This is to certify that the

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MINIMIZING THE RISK AND COST
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MINIMIZING THE RISK AND COST OF TRANSPORTING RADIOACTIVE MATERIAL

By

James Thomas Carrick

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To my wife, Mary

and to my parents,

Thomas and Helen Carrick

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ABSTRACT

MINIMIZING THE RISK AND COST OF TRANSPORTING RADIOACTIVE MATERIAL

By

James Thomas Carrick

A method is developed to minimize the risk and cost of shipping radioactive material. The model includes a procedure to assess the risk of transporting radioactive material during accident and accident-free situations. An algorithm for routing the shipments on a network by minimizing the risk or cost is also provided, as is its implementation as a computer program.

The method is applied to shipments of low-level radioactive waste in the Midwest Interstate Low-Level Radioactive Waste Compact. The shipments flow from the waste generators in the region to potential repository sites. The risk and cost of these shipments is evaluated for numerous sites within the region. Maps of the region are generated in which repository sites of equal risk or cost are connected to produce contour lines. The risk and cost estimates of each potential repository are then combined through a normalization procedure to provide a relative ranking of the combined risk and cost index. Areas with extreme values of risk, cost or combined index are noted.

The model is also applied to the state of Michigan for low-level radioactive waste shipments originating within Michigan. The results are displayed in the manner previously described.

Sensitivity analyses are performed to test the behavior of the model. Conditions tested are: the withdrawal of one state from the Compact, accident rates reduced by a factor of 10, shipment volumes reduced by a factor of two and requirement of high-integrity containers during shipment. The model performs as expected during the sensitivity analyses. Volume reduction appears to be the policy with the greatest impact on reducing transportation cost, requiring high-integrity containers provides the greatest reduction in risk estimates.

General conclusions are:

1. The risk of transporting radioactive material can be quantified,
2. Risk is useful as a criterion for routing radioactive material shipments,
3. Parameters such as risk and cost can be combined through a normalized index,
4. The risk associated with shipping low-level radioactive waste is small in comparison with other transportation risks, and
5. The method used in this research may be applicable to the shipment of other hazardous material with the formulation of appropriate risk models.

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LOW-LEVEL RADIOACTIVE WASTE ISSUES

Historical Perspective

Beginning with the Manhattan Project during World War II, scientists and engineers have recognized the need to separate radioactive materials from normal waste materials for disposal. The disposal method first chosen for the radioactive waste generated by the Manhattan Project was shallow land burial. During the post-war period, the burial grounds were located on the Project sites to satisfy security needs. An added benefit to this method of site selection was the minimization of risk to the public during transportation of the waste since the disposal sites were adjacent to the facility generating the waste [7]. With the expansion of the Federal nuclear weapons and power programs during the 1940's and 1950's, more than a dozen government operated disposal sites were established at the laboratories, test and production facilities engaged in nuclear research.

Refinements in the understanding of the health effects of radiation led to the classification of radioactive wastes by such categories as isotopic content, Curie content, waste form or source of waste. Accordingly, wastes were classified as spent fuel, high-level waste (HLW), transuranic waste, mine and mill tailings, or low-level waste (LLW). Classifying the wastes allowed for their separation at the waste generating facilities. Thus each waste class could be handled in a manner which limited the amount of radiation exposure received by the workers and yet was effective and economical for each class.

Spent fuel is exactly that, fuel that has been used in a nuclear reactor. Spent fuel typically contains large quantities of fission and activation products and as a result is highly radioactive for a number of years following its removal from the reactor in which it was used. This radioactivity is generally allowed to decay for a number of years prior to the treatment or final disposal of the spent fuel. Spent fuel generally emits energetic beta and gamma radiation which is highly penetrating.

High-level waste (HLW) is the waste stream generated during the reprocessing of spent fuel. During reprocessing, spent fuel is cut into sections and the fissionable isotopes remaining in the fuel matrix are chemically separated from the non-fissionable isotopes. The uranium and plutonium thus recovered can be reloaded into new fuel bundles. The HLW comprises the remnants of the fuel following this separation. HLW is also highly radioactive as it contains the fission and activation products found in the spent fuel.

Transuranic waste (TRU) is material other than spent fuel or HLW which contains elements with atomic number (Z) greater than that of uranium (Z=92). The concentration of transuranic elements must exceed a limit established by the Federal government to be considered transuranic waste. TRU decays through the emission of alpha particles which is not a penetrating form of radiation. The gamma radiation emitted during the alpha decay process is generally of low energy.

