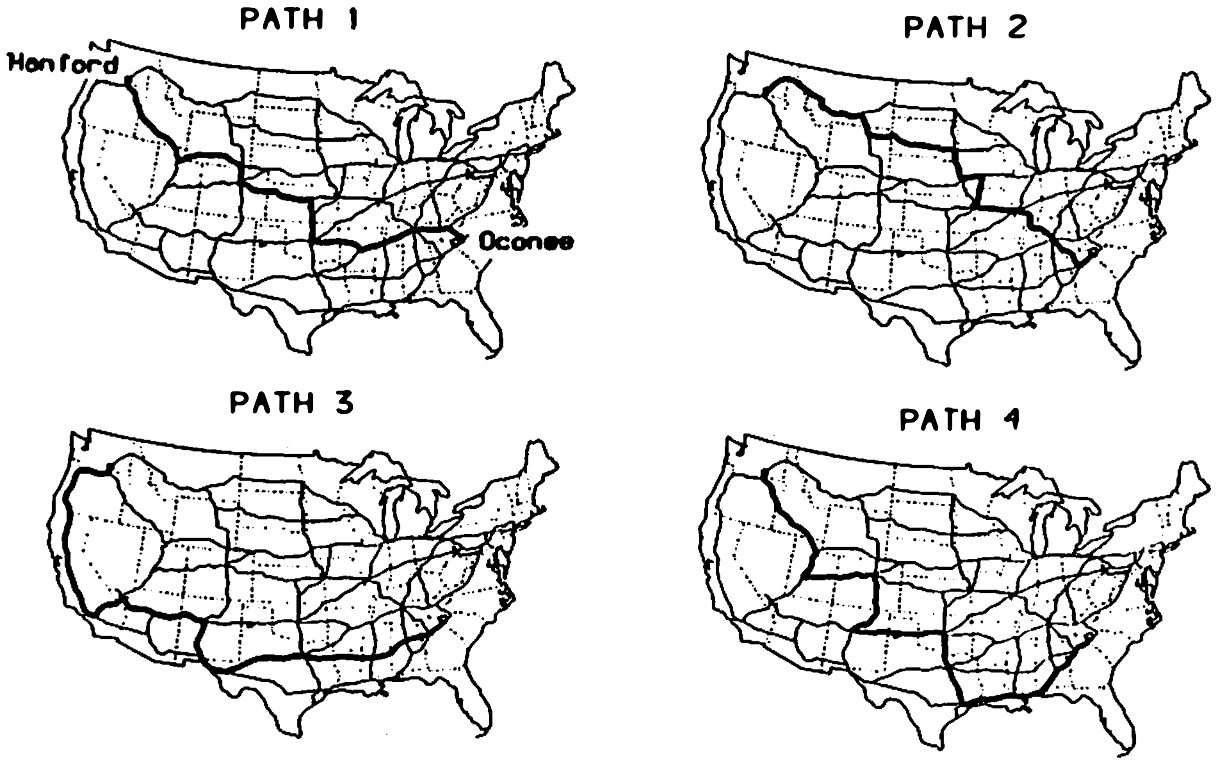


Figure C.11 Four Paths Between Oconee Power Plant and Hanford Repository Which Minimize Expected Accident Risk to the Population.

Only six paths are used by the model for the transfer of spent fuel from Palo Verde to Hanford. Societal risk values rise from 317 to 851, while path values decrease from 317 to 142 (Figure C.12).

The initial least risk path from Palo Verde heads in a northerly direction from the reactor through Arizona, Nevada, Utah, Idaho, and Oregon before it crosses into Washington (Figure C.13). The next five paths branch out over much of the interstate network in the West dispersing the risk values over a greater population, but at a much reduced rate. These routes can be compared with the changing values in the risk scattergram for spent fuel shipments from Palo Verde to Hanford (Figure C.12).

Expected Accident Risk to Property

Millstone and Oconee have similar initial risk values of $109 million on the first run, but the pattern of the path and societal risk differs considerably after this. On the routes from Millstone, the societal risk takes a large jump from the first to the second iteration to $148 million (Figure C.14). On each successive run, the societal risk moves from an upper limit of $155 million to $137 million. Path values decline from $109 million to $2

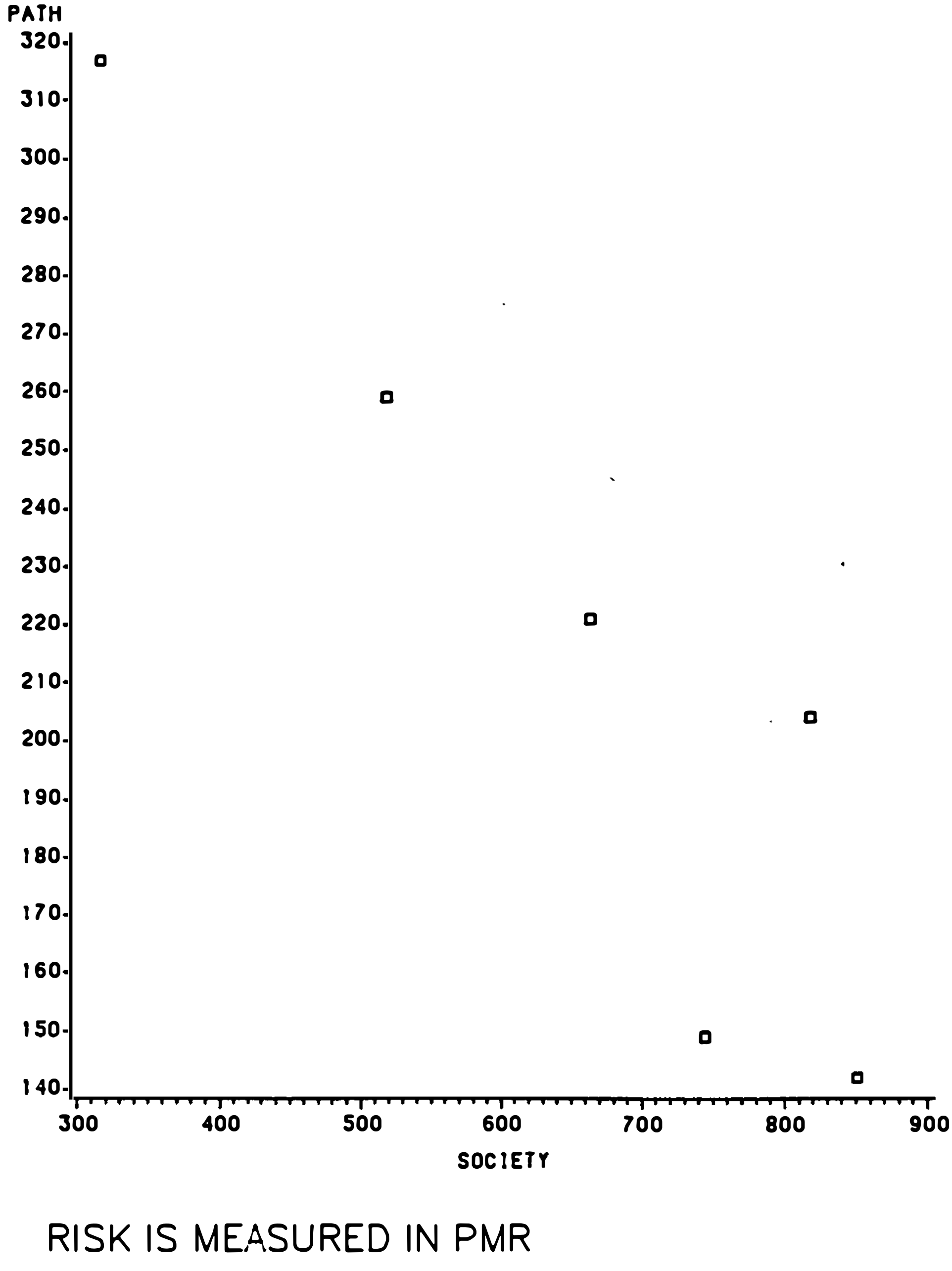


Figure C.12 Path Risk vs. Societal Risk Between Palo Verde Power Plant and Hanfrod Repository for Expected Accident Risk to the Population.

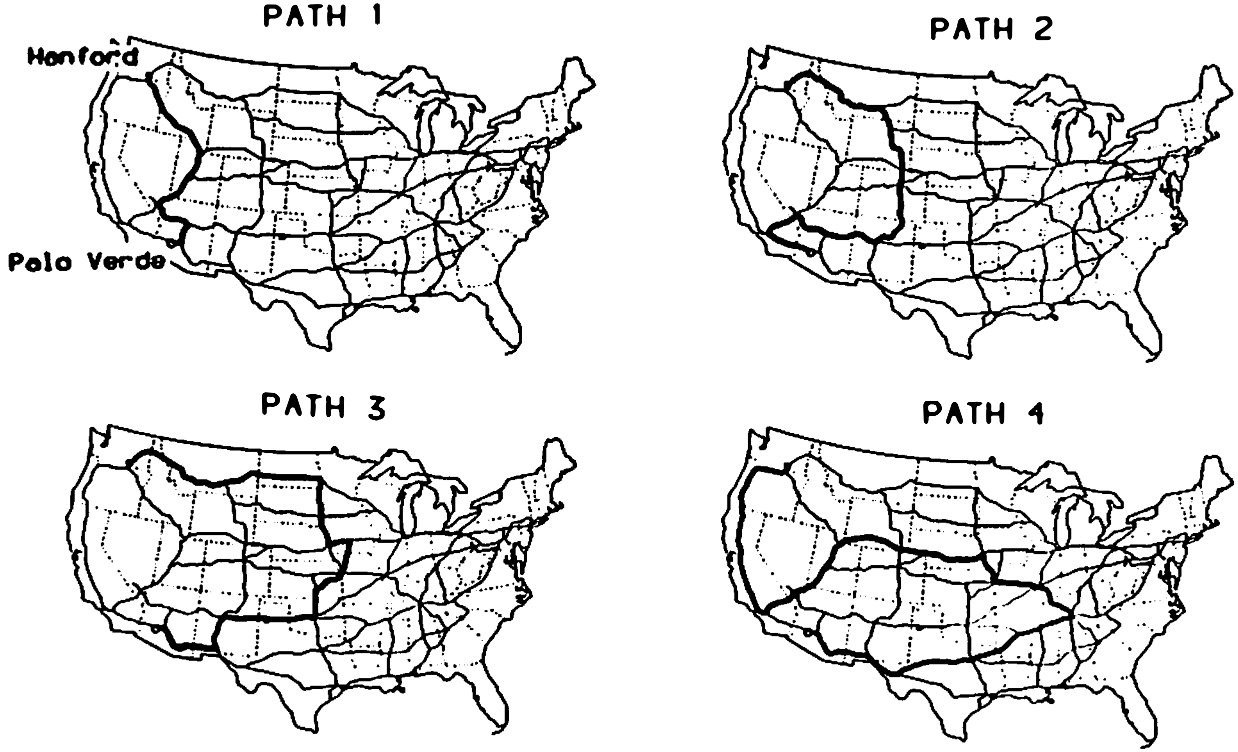


Figure C.13 Four Paths Between Palo Verde Power Plant and Hanford Repository Which Minimize Expected Accident Risk to the Population.

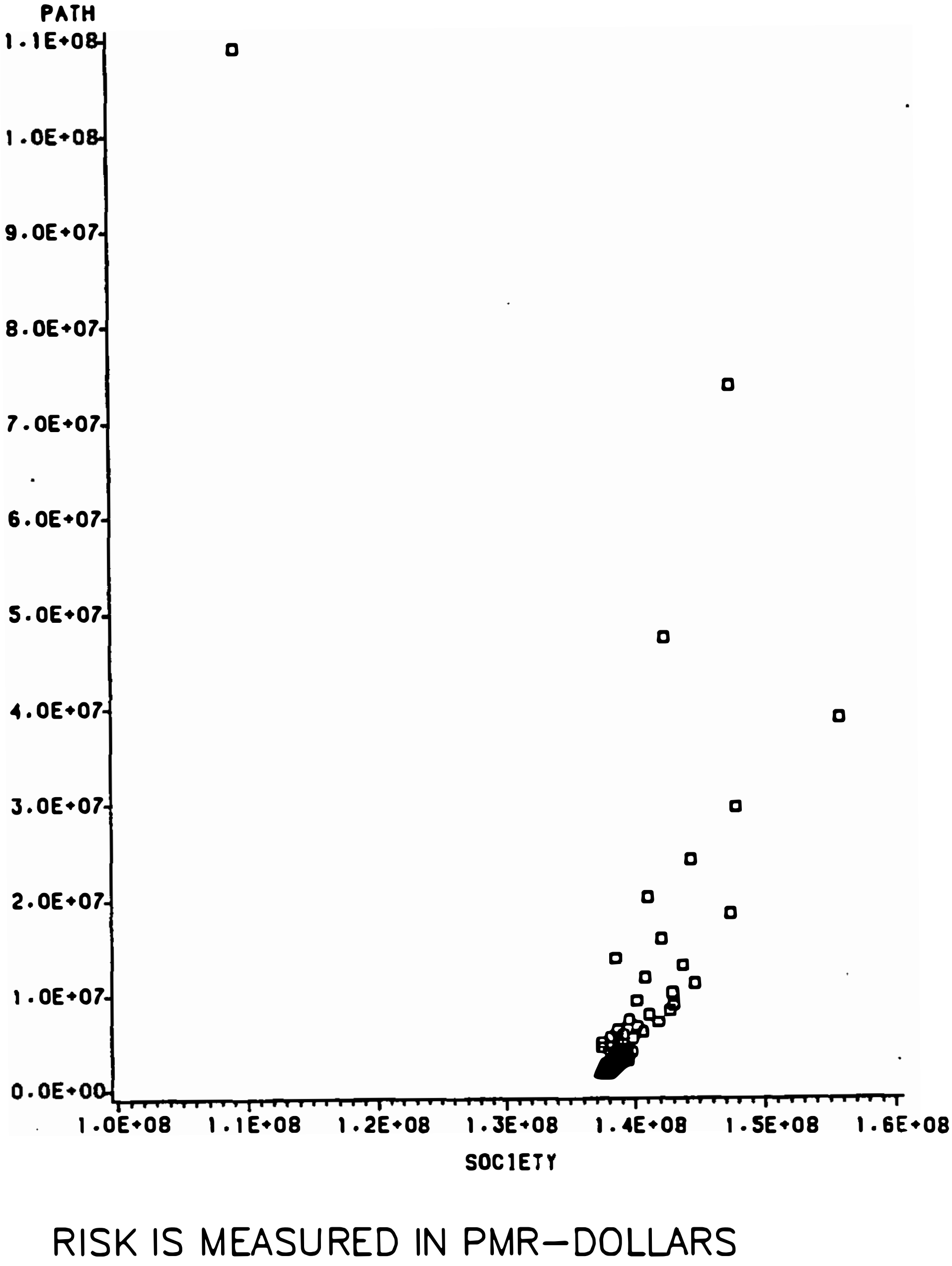


Figure C.14 **Path Risk vs. Societal Risk Between Millstone Power Plant and Hanford Repository for Expected Accident Risk to Property.**

million. The largest drops in path risk are during the first six iterations.