Mine and mill tailings are wastes generated in the mining of uranium or thorium ore or in the processing of uranium ore into a substance known as yellowcake. Alpha decay is the primary mode of decay for tailings. Treatment of tailings is relatively simple because of the low concentration of radioactivity in the ore. The main concern with tailings is to limit inhalation of dust because of the hazard posed by alpha particles absorbed by lung tissue.

Low-level waste (LLW) is defined by exclusion, that is, LLW is any radioactive waste not defined by the other waste classes.

The shallow land burial method of disposal was found inappropriate for highly radioactive classes of waste like HLW and spent fuel because of the poor radiation shielding qualities of soil. This method however, was still useful for the disposal of LLW and during the 1950's the government continued to dispose of its LLW at government owned and operated sites.

The late 1950's brought the advent of commercial nuclear power and the use of radioisotopes in industry and medicine. The LLW generated by these commercial enterprises was initially disposed of by ocean disposal firms at a small number of Atomic Energy Commission (AEC) approved ocean disposal sites. In 1960, due to potential problems with ocean disposal (such as monitoring of the waste), the AEC allowed commercial waste to be disposed at government sites while commercial shallow land burial sites were being developed [7,21]. The first commercial LLW disposal site was opened in 1962 at Beatty, Nevada. This site was followed over the next nine years by sites in Kentucky, New York, Washington, Illinois and South Carolina. To promote the opening and use of commercial sites, waste generated by government nuclear operations were frequently shipped to those sites between 1963 and

1979 [7]. With the opening of commercial sites, the federally operated disposal sites no longer accepted commercial waste.

In retrospect, the major criteria for site selection by the commercial disposal site operators appear to have been the site's soil and hydrogeological characteristics and the proximity of the site to potential users [7,21]. The Beatty, Nevada site is located close to the Nevada Nuclear Weapons Test Site. The Maxey Flats, Kentucky location is near a number of facilities in the front end of the nuclear fuel cycle such as the Paducah Gaseous Diffusion Plant and the Portsmouth Gaseous Diffusion Plant. The West Valley, New York facility is located adjacent to a nuclear fuel reprocessing plant. The Richland, Washington site is within the Hanford Reservation, a large government facility involved in nuclear power and weapons research. Sheffield, Illinois is centrally located for a number of commercial nuclear power stations, research universities and pharmaceutical manufacturers. Barnwell, South Carolina is next to another major government facility, the Savannah River Plant. It is apparent that the commercial disposal site operators gave considerable importance to being located near the waste generators [21]. While this may have been economically motivated, at least initially it also limited the risk of public exposure to the transportation of LLW.

Operational problems drastically changed the LLW disposal situation during the 1970's. The first problem to occur was the detection of radionuclides leaching from both the Maxey Flats, Kentucky site and the West Valley, New York site. As a result both sites were closed, West Valley in 1975 and Maxey Flats in late 1977. In 1978 the Sheffield, Illinois site reached its licensed capacity and was closed pending the outcome of a site expansion application filed in 1976. During the licensing process the site operator, U.S. Ecology, Inc., requested that the process be terminated. The site has remained closed [8,21].

Since the mid-1970's the volume of waste generated steadily increased. The generating facilities were concentrated in the areas of the country (the Northeast and Great Lakes regions) which following 1978 had no disposal sites. In 1979, the section of the country north of Tennessee and North Carolina and east of the Mississippi River produced 58% of the total volume of LLW. The Barnwell, SC site (operated by Chem-Nuclear Systems, Inc.) bore the brunt of the northern and eastern site closures. In 1979, 80% of the LLW generated in this country was sent to there for disposal [43].

These factors combined with poor shipping practices on the part of the waste generators to cause a crisis in mid-1979. Between April and July of 1979, 63 packaging deficiencies were noted during a receipt package inspection program at the Barnwell site [9]. In July, 1979 the Governor of Nevada ordered the Beatty site closed after two major shipping incidents occurred at the site. The first incident was a fire on a truck carrying improperly packaged medical waste into the site. The second incident involved contaminated water leaking from a shipment of demineralizer resin originating at a nuclear power plant [10,22]. The site was reopened late in the month after the governors of Nevada, South Carolina and Washington jointly demanded stricter enforcement of the federal rules governing LLW shipments. The Beatty site was again closed from October to December, 1979 when several waste drums were discovered buried outside of the site fence. It was decided that these drums had most likely been buried at the end of one of the older trenches and the fence was later built without finding the exact location of the end of the old trench [21,22]. Also in October of that year, the Governor of Washington closed the Richland site because of three packaging or shipping problems. The site was reopened in November, 1979 when Federal regulatory agencies made assurances that transportation regulations would be enforced [10].