The spent fuel from Millstone initially takes a minimum risk path along a more southerly route than the incident free transport risk and expected accident risk to the population shipments have taken (Figure C.15). This avoids the highly urbanized areas of the Great Lakes states. The path turns back toward the Northwest in Nashville, Tennessee.

The Oconee to Hanford path-societal risk values show an inverse relationship with each other for the first eleven iterations of the model (Figure C.16). The path risk values drop from $11 million to $2 million, while the societal risk values increase from $11 million to $25 million. At this point, both risk values begin to gradually decline.

The initial route taken by the shipments from Oconee runs directly from Atlanta, Georgia to Omaha, Nebraska (Figure C.17). It then runs due west to Kansas City, Missouri, where it then turns north to Des Moines, Iowa. From here, the shipments travel west to Salt Lake City, Utah. The final leg of the journey runs from Salt Lake City to Hanford.

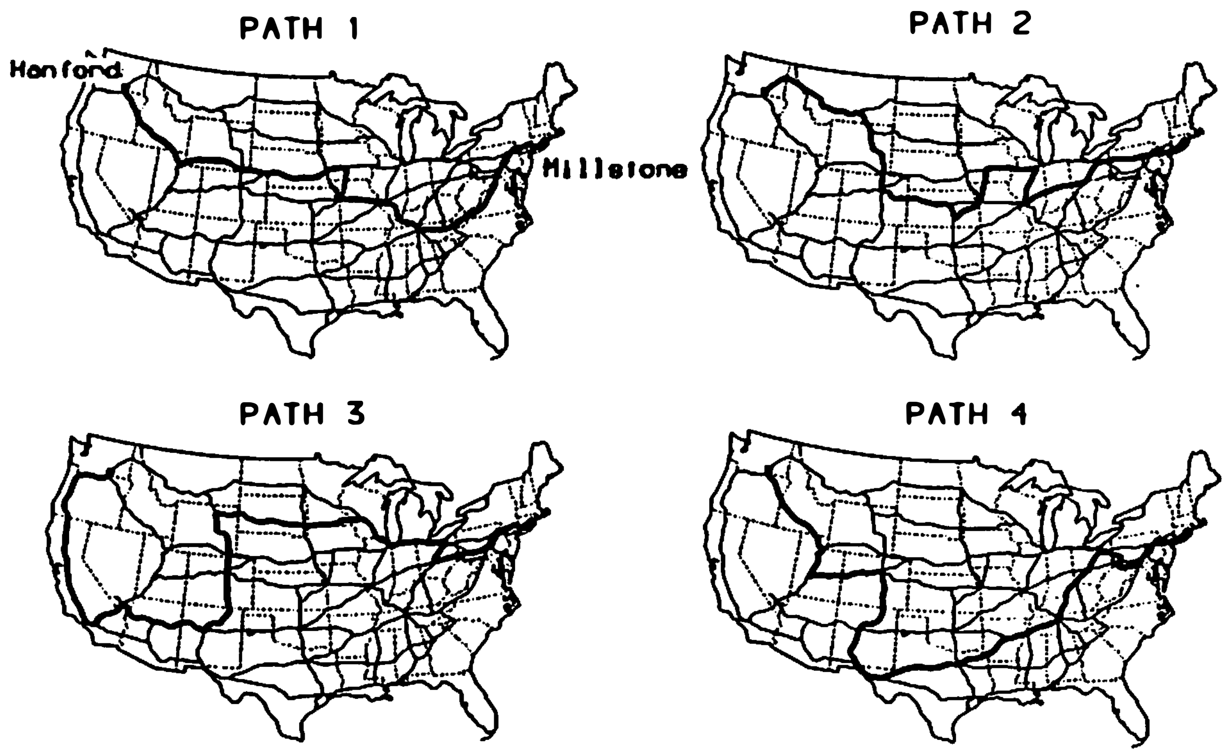
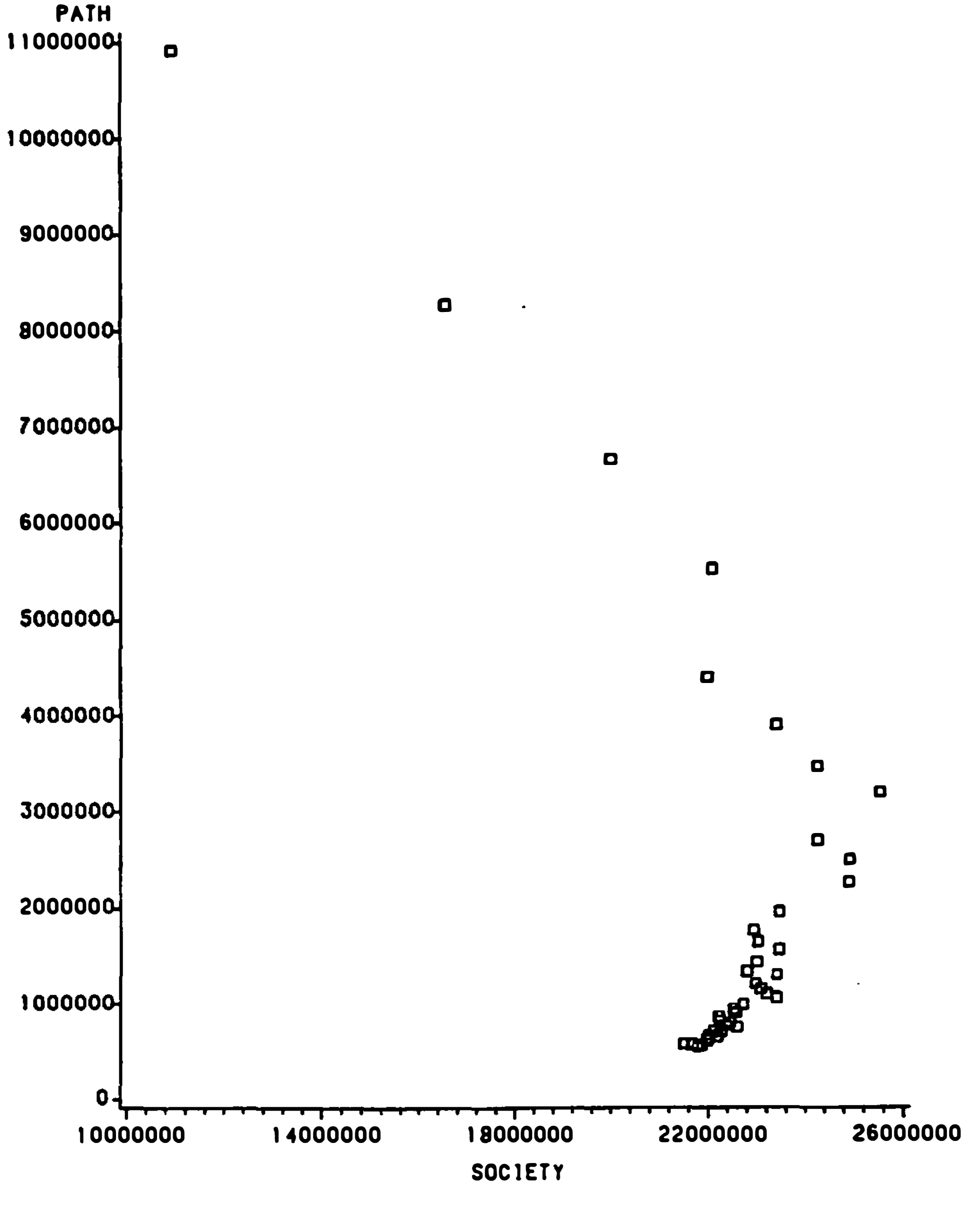


Figure C.15 Four Paths Between Millstone Power Plant and Hanford Repository Which Minimize Expected Accident Risk to Property.



RISK IS MEASURED IN PMR—DOLLARS

Figure C.16 Path Risk vs. Societal Risk Between Oconee Power Plant and Hanford Repository for Expected Accident Risk to Property.

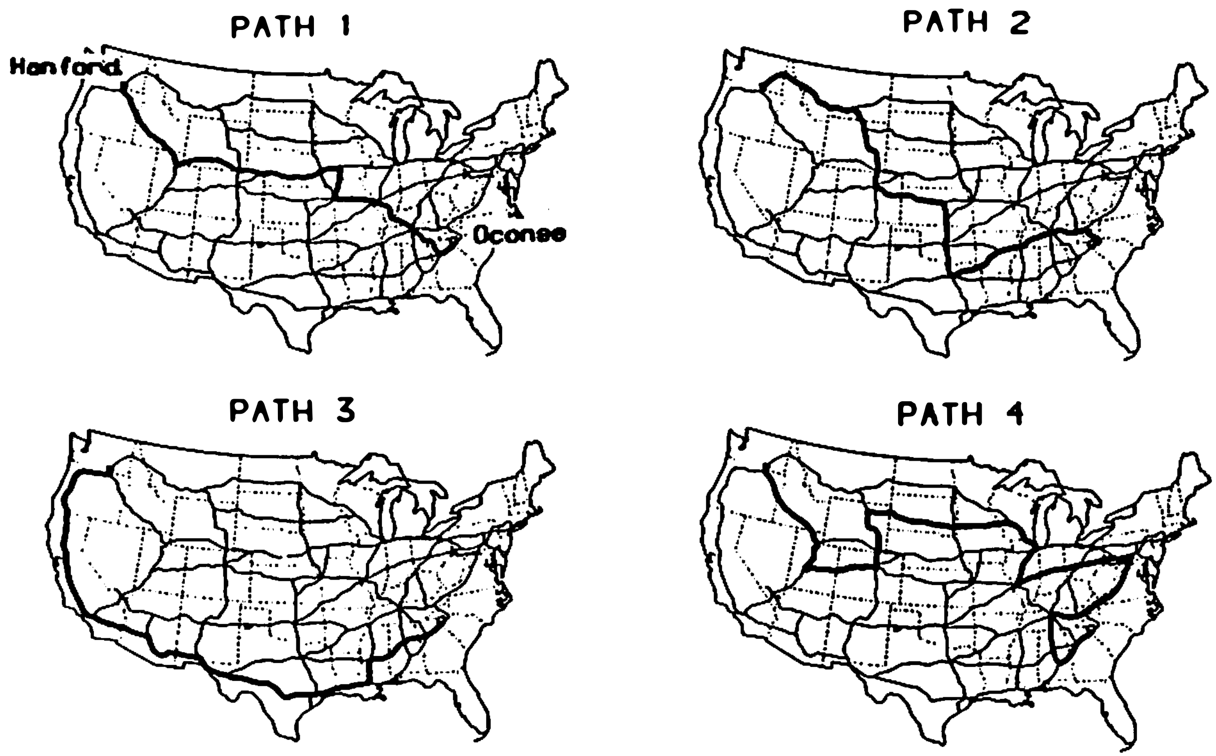


Figure C.17 Four Paths Between Oconee Power Plant and Hanford Repository Which Minimize Expected Accident Risk to Property.

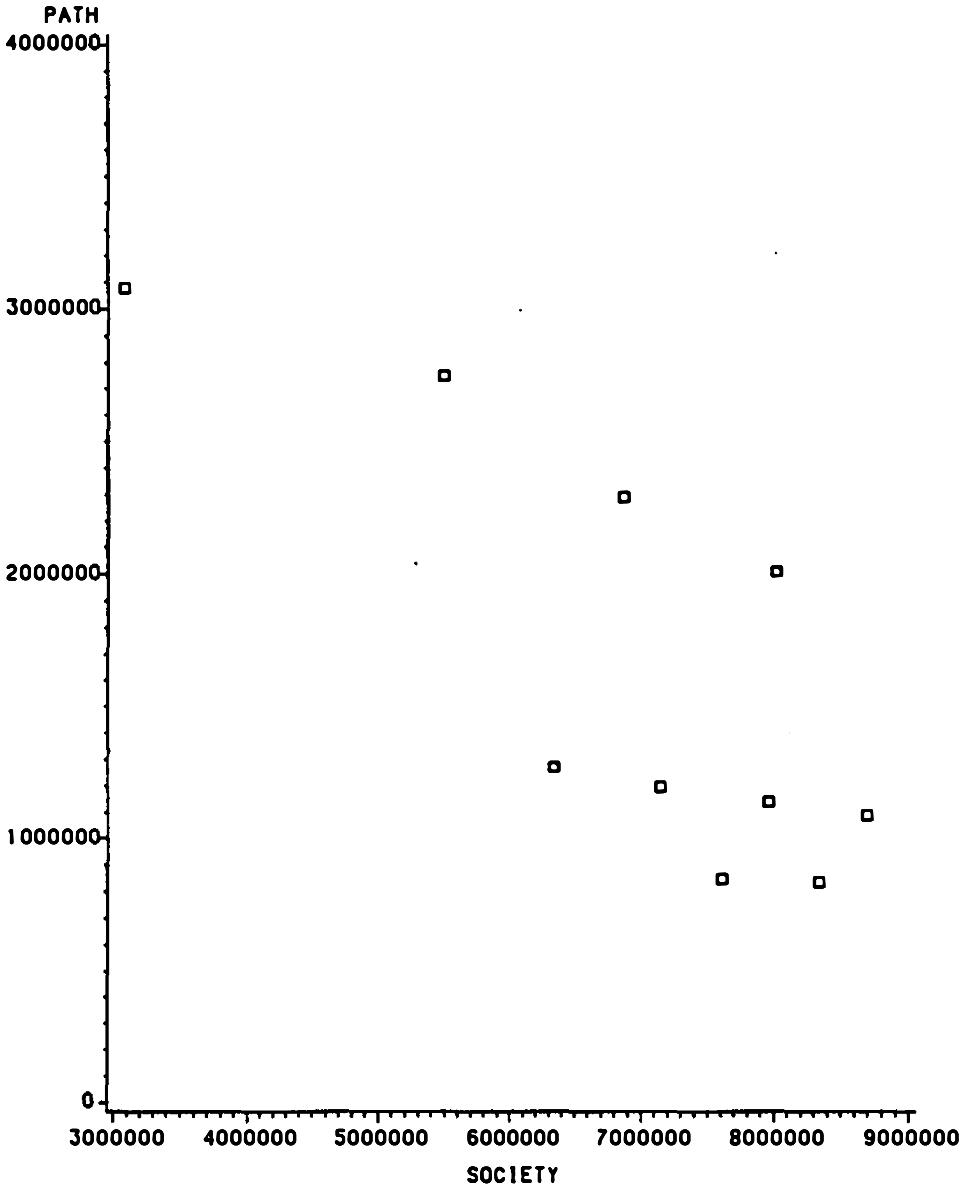
The Palo Verde risk scattergram shows the standard initial declining path values and rising societal values (Figure C.18). After the fourth iteration, the societal values drop substantially. They then begin to rise again for four iterations before they drop again for a second time.