While the Beatty and Richland sites were closed, the Governor of South Carolina announced that the volume of waste accepted by the Barnwell site would be cut in half from the amount received in October, 1979. This reduction would be phased in over a two year period [43].

In response to the governors' actions and with the support of the National Governors Conference and the National Conference of State Legislatures, Congress enacted the Low-Level Waste Policy Act (PL 96-573) in December, 1980. This legislation [56] set the Federal policy on LLW as:

1. Each state is responsible for the disposal of commercial LLW generated within its borders,

2. A regional basis for the management of LLW is the most efficient and safe method,

3. States may enter into compacts to establish and operate regional LLW disposal facilities,

4. Congress must consent to the compacts, and

5. After January 1, 1986, any approved compact may restrict the use of the regional disposal facilities under the compact to the disposal of LLW generated within the region.

Since this Act was passed, the three remaining disposal sites have continued to accept shipments of LLW [22]. Because of delays in meeting the 1986 deadline, the Act was amended in December, 1985 and a new deadline of January 1, 1993 was set. Further provisions were:

1. Annual capacity for LLW was fixed at 2.8 million cubic feet,

2. Disposal volume is allocated to utility generators based on type of nuclear reactor, the remaining generators are served on a first-come, first-served basis,

3. Open disposal sites are allowed to add a surcharge on wastes from outside the region containing the site, and

4. Milestones for opening additional sites were established. Penalties for failure to meet these milestones were also established.

Regional Compacts Formed

In response to the Low-Level Waste Policy Act, states have been forming compacts to manage the disposal of LLW. Generally these compacts are based on geographic location although the states need not be contiguous.

Geography was the basis for the formation of the Midwest Interstate Low-Level Radioactive Waste Compact (MILLRWC), comprised of Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio and Wisconsin (figure 1).

The MILLRWC is one of the largest compacts both in terms of area and number of states. Smaller compacts are more common, for example, Illinois has established a compact with Kentucky, creating a gap along the southern rank of the Midwest Regional Compact. Other states, Texas is an example, have chosen to go it alone.

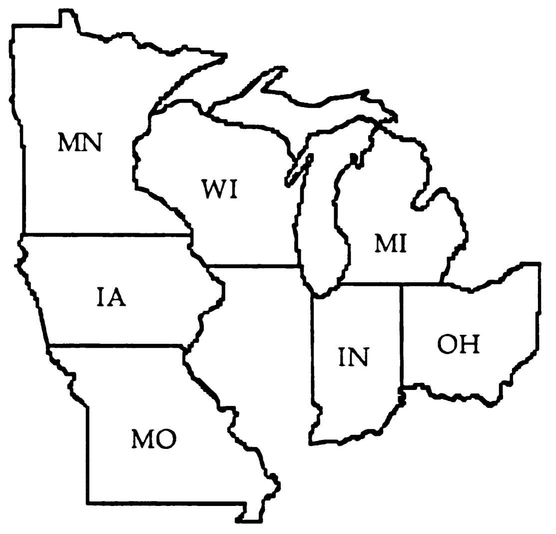

Figure 1. The MILLRWC

Once a compact is established, the states forming the compact accept the responsibility for managing LLW in that compact. This includes establishing a site or sites within the compact area for disposal or processing of the LLW generated within that area. The operation of the sites and long-term care for those sites are other responsibilities of the compact. Site selection will be both a technical and a political process. The opportunity exists to make this process one based on reason and knowledge gained from past experience at the commercial facilities and the government sites. Clearly factors such as the geology and hydrology will determine if a site is or is not suitable. Also of concern are the land use and resource use plans of the proposed sites. While these concerns will at least partially determine the capital costs of preparing a site as a LLW disposal facility, the location of the site chosen will also affect the operating costs. The labor and transportation components of the site operating costs will depend on where the site is located within a region.

Problem Statement and Research Outline

This research will provide a method to estimate the impact of transporting LLW to proposed disposal sites and then optimize the choice among alternative sites by selecting the site which minimizes the effects of transportation. To do this, a transportation model will be developed, the major components of which are a catalog of LLW shipment origins in a region, a definition of possible shipping routes in that region, a cost function to produce both out-of-pocket costs and the costs to society of LLW shipments, and finally, an algorithm to choose the optimal routes from all generators to each proposed disposal site, allowing the selection of the site with the smallest transportation impact.