Palo Verde's first least risk path runs east from Arizona to New Mexico (Figure C.19). It then turns north to Cheyenne, Wyoming. From here, it travels northwest to Hanford via Salt Lake City, Utah.

Comparison of Risk and Transport Cost

A least cost run was made from each of the three reactors to the Hanford repository. This is then compared in cost and risk to the MTTRM path.

The minimum cost path from Millstone to Hanford runs due west from Connecticut to Chicago, Illinois (Figure C.20). From here it takes a northern route through Wisconsin, Minnesota, North Dakota, Montana, Idaho, and Washington. The cost of this route is $1,156,858 for the 153 shipments. The initial risk value for incident free transport is 7,982 pmr. This compares with an initial least risk path value of 7,892 pmr at a cost of $1,185,608. When the change in risk and cost between the



RISK IS MEASURED IN PMR—DOLLARS

Figure C.18 Path Risk vs. Societal Risk Between Palo Verde Power Plant and Hanford Repository for Expected Accident Risk to Property.

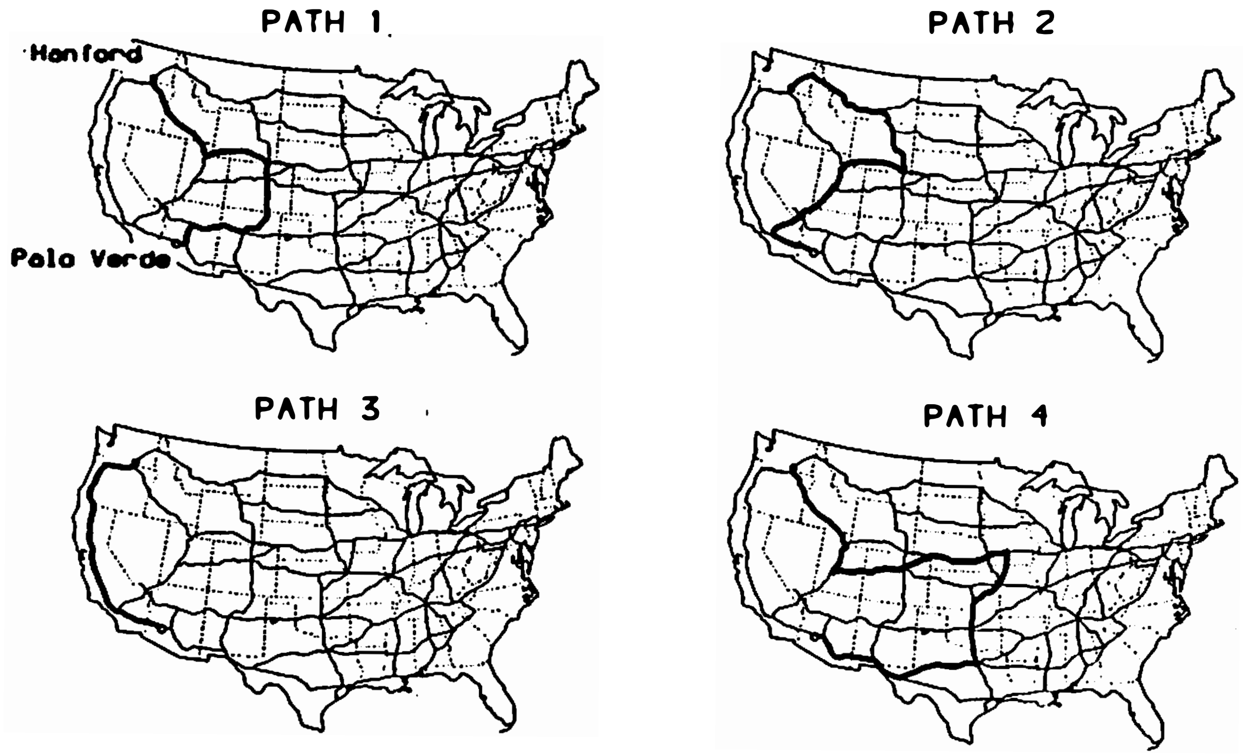


Figure C.19 Four Paths Between Palo Verde Power Plant and Hanford Repository Which Minimize Expected Accident Risk to Property.

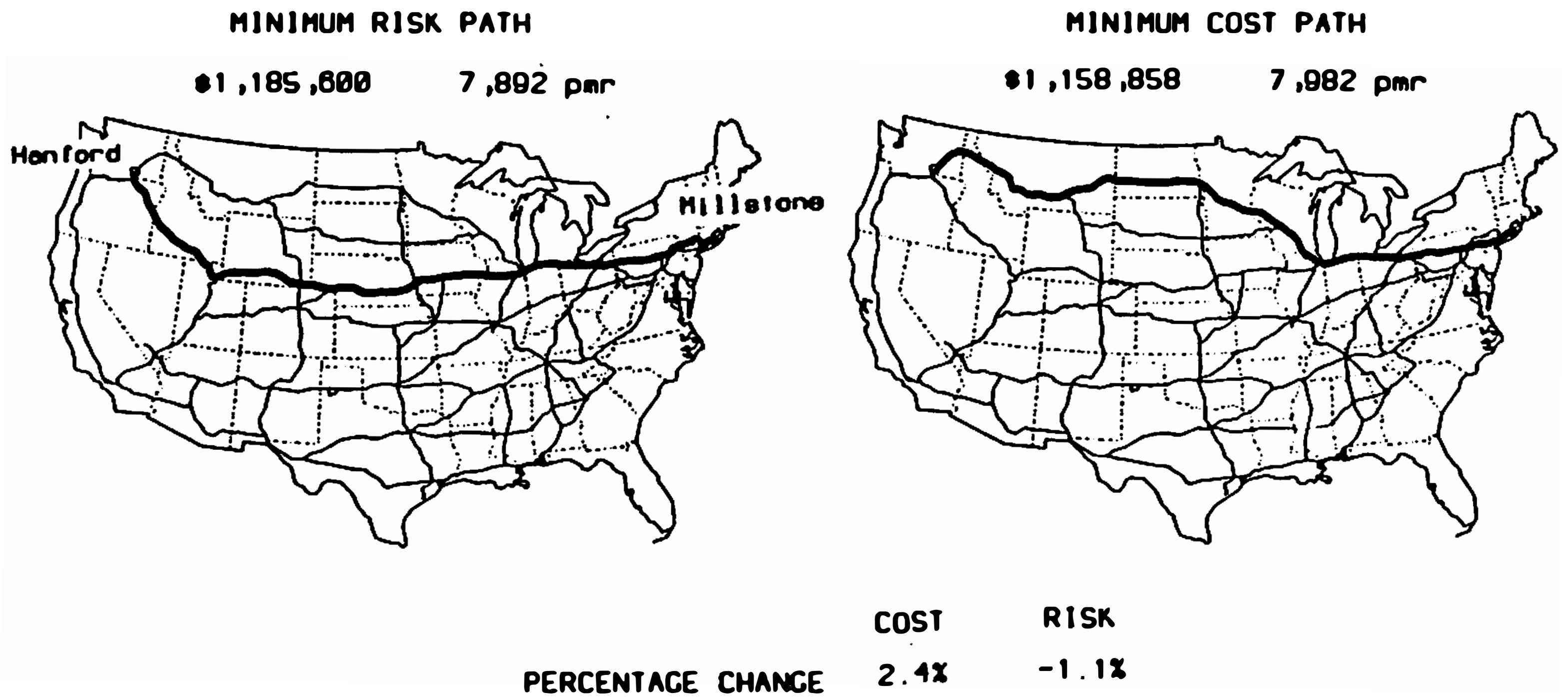


Figure C.20 Minimum Risk and Minimum Cost Paths Between Millstone Power Plant and Hanford Repository for Incident Free Transport Risk.

two routes are compared, there is a small difference. The least risk route costs 2.4 percent more, but only provides 1.1 percent greater safety.

The accident rate risk factors generate a greater degree of difference between cost and risk. One of the reasons is the large weight which has been used to generate these paths. The initial minimum risk path from Millstone for accident risk to the population is 9,850 pmr, while the least cost route has a much higher risk of 50,650 pmr. This is because the least cost route runs through densely populated urban centers such as New York City and Chicago, while the minimum risk route takes a longer less densely populated path to the south (Figure C.21). When the cost and risk differences between these two routes are compared, a 24 percent increase in cost yields an 81 percent decrease in risk of exposure.

When the accident risk to property on the Millstone to Hanford route is considered, there is also a substantial different in shipment cost and risk. The initial minimum risk route costs 20 percent more that the minimum cost route, but it is 47 percent safer (Figure C.22).

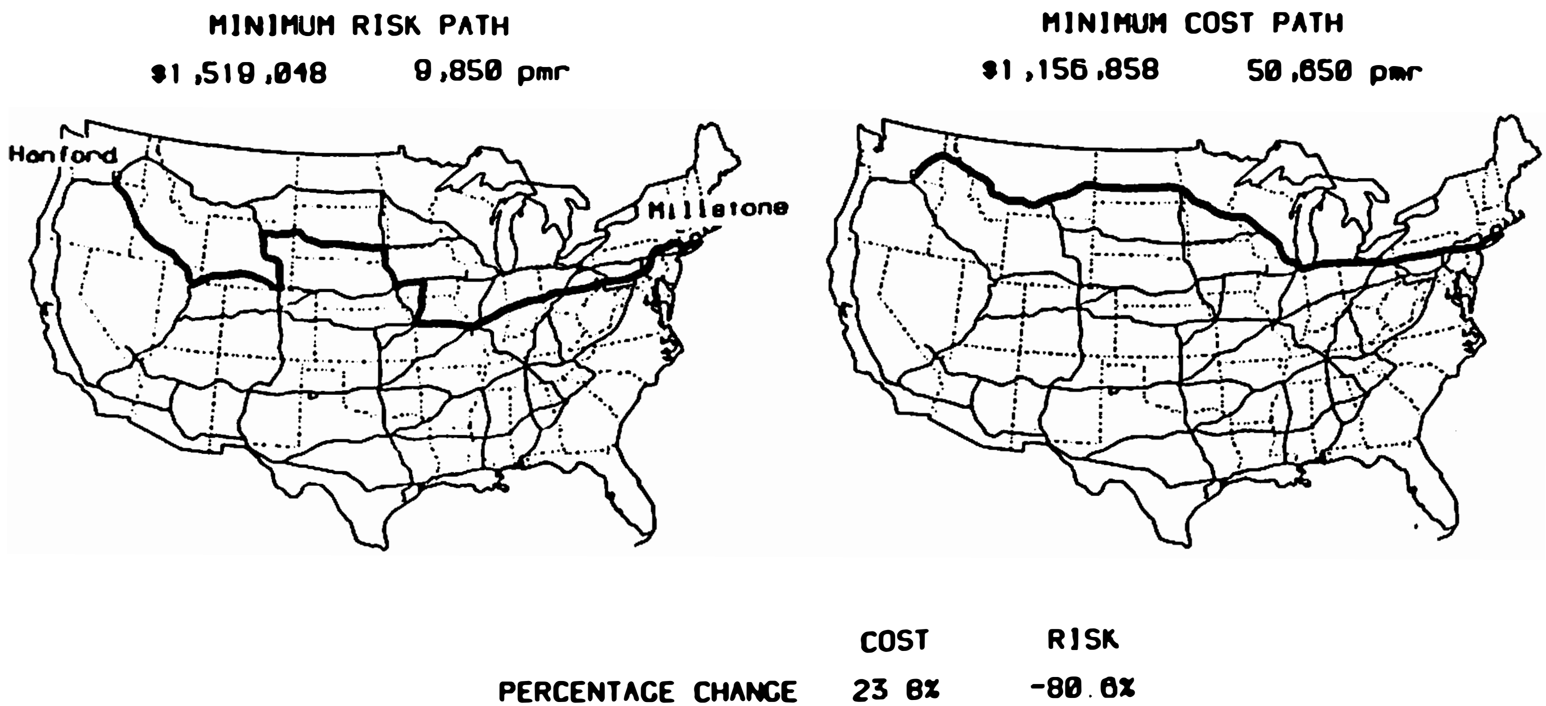
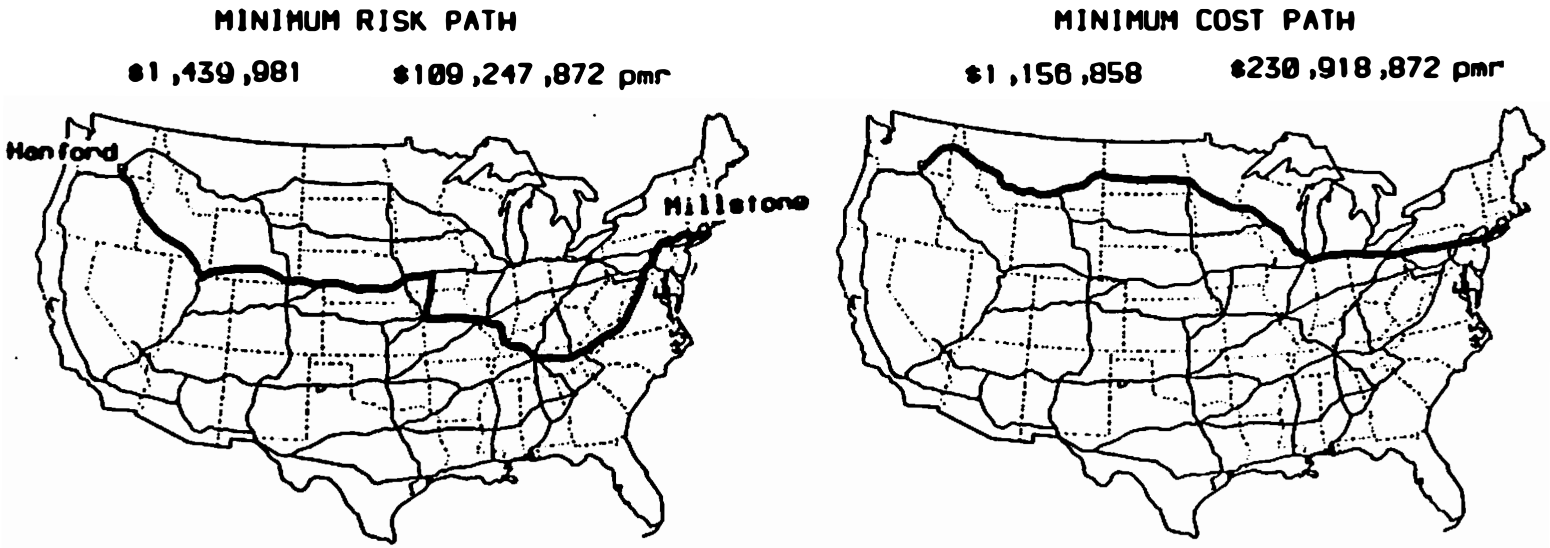


Figure C.21 Minimum Risk and Minimum Cost Paths Between Millstone Power Plant and Hanford Repository for Expected Accident Risk to the Population.