The shipment catalog will be used to characterize the LLW shipments within the region of interest. Three major categories of waste generator will be considered:

Commercial nuclear power plants,

Institutional generators and

Industrial generators.

Institutional generators include universities, hospitals and research facilities. Industrial generators include radiopharmaceutical manufacturers, fuel-fabrication facilities and manufacturers of industrial and consumer products which use radioactive material. Cataloged for each generator will be:

Annual number of shipments,

Annual volume shipped,

Isotopic content of waste shipped, and

Physical form of waste shipped.

The cost function will allow the direct cost to the shipper to be combined with the cost borne by society due to the radioactive nature of the LLW shipments. The direct cost is based on the distance over which the waste is shipped and the type of waste shipped. The radiological cost or risk will be determined by assessing the probability of a LLW shipment being involved in an accident and then quantifying the consequences of such an accident. Also quantified will be the radiological impact of incident-free shipments. The radiological consequences will be estimated through the use of internal and external dose models. The expected radiological impact of shipping LLW will be calculated by multiplying accident consequence with the probability of an accident on each link.

Once the shipping cost or risk for each link has been determined, the optimization algorithm will route the shipments from each waste generator to a proposed disposal site. A dynamic programming model will be used to optimize the network. The lowest cost (risk) routes to each disposal site will then be totalled to produce the transportation cost (risk) for that site. The proposed repository sites will then be compared to determine the least costly alternative. Cost and risk estimates will be combined to allow optimization of the network with respect to the resultant combined total impact parameter.

To test the model, data from the Midwest Regional Compact will be used. The Compact has contracted ERM Midwest, Inc. to produce a shipment catalog. The remaining data will be gathered specifically for this research. Potential disposal sites will be assumed to exist in each state of the compact.

The model will then be used to choose the optimal location from among these assumed sites.

Chapter 2 of this dissertation presents a review of literature relevant to the problem. Chapter 3 is a discussion of risk assessment as it relates to the problem. The components of the transportation model are developed in Chapter 4 and then combined into a method capable of solving the problem at hand. The application of the model to the Midwest Regional Compact is presented in Chapter 5. Finally, Chapter 6 presents the conclusions drawn from this research.

Chapter 2

LITERATURE REVIEW

Siting of Low-Level Waste Repositories

Little has been written about siting LLW repositories because the need for such studies did not exist until recently. Clancy, Gray and Oztunali [7] reviewed the history of LLW disposal for the Nuclear Regulatory Commission. Their review included the major Federal sites as well as the six commercial repositories. Generally, they found that disposal areas have been situated near waste generators either for reasons of security or to minimize the transportation of the wastes. For example, the Federal Government established a disposal site on the Hanford Reservation near Richland, Washington during World War II to accept the wastes from plutonium production at nearby facilities. Another example is the Barnwell, South Carolina site which is located adjacent to the U. S. Department of Energy Savannah River Plant and is in close proximity to a number of commercial nuclear power plants.

Similar reasoning is being explicitly incorporated into the siting processes currently under consideration by some compacts formed as the result of the LLWPA. Colglazier and English [11] report that waste transportation is an issue to be dealt with by the Illinois Department of Nuclear Safety as part of the siting process used by the Central Midwest Compact. They also note that the Southeast Interstate Compact is to consider "the minimization of waste transportation" in its site selection. This is also one of the factors to be used in identifying the host state in the MILLRWC.

Network Models

Theoretical Basis

Networks, or their geometric equivalents, graphs, have long been the object of study by mathematicians. Euler applied graph theory to the problem of traversing the seven bridges of Königsberg in 1736. In the Nineteenth Century, the mathematician W. R. Hamilton introduced a game based on his work in networks and graphs. These and dozens of other applications of network theory are described in a text by Busacker and Saaty [4]. This text, one of many on the topic, describes both the graphical representation of networks and their representation by matrix methods. A more detailed description of the matrix formulation of networks is given by Fenves and Branin [23]. This formulation uses network properties such as connectivity, incidence and circuitry to define matrices which provide a mathematical description of the network. For example, an incidence matrix relates the nodes on the network with the segments entering each node. This matrix gives rise to a tree matrix in which all nodes in the network are connected. The path from any node to another along the tree can be derived from the tree matrix: the inverse of the tree matrix equals the transpose of the path matrix. So, from a theoretical viewpoint, it is a short exercise in matrix algebra to move from a network description to solving for paths through the network. From a practical point of view however, complications arise due to the large size of the incidence matrix for even modest networks such as the one being studied in this research. The limited access highway network in the eleven state area containing the Midwest Regional Compact along with Illinois, Kentucky, Tennessee and West Virginia is composed of about 300 nodes (or interchanges) and 1000 segments connecting those nodes (figure 2). The incidence matrix is thus composed of 300,000 entries, most of which are empty or zero since the network is sparse, as is the case with most networks normally encountered. To represent this matrix on a computer would require 0.6 megabytes of memory for integer values or at least 1.2 megabytes of memory for real numbers. This limits the usefulness of the matrix method in dealing with real network problems.

A second method of dealing with transportation networks is through linear programming (LP). A special class of problems commonly referred to as transportation problems can be solved by linear programming. Hillier and Lieberman [30] provide examples of the transportation problem and solution techniques in their text. Generally, the solution concerns the distribution of a commodity from a set of origins to a set of destinations so as to minimize the distribution cost. Since the emphasis of the analysis is on origin-destination pairs, network-level detail on a segment by segment basis is lost. So, linear programming is not well suited for selecting from among a variety of alternative paths between an origin and destination.

A third technique for analyzing networks is through dynamic programming. In his text, Danø [16] describes dynamic programming as a procedure in which a complex problem is decomposed into a series of subproblems,

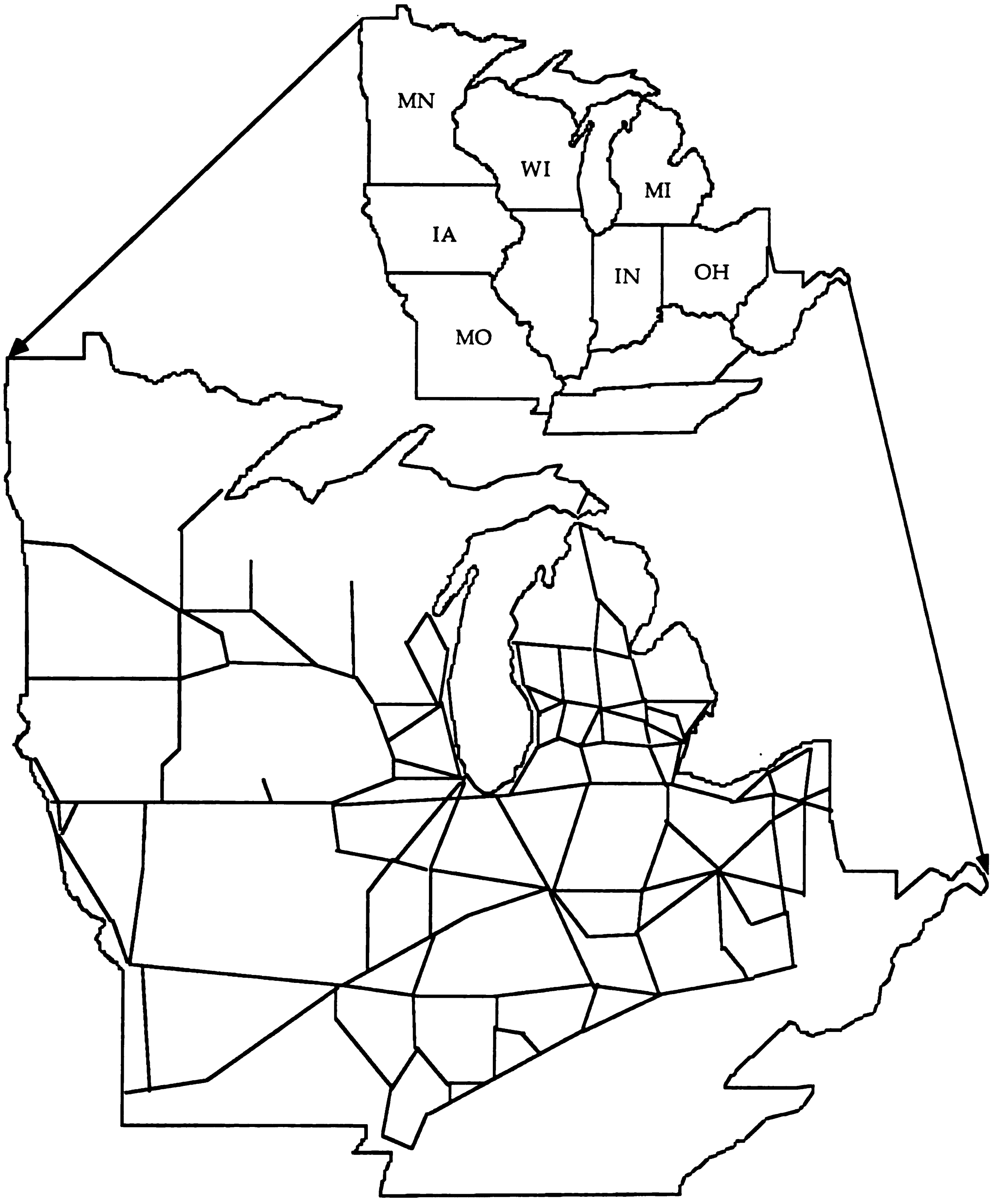

Figure 2. Transportation Network for the MILLRWC

each involving fewer variables. The solutions to the subproblems are combined to obtain a solution to the original problem. He also presents an example of dynamic programming applied to the problem of solving the shortest path between two nodes on a network. This is accomplished through backward recursion, that is, tracing the shortest path back from the destination to the origin.

A similar method (with the exception that it operates in the forward direction) is described in Price [55]. This approach is in the form of an algorithm attributed to Dijkstra [17] which will calculate the shortest path on a network possessing nonnegative weights. In this technique, a label is assigned to each node representing the distance (or some other weight measure) from the origin at each stage of the analysis. A node is considered permanently labelled if no shorter path from the origin exists, otherwise the label is referred to as temporary. The permanent label for each node is the distance along the shortest path to the origin. Also recorded is the predecessor node for each permanently labelled node. This node represents the first connection along the path between any permanently labelled node and the origin. Tracing along the path from one predecessor node to the next generates the shortest path from the origin.

Initially all nodes are temporarily given a label of ∞ with the exception of the origin, S, which is assigned a permanent weight of zero (0). The nodes connected to the origin are then given labels equal to their weight from the origin. The node with the smallest temporary label is assigned that label permanently. So at this time there are two nodes with permanent labels, the origin, S, and the node nearest to it (call this node A). The process continues by examining those nodes with temporary labels which are connected to A. The weight from A to each of these nodes is added to the label of A (which is the weight between A and