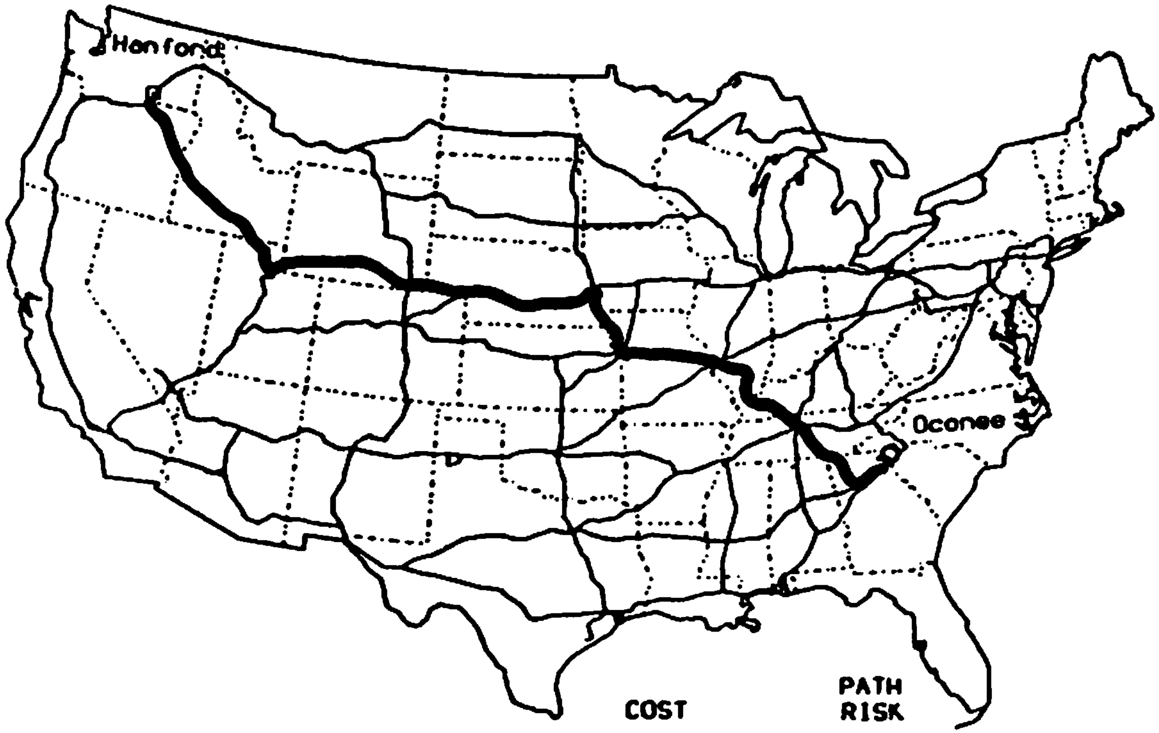
	COST	RISK
PERCENTAGE CHANGE	19.7%	-47.3%

Figure C.22 Minimum Risk and Minimum Cost Paths Between Millstone Power Plant and Hanford Repository for Expected Accident Risk to Property.

The shipment path from the Oconee reactor to Hanford which minimizes cost is the same route which initially minimizes incident free risk (Figure C.23). Both cost $943,328 and have a risk of 6,281 pmr.

There is a substantial difference in the pattern of flow between the least cost route and the path which has the least expected accident risk to the population. Oconee's least cost path runs directly from Atlanta to Omaha. From here, it turns due west to Salt Lake City. At this point, it goes to the northwest to Hanford. The least risk route runs west through North Carolina, Tennessee, Arkansas, and Oklahoma (Figure C.24). It then turns north through Kansas and Colorado. The two routes finally join for the last leg of the trip in Cheyenne, Wyoming. This more southern route avoids some of the major urban population centers such as Atlanta, St. Louis, and Kansas City through which the least cost route runs. This longer least risk route costs 5.6 percent more, but it decreases the risk factor by 40.8 percent.

The path which minimizes the probability of property loss follows the least cost route for most of the way between Oconee and Hanford (Figure C.25). The one exception is in Missouri and Iowa, when the least risk path avoids going through the Kansas City area. This one detour



	COST	PATH RISK
LEAST COST PATH	$843,328	6,281 PMR
LEAST RISK PATH	$843,328	6,281 PMR
PERCENTAGE CHANGE	0%	0%

Figure C.23 Minimum Risk and Minimum Cost Paths Between Oconee Power Plant and Hanford Repository for Incident Free Transport Risk.

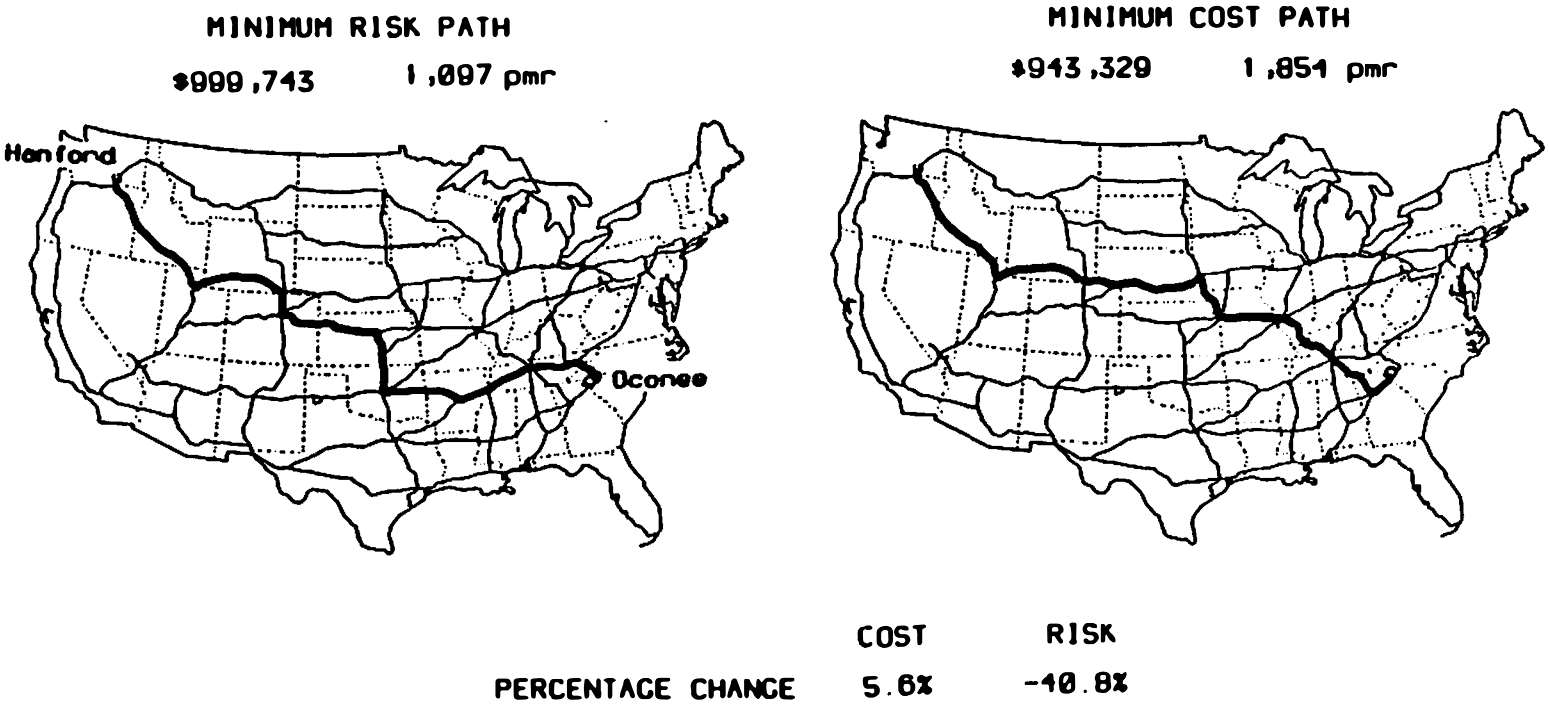
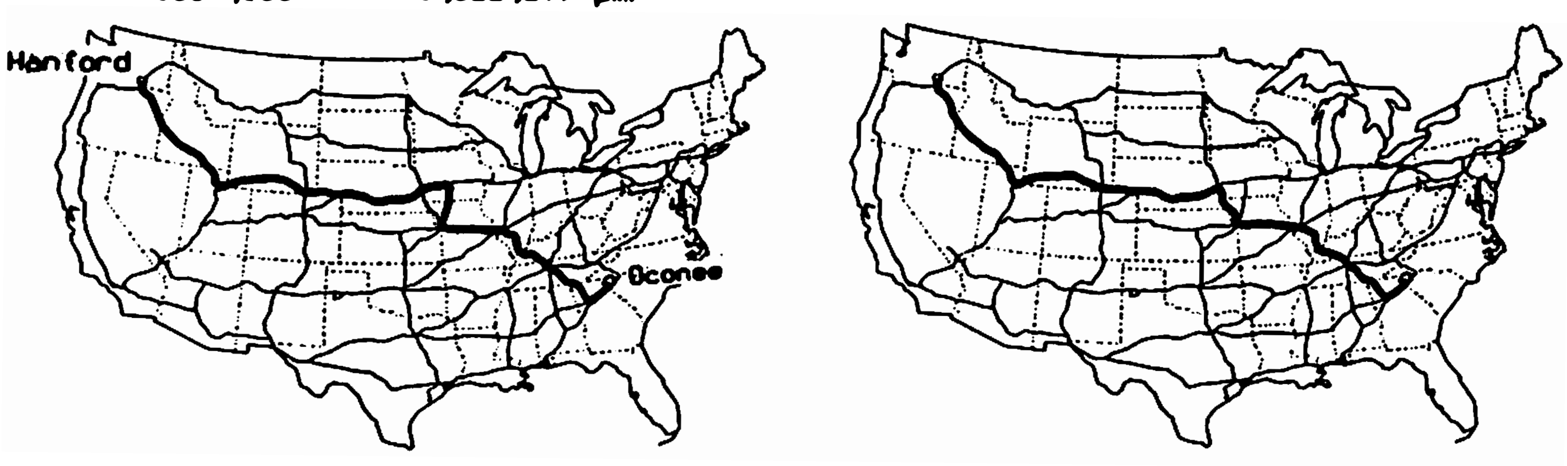


Figure C.24 Minimum Risk and Minimum Cost Paths Between Oconee Power Plant and Hanford Repository for Expected Accident Risk to the Population.

MINIMUM RISK PATH		MINIMUM COST PATH	
$984,699	$10,922,217 pmr	$943,329	$11,995,670 pmr



	COST	RISK
PERCENTAGE CHANGE	4.2%	-8.9%

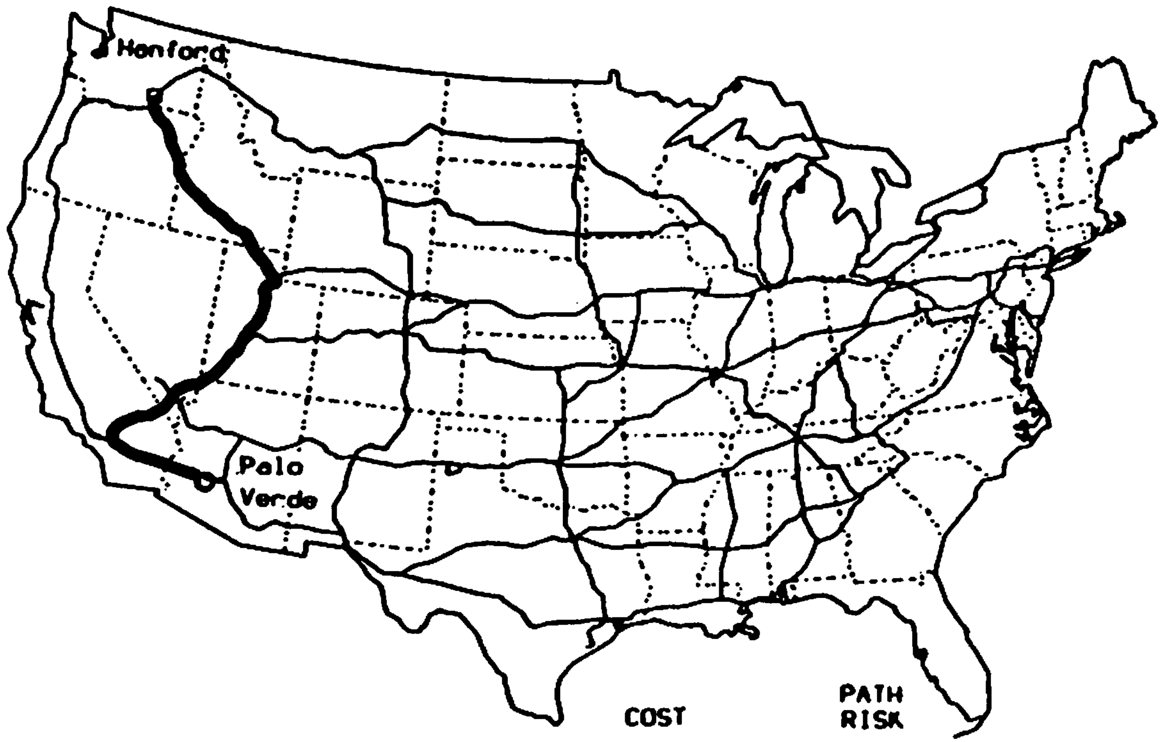
Figure C.25 Minimum Risk and Minimum Cost Paths Between Oconee Power Plant and Hanford Repository for Expected Accident Risk to Property.

increases the cost of the projected shipments by 4 percent while decreasing the risk by about 9 percent.

The incident free risk path from Palo Verde reactor to Hanford goes over the same route as the minimum risk path (Figure C.26). Both have a risk value of 3,862 pmr and a cost of $589,701.

The initial path from Palo Verde which minimizes accident risk to the population avoids the densely populated Southern California area by traveling north and west through Arizona (Figure C.27). In Las Vegas, it joins the least cost route for the rest of the trip. This one deviation at the beginning of the trip results in only a one-half percent increase in cost, but a 46 percent decrease in risk.

The first path from Palo Verde which minimizes risk to property value has the highest cost of these three examples. It deviates to an eastern route for the first half of the trip and does not join the least cost path until it reaches Salt Lake City, Utah (Figure C.28). This more circuitous path results in a 28 percent increase in cost and a 39 percent decrease in risk.



	COST	PATH RISK
LEAST COST PATH	$589,701	3,862 PMR
LEAST RISK PATH	$589,701	3,862 PMR
PERCENTAGE CHANGE	0%	0%

Figure C.26 Minimum Risk and Minimum Cost Paths Between Palo Verde Power Plant and Hanford Repository for Incident Free Transport Risk.

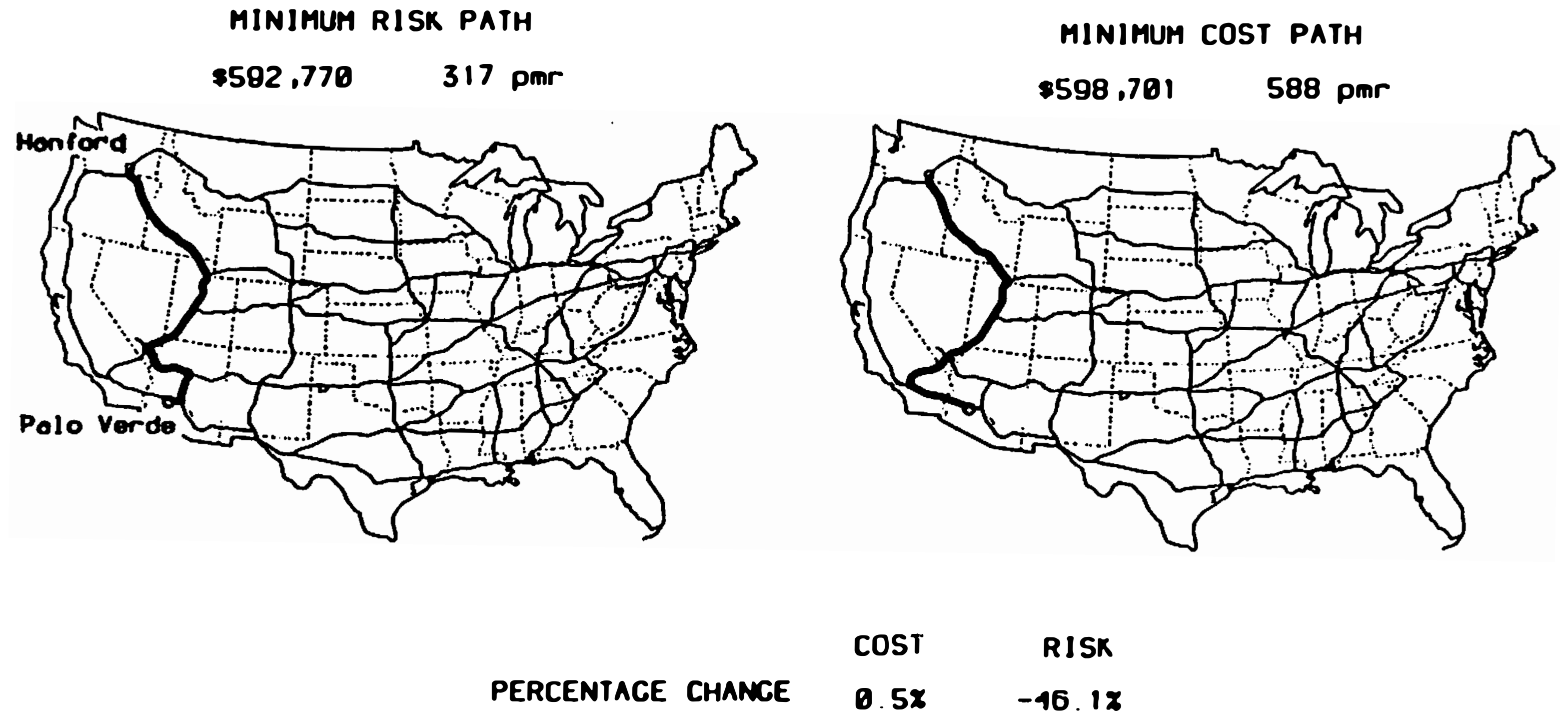


Figure C.27 Minimum Risk and Minimum Cost Paths Between Palo Verde Power Plant and Hanford Repository for Expected Accident Risk to the Population.

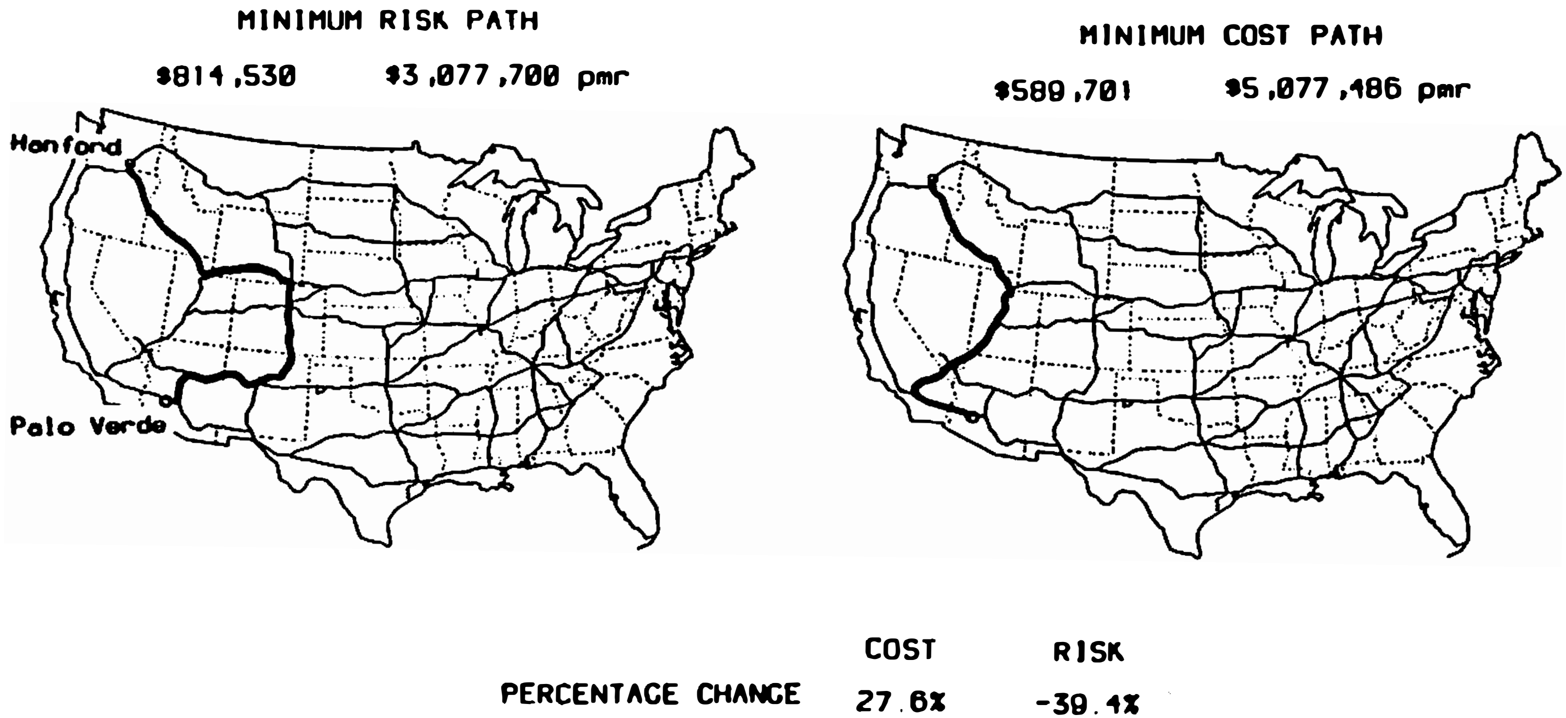


Figure C.28 Minimum Risk and Minimum Cost Paths Between Palo Verde Power Plant and Hanford Repository for Expected Accident Risk to Property.

APPENDIX D

MULTIPLE REACTORS TO A SINGLE REPOSITORY MAPS

The set of maps in Appendix D shows the minimum cost and MTTRM paths for the Deaf Smith, Hanford, Yucca Mountain, and MRS sites. The incident free transport risk, expected accident risk for the population, and expected accident risk for property are each represented by a map.

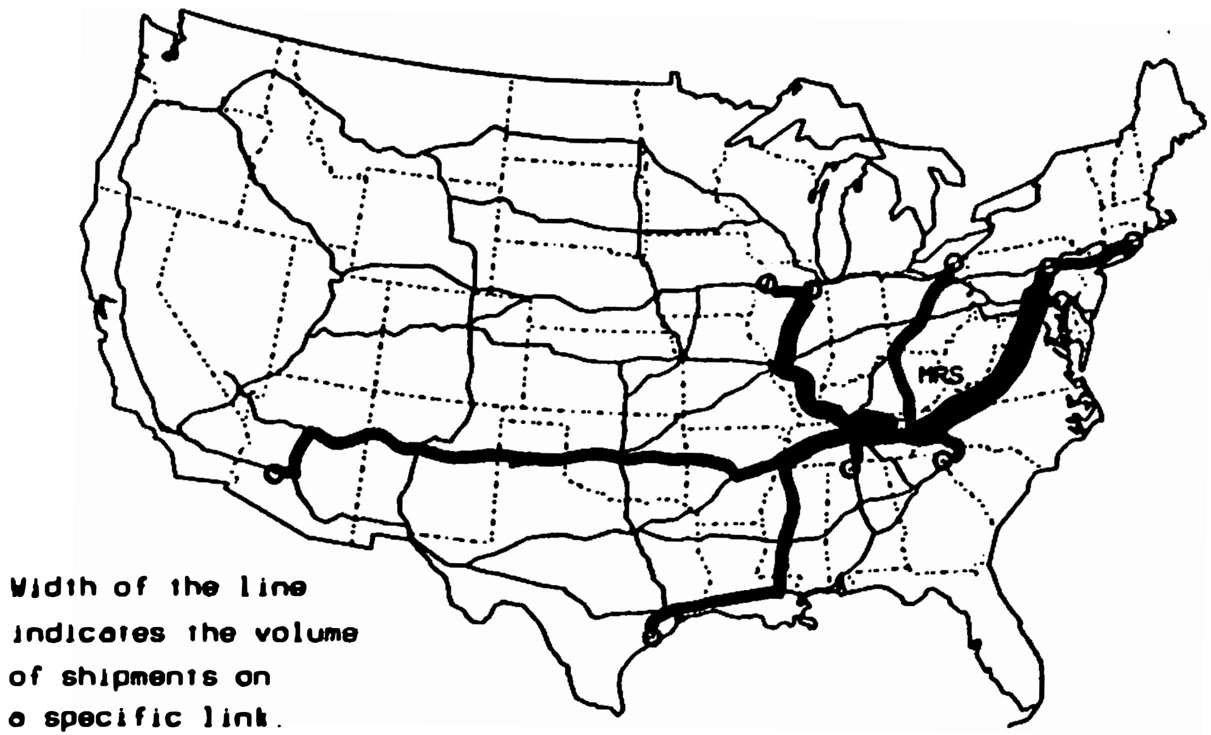


Figure D.1 Minimum Cost Paths Between Ten Reactors and the MRS.

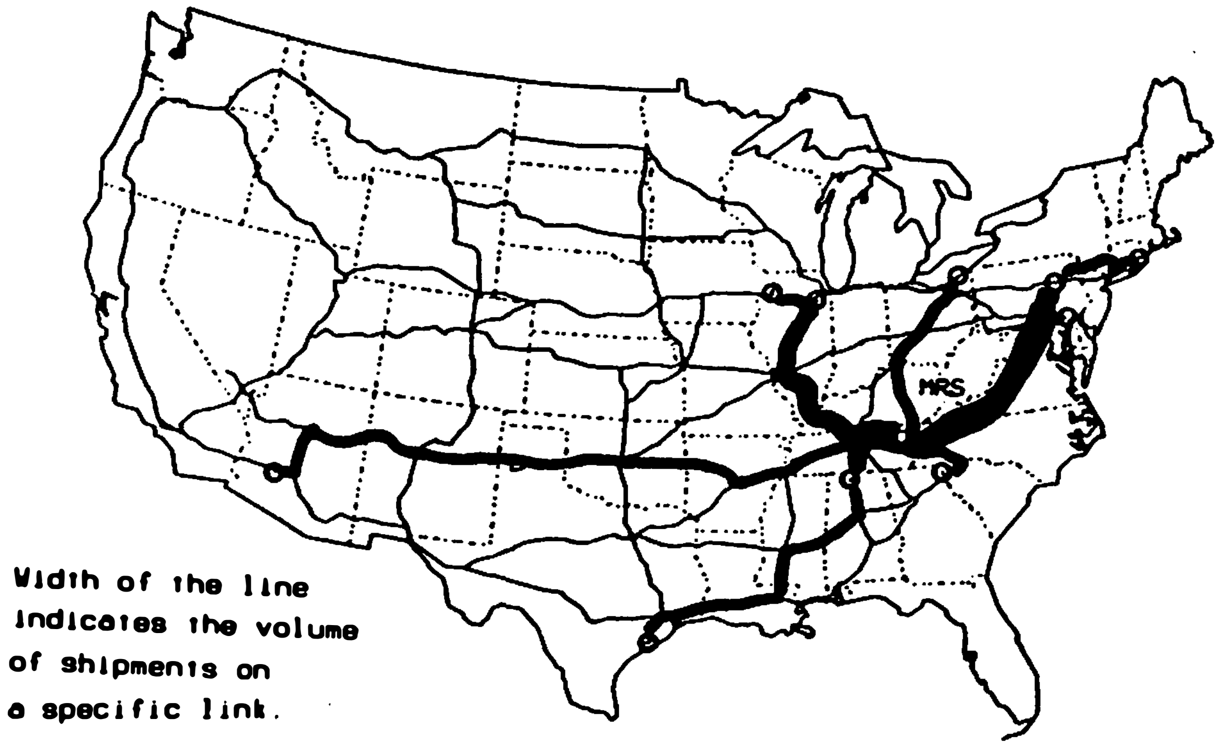


Figure D.2 MTTRM Paths Between Ten Reactors and the MRS Which Minimize Incident Free Transport Risk.