S). If this new weight value is less than the temporary label for any node connected to A, the new value becomes the temporary label. If the new weight value is not less than the previous temporary label, then the weight from the origin to that node is less than the weight by way of A, and the temporary label is not replaced. Again the node with the lowest temporary label is given that label permanently. The process continues recalculating the temporary labels and assigning permanent labels until either the desired destination is reached or the entire network is assigned permanent labels.

Converting the Dijkstra algorithm into a computer program results in a procedure which makes efficient use of both computer time and memory. The efficiency of this algorithm is documented in a text by Syslo, Deo and Kowalik [71]. Also included is an implementation of the algorithm in Pascal. The listing requires only 50 lines of computer code excluding input and output statements. Unlike the matrix method of analyzing networks, the Dijkstra algorithm can take advantage of the sparse nature of the data and make use of more compact data structures such as lists linking adjacent nodes. As an example, the network previously mentioned as requiring 0.6 megabytes to describe with a matrix could be described in 0.01 megabytes using a linked adjacency list. The Dijkstra algorithm appears to be the best method available for determining the shortest path in a network.

Application of Network Models to Hazardous Materials

In general, all of the methods of network analysis have been applied to the study of transportation systems, the method of analysis chosen depending upon the objective of the particular study. Recent applications have examined the shipment of hazardous or radioactive materials using both linear programming and dynamic programming as optimization techniques.

Hasit and Warner [28] describe a linear programming model used in the regional planning of solid waste management. This model, the Waste Resource Allocation Program (WRAP), optimizes an objective function which is the sum of the transportation costs for waste shipment, the capital and operating costs of disposal or waste processing sites and the site preparation costs minus any revenues generated from the waste. The decision variables are the shipment and processing activities, that is, the amount of waste to be shipped from a region to specified facilities for disposal or processing. Emphasis has been placed on incorporating realistic values for the costs used in the objective function. Hasit and Warner report that the model has been successfully used to reduce regional waste disposal costs by providing a basis for integrated long range planning of waste disposal facilities. Note that since this model is an LP, it does not determine the best routes for shipment based upon transportation costs but instead has as input the distances along chosen routes between all source and disposal site pairs.