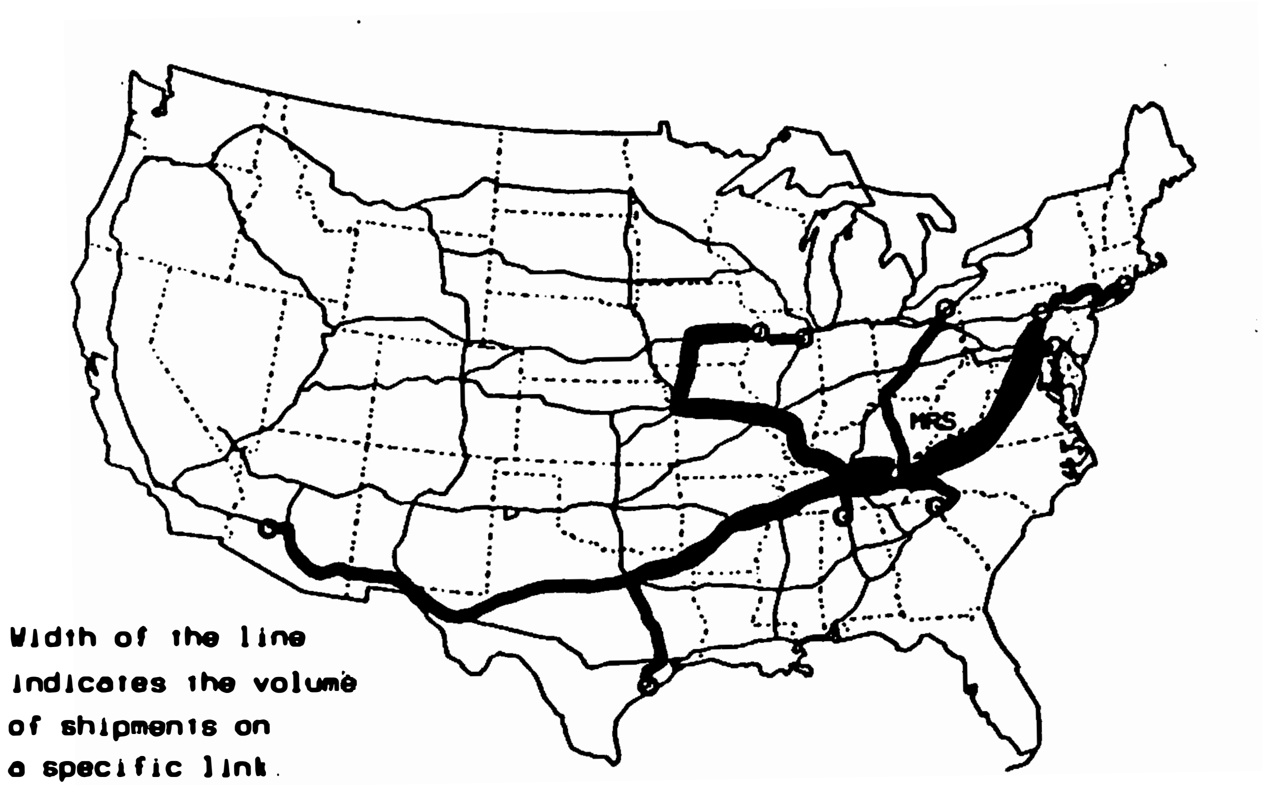


Figure D.3 MTTRM Paths Between Ten Reactors and the MRS Which Minimize Expected Accident Risk to the Population.

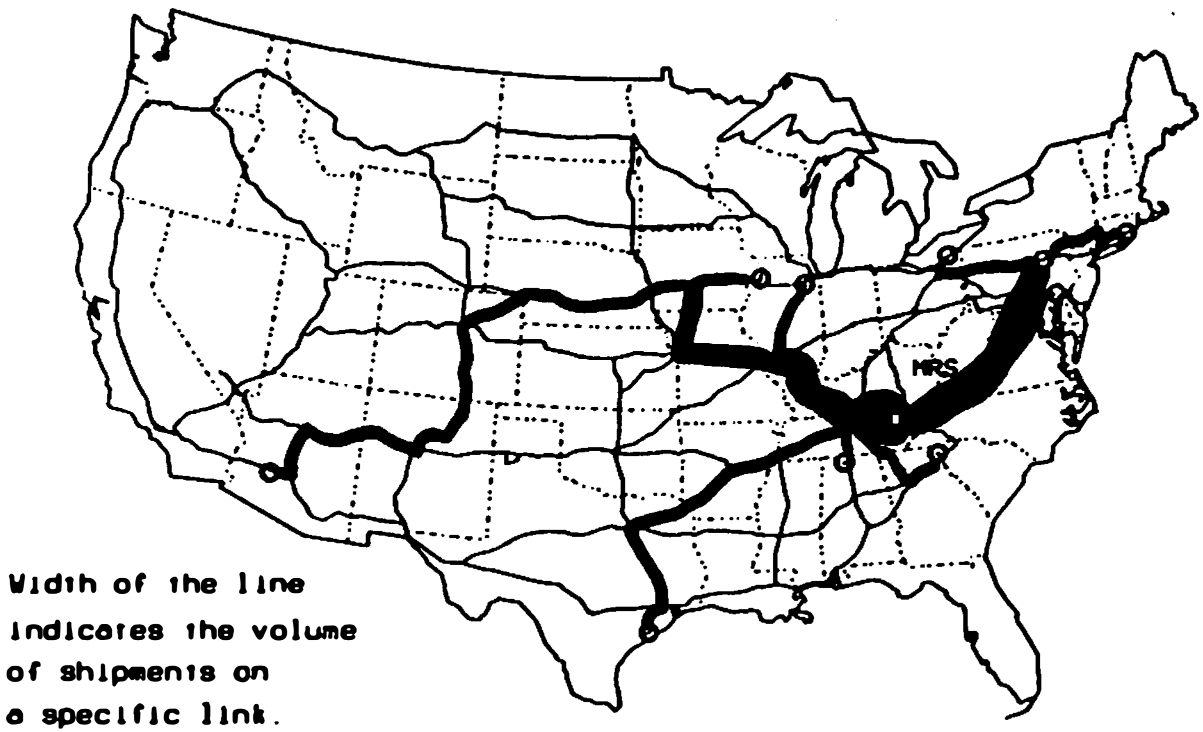


Figure D.4 MTTRM Paths Between Ten Reactors and the MRS Which Minimize Expected Accident Risk to Property.

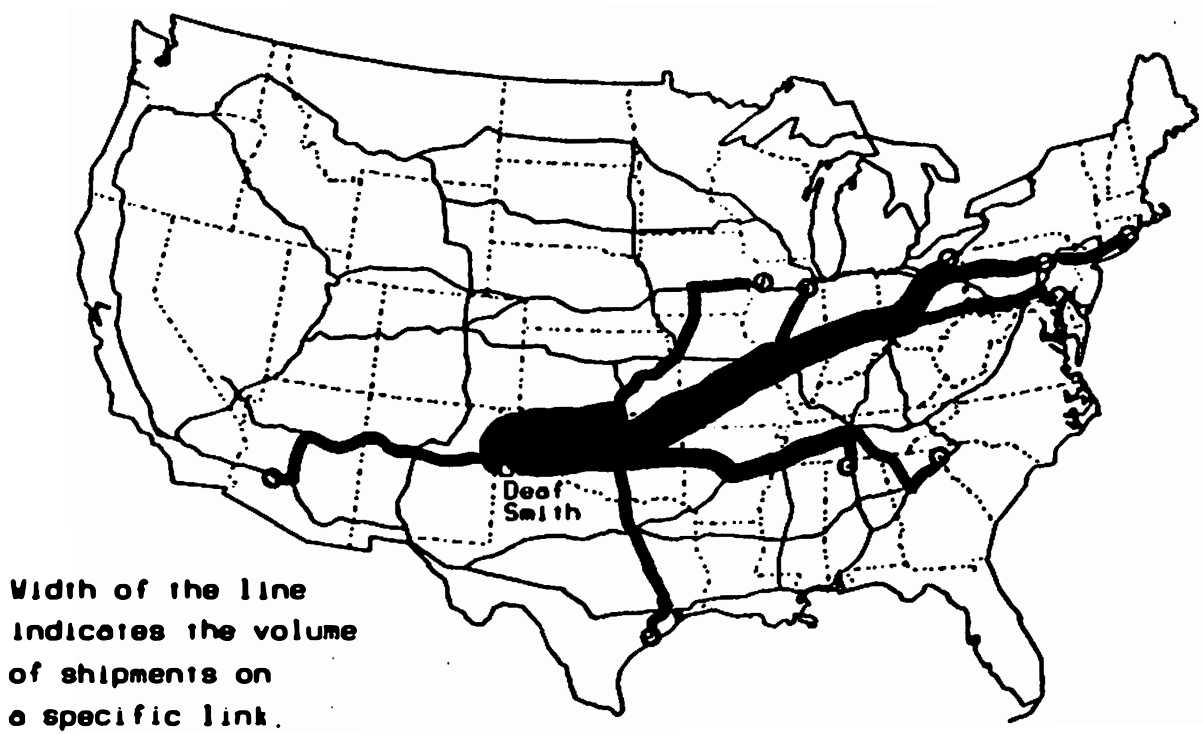


Figure D.5 Minimum Cost Paths Between Ten Reactors and Deaf Smith Repository.

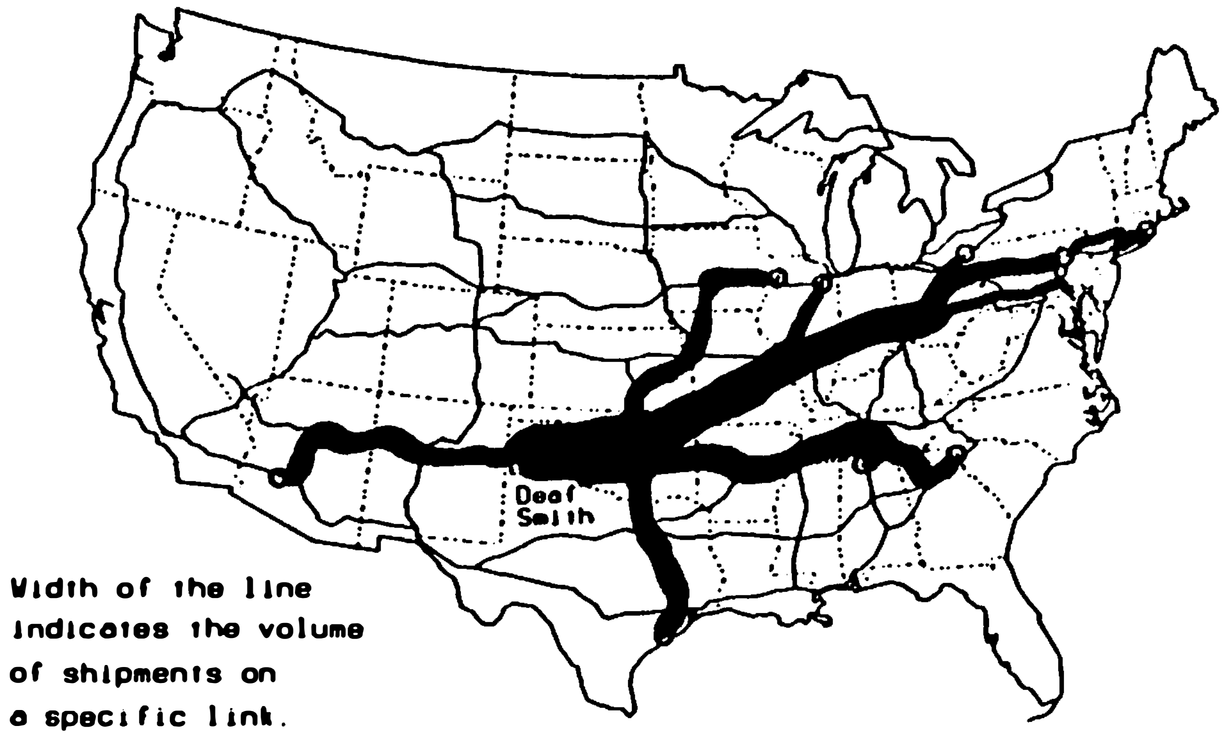


Figure D.6 MTTRM Paths Between Ten Reactors and Deaf Smith Repository Which Minimize Incident Free Transport Risk.

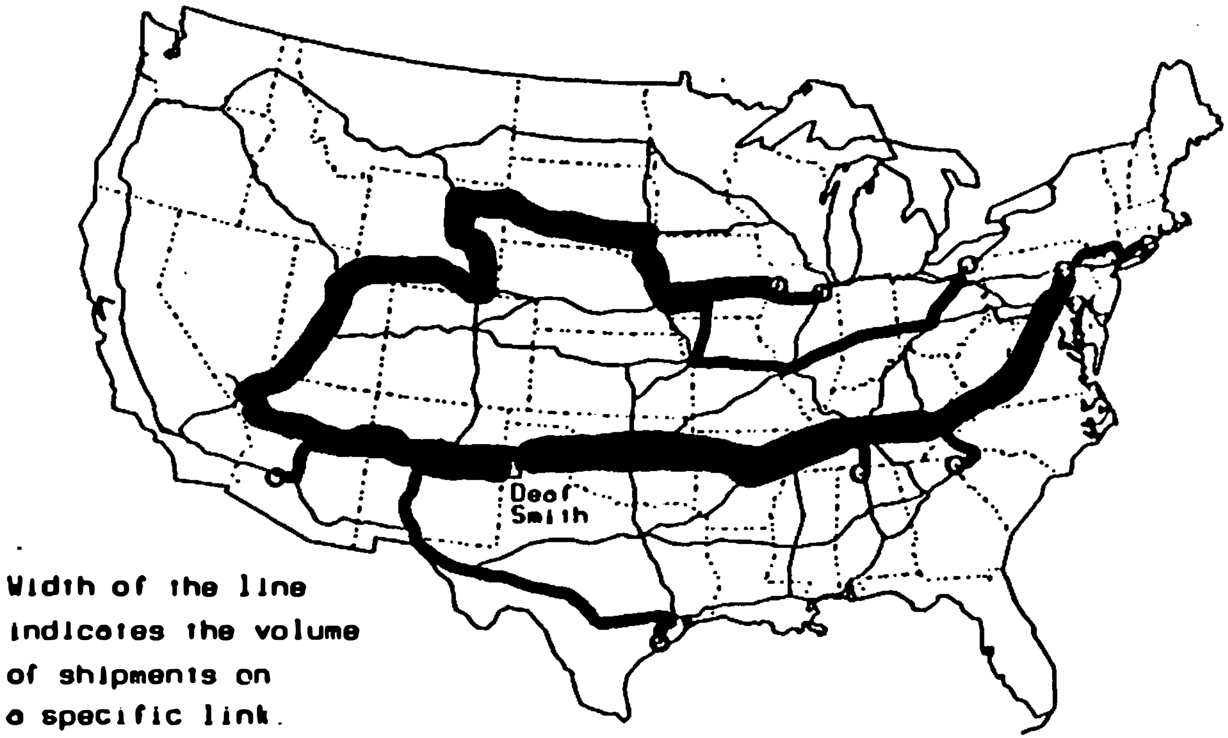


Figure D.7 MTTRM Paths Between Ten Reactors and Deaf Smith Repository Which Minimize Expected Accident Risk to the Population.

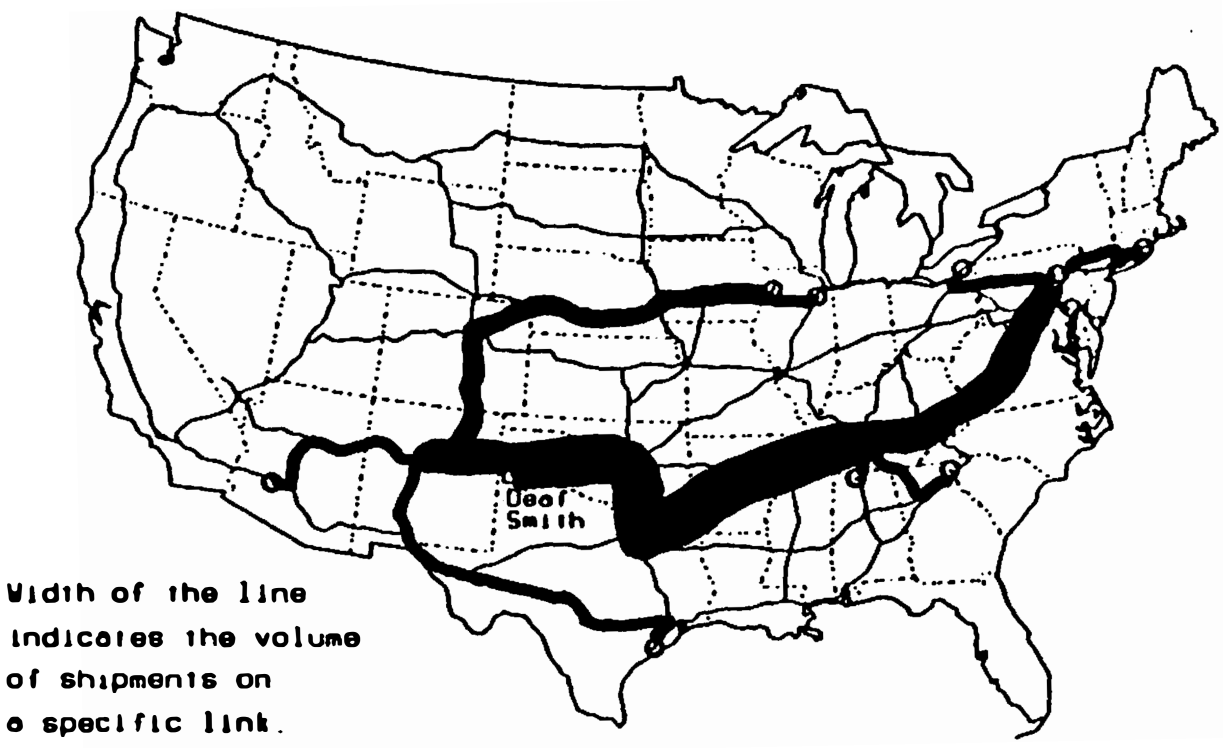


Figure D.8 MTTRM Paths Between Ten Reactors and Deaf Smith Repository Which Minimize Expected Accident Risk to Propesty.

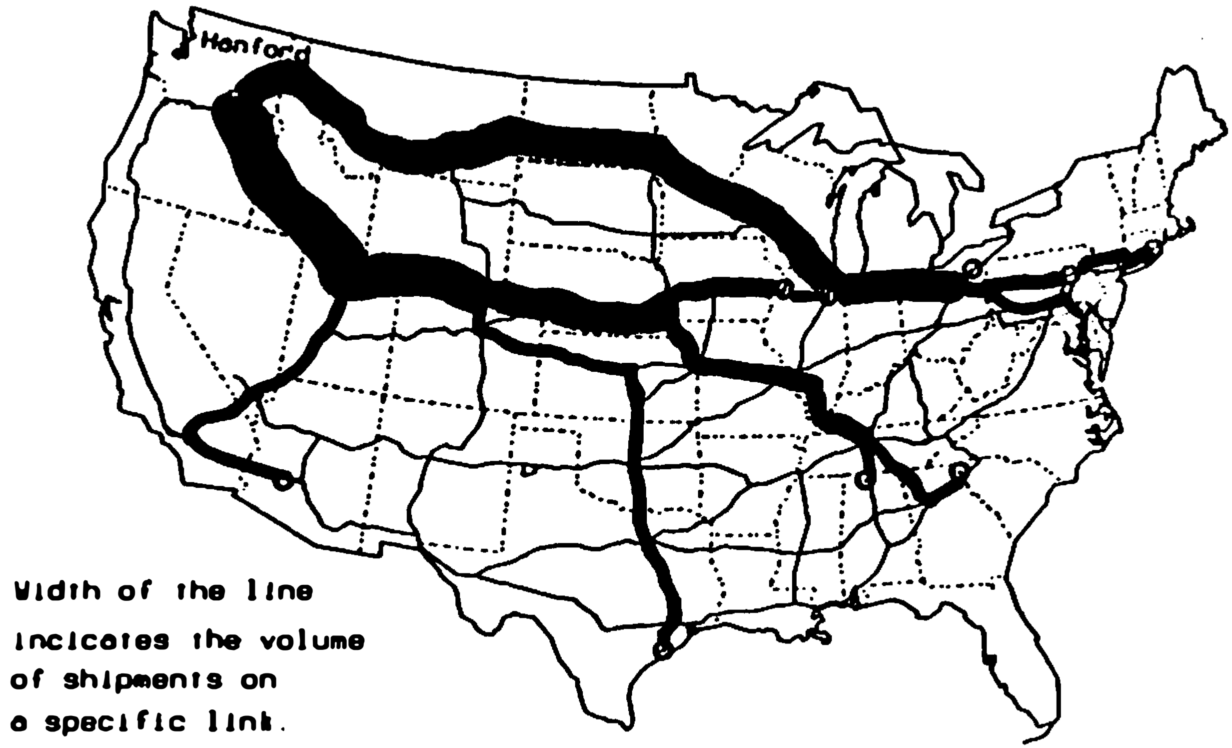


Figure D.9 Minimum Cost Paths Between Ten Reactors and Hanford Repository.

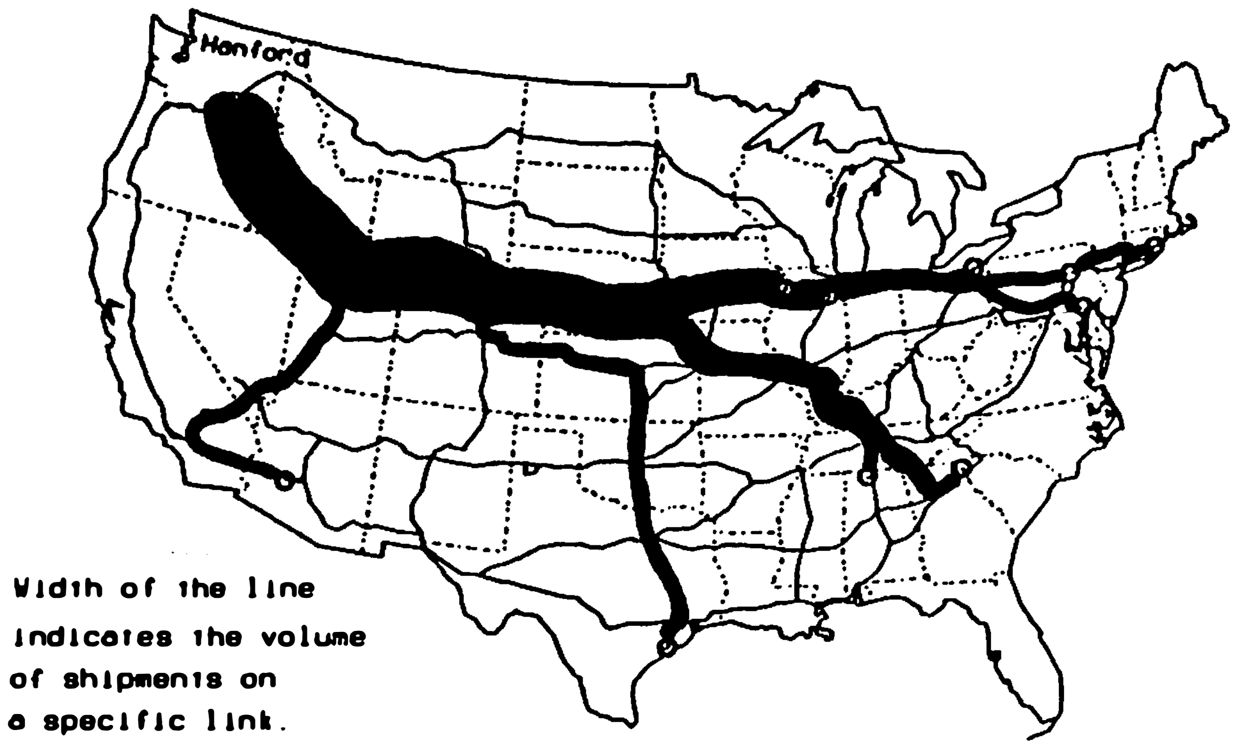


Figure D.10 MTTRM Paths Between Ten Reactors and Hanford Repository Which Minimize Incident Free Transport Risk.

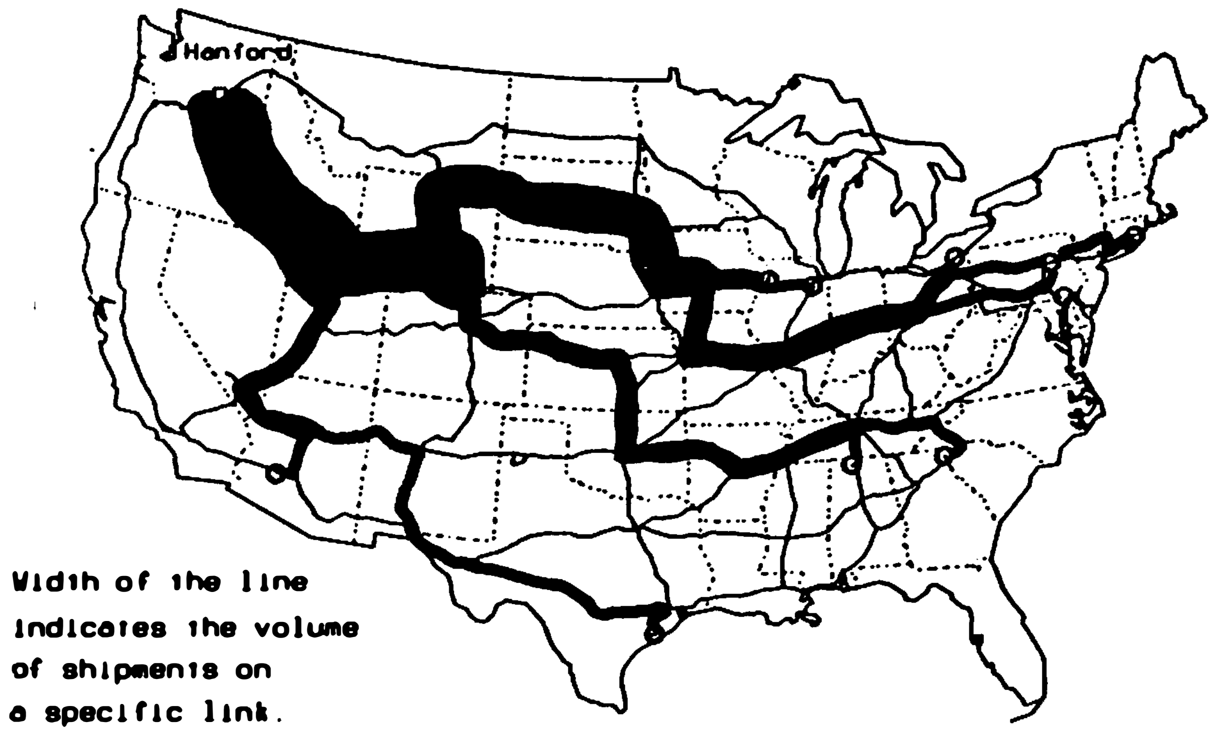


Figure D.11 MTTRM Paths Between Ten Reactors and Hanford Repository Which Minimize Expected Accident Risk to the Population.

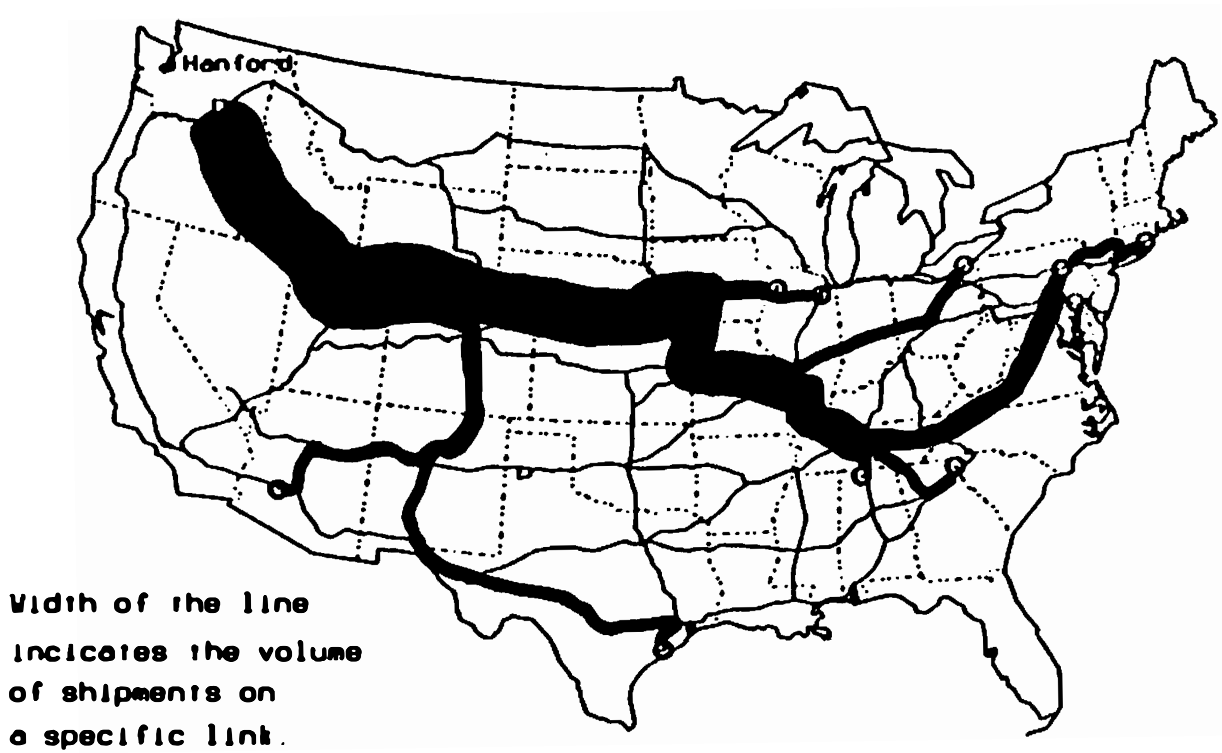


Figure D.12 MTTRM Paths Between Ten Reactors and Hanford Repository Which Minimize Expected Accident Risk to Property.

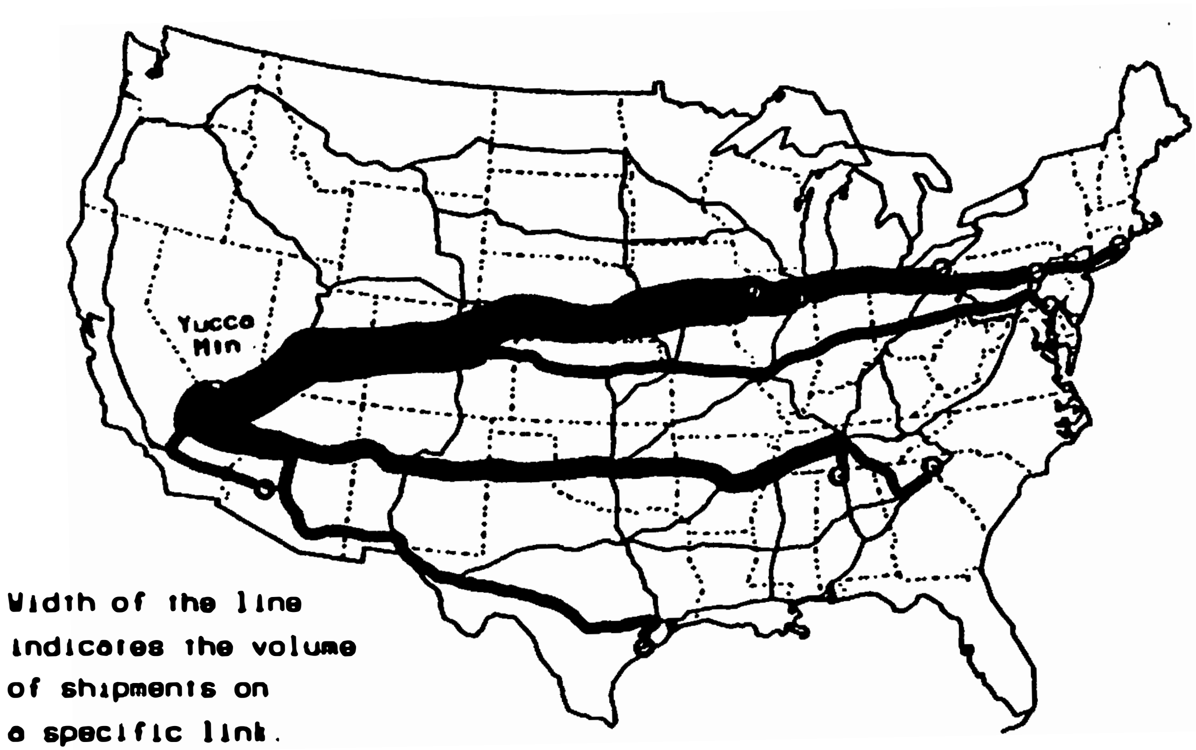


Figure D.13 Minimum Cost Paths Between Ten Reactors and Yucca Mountain Repository.

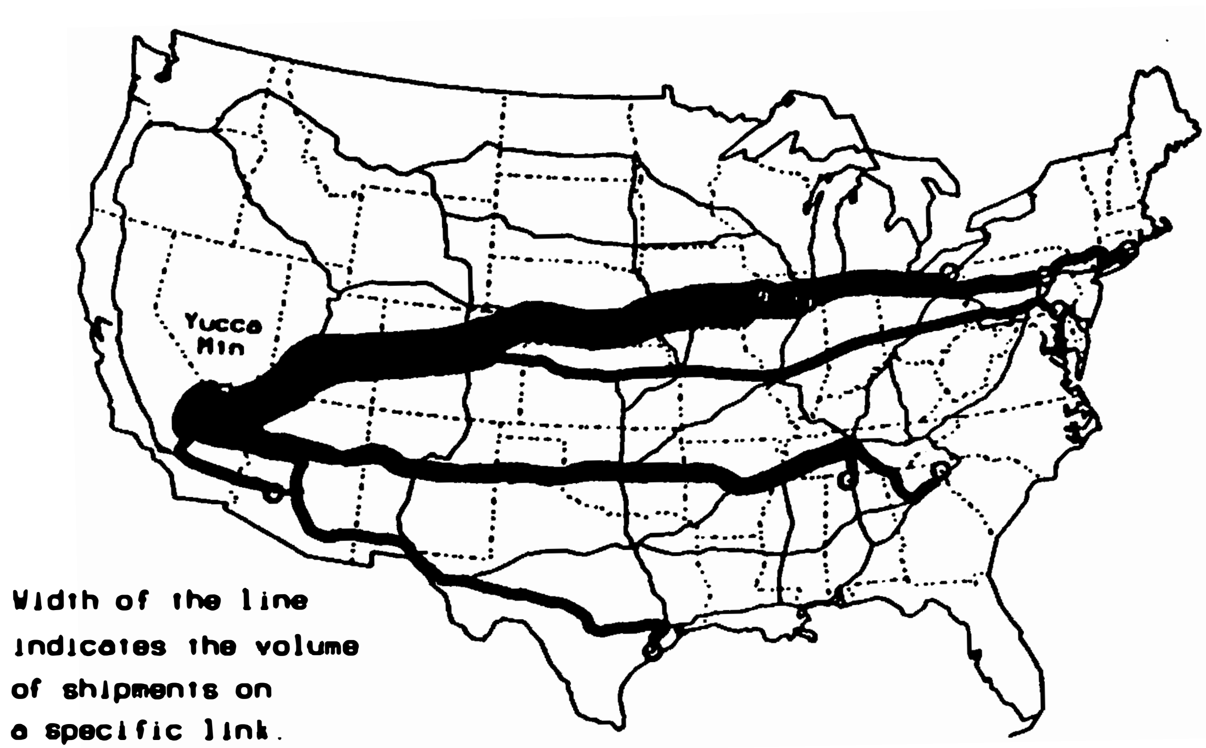


Figure D.14 MTTRM Paths Between Ten Reactors and Yucca Mountain Repository Which Minimize Incident Free Transport Risk.

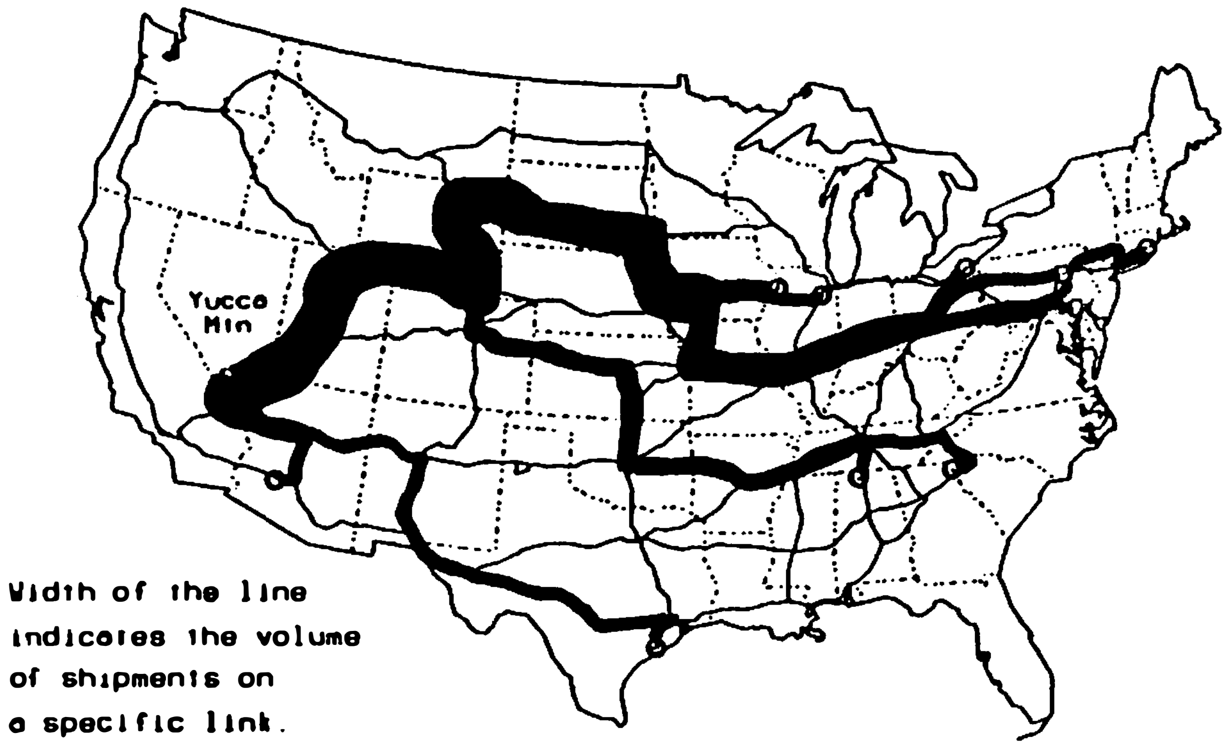


Figure D.15 MTTRM Paths Between Ten Reactors and Yucca Mountain Repository Whcih Minimize Expected Accident Risk to the Population.

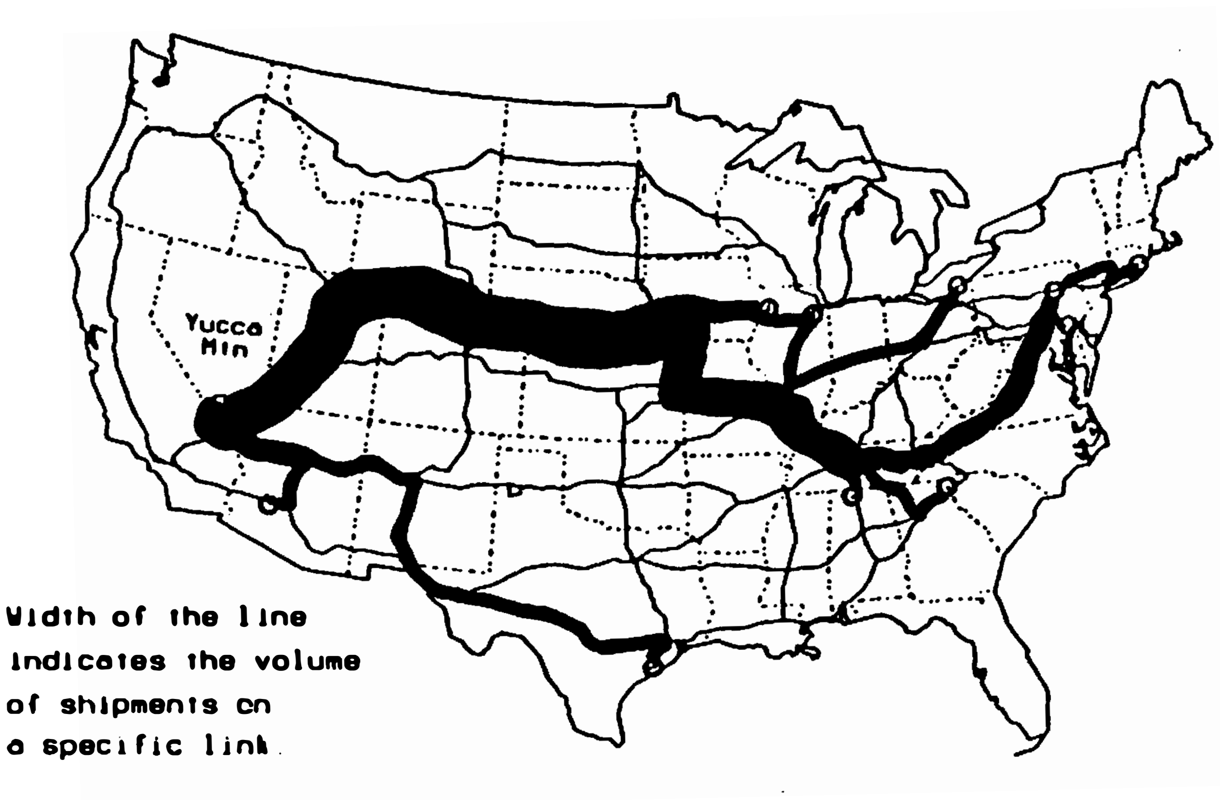


Figure D.16 MTTRM Paths Between Ten Reactors and Yucca Mountain Repository Which Minimize Expected Accident Risk to Property.

VITA

Ivor Glen Harrison was born in Albany, New York in 1949. He received his first ten years of schooling in Little Rock, Arkansas. His last two years of high school were spent at Verdun American School in France where he graduated in 1967. He attended the University of Central Arkansas at Conway from 1967 to 1971. He graduated with a double major in Geography and History in 1971. After teaching secondary school two years, he entered the master's degree program in the Department of Geography at the University of Arkansas at Fayetteville. He graduated with a master's degree in 1978. After an additional year of teaching secondary school, he entered the Ph.D. program in Geography at the University of Tennessee.

While at the University of Tennessee, he lectured in Economic Geography, worked as a student researcher at Oak Ridge National Laboratory, and participated in a research project on the transportation of food aid in Africa. His major areas of research interest are in economic, transportation, and urban geography. He completed his Ph.D. in June 1986.