The WRAP model was used by Jennings and Sholar [41] to study the shipment of hazardous waste in Kentucky. They added the element of risk estimation to the network analysis performed by WRAP. Their estimates of the risks involved in transporting, treating and disposing of the hazardous material were of a relative nature, that is, Jennings and Sholar provided a cardinal ranking of risks for various hazardous materials and treatment or disposal processes. They then optimized the network with and without using the risk estimates. They concluded that WRAP is useful in weighing waste management policies whether risk is a consideration or not. In terms of calculated risk, the optimal solution they obtained ignoring risk did not differ significantly from the solution in which risk was minimized, but the treatment and disposal practices did vary significantly. Calculation of relative risk values also pointed out inconsistencies in proposed regulatory policies, in one case a proposed regulation resulted in an increase in both cost and risk over the status quo. Jennings and Sholar noted that their method of estimating relative risks was only a surrogate for more thorough risk evaluation techniques.

Application of Network Models to Radioactive Materials

Transportation of radioactive material has been studied primarily at the national laboratories, especially Sandia National Laboratories (SNL) and Oak Ridge National Laboratory (ORNL). Joy, Johnson and their collaborators at ORNL have produced a number of papers on transporting radioactive material, two of which are relevant to this research. Reference 45 is a review of four U. S. Department of Energy computer programs maintained at ORNL. One is a routing model for rail shipments, another routes highway shipments. Two other programs provide a data base for use in transporting radioactive material, AIRPORT contains information on 800 airports in the continental U. S., and the LEGISLATIVE AND REGULATORY INFORMATION SYSTEM acts as network for gathering and disseminating information affecting the transportation of radioactive or hazardous materials.

The rail shipment model is called INTERLINE and is composed of 17,000 links on the nation's rail system. Transfer points are defined so as to reflect the tendency of traffic to remain on a single railroad's line as long as possible. The route is determined by the minimum impedance path between origin and destination. The second routing model, HIGHWAY, is a computerized road atlas of the U. S. describing 240,000 miles of road. The complete

Interstate system and U. S. system (except for those links closely paralleling an Interstate route) are included as well as most principal state routes and a number of county and local roads. Again, routes are determined by minimizing impedance values where impedance is a function of distance and driving time on any given road segment. Certain routing constraints can be imposed on the model, such as avoiding high population areas.

In reference 44, Joy, et al. used HIGHWAY to route shipments of spent fuel between Richland, Washington and Barnwell, South Carolina. Three different routing criteria are used to test HIGHWAY:

1. No special constraints,
2. Avoidance of high population density areas,
3. Maximize the use of the Interstate system.

The routes were chosen to minimize an impedance function based on the distance and estimated driving speed of each segment, subject to the relevant constraint. Avoiding high population density areas resulted in a 5% distance increase, a 12% driving time increase and a decrease in the use of Interstate routes by 38%. Maximizing Interstate use resulted in a 6% distance increase, a 3% driving time increase and an increase in the use of Interstate routes by 7%. The authors note that population density information was to be added to the data base to allow the calculation of radiation exposure to the public from radioactive material shipments.

Brogan and Cashwell [2] note that the coarseness of the data used by the routing algorithm in HIGHWAY limits the usefulness of this program for intrastate levels of analysis. They call for additional parameters to be used for routing at this higher level of detail. Geometric considerations, roadway capacities and land use data are among the parameters they recommend.

Cox [13], in his dissertation prepared for Cornell University, examines the transportation of spent nuclear fuel. In doing so, he modifies Dijkstra's algorithm so that more than one parameter can be evaluated to determine the shortest path in a network. The values of the decision parameters are represented as the components of a vector. The vector components are assumed to be linearly independent. Each link on the network is defined by its endpoints and parameter vector. In determining a path, the vectors are added component-wise to produce a resultant vector which is compared to the best or "dominant" vectors recorded for each node. A dominant vector is one in which every component is less than or equal to the respective components of all other vectors. That is, vector $\vec{X}$ dominates vector $\vec{Y}$ if and only if $X_i \leq Y_i$ for all components i. The result of Cox's modified algorithm is a set of paths with final vectors that dominate all other paths. An example he provides has three paths in the solution set with final vectors of (4,6), (5,5) and (6,4). The method cannot choose from among these solutions because of its assumption that the parameters should not be combined into a unified measurement during the routing analysis but should rather be left for "the political decisionmakers." [14] Still, this begs the question, "Which route should be used?" since surely at least one route will be used.

Cox proceeds to apply his algorithm to a case study [15] in which spent nuclear fuel is shipped by truck on Interstate routes from Maine to Louisiana. Two parameters are used by the decision-making algorithm, shipping cost and risk exposure. Actually surrogates for these parameters are used in the analysis because of difficulty in measuring the variables of interest. Travel time was taken as an approximation of the shipping cost and the population within 0.5 miles of each network link replaced the risk exposure. No attempt was made to quantify the magnitude of the risk or to estimate the health effects caused by the postulated exposure. The end product is a set of six paths, each with a final vector of (total travel time, total number of persons "exposed"). The parameter values for the paths range from (35 hours, 810,000 people exposed) to (40 hours, 475,000 people exposed). Weighing the results is left to the decisionmakers.

Risk of Transporting Materials

Risk of Shipping Hazardous Materials

A discussion of risk, consequences and risk assessment will be deferred until chapter 3 but some applications of risk assessment to transportation will be reviewed here.

Wright and Glickman [87] have surveyed research performed between 1978 and 1984 outside the United States and Canada on hazardous materials transportation. Included in the survey is a section on risk assessment. All of the papers dealt with non-radioactive hazardous materials. The nine papers discussed fall into three categories: public perception, emergency planning and risk analysis. The emphasis was on the modelling of risks, seven papers dealt with risk analysis and quantification with application to specific cases or materials. One paper dealt with the public perception and acceptance of risk while the final paper dealt with familiarizing emergency response personnel and transportation workers with the risks involved in transporting hazardous materials.

The current use of risk assessment is reviewed by Rowe [58] for the National Cooperative Highway Research Program. Three categories of risk assessment are described: enumerative indices, regression models and probabilistic risk assessment models. An enumerative index develops a rating or score for risks. Typically, parameters relevant to the hazardous activity are counted. Weights are assigned to each parameter based on empirical evidence or some other rationalized criterion. The weighted counts are then combined mathematically. The resulting score can be ranked against other comparable activities.

Regression models use measurable parameters to estimate the probability of an accident per vehicle mile. Parameters such as average daily traffic (ADT), number of signals, type of road and condition of road are used. A consequence estimate is determined through the population density of those at risk. The probability and consequence are combined to arrive at risk. The models are route and site specific because they are calibrated to actual conditions or data.

Probabilistic risk assessment models also make use of accident probability and consequence magnitude. The models currently in use differ in their definition of risk, their level of detail and their methods for generating data. One model defines risk as the conditional probability of an accident causing some loss, while three other models examined define risk as the product of the conditional probability and consequence magnitude. The level of detail covered ranges from analysis of specific materials and routes to the use of aggregated data for risk estimates. Probability data is generated in some cases by fault-tree analysis while other models use average accident rates. The magnitude of consequences are estimated by dispersion models, simulations and other techniques.

An example of a risk assessment model for hazardous materials transportation is presented by Scanlon and Cantilli [62]. Their approach is to estimate a risk level *index* for a community. A linear model is used to calculate the risk level index:

$$RL_{mvi} = L_{tv} \bullet (N_i + N_{hc} + N_{vc} + C_p + C_m + N_{rh} + C_{tc})$$

$$RL_{hmi} = RL_{mvi} \bullet (5.5P_{ex} + 2.5P_{fl} + 4.0P_{cg} + 1.0P_c + 1.0P_p) \bullet L_v \bullet L_d$$

$$CR = RL_{hmi} \bullet (D_p + N_a + V_\$ + N_s)$$

Where: CR = Community Risk

RL_{mvi} = Risk Level of Motor Vehicle Incident

L_{tv} = Traffic Volume Level index (from 1 to 10) based on ADT

N_i = Number of Intersections per mile

N_{hc} = Number of Horizontal Curves per mile

N_{vc} = Number of Vertical Curves per mile

C_p = Condition of Pavement index

C_m = Condition of Median index (from 1 to 10)

N_{rh} = Number of Roadside Hazards per mile index (1 to 10)

C_{tc} = Condition of Traffic Control devices index (from 1 to 10)

RL_{hmi} = Risk Level of Hazardous Material Incident

$P_{ex,fl,cg,c,p}$ = Proportion of ADT of Explosives vehicles, Flammable Liquids vehicles, Compressed Gas vehicles, Corrosives vehicles and Poisons vehicles respectively. Multipliers are empirical comparisons of impact of incidents involving such vehicles.

L_v = Vehicle Level index

L_d = Driver Level index

D_p = Population Density index (scaled from rural to heavily urbanized)

N_a = Number of hazardous materials Actors (generators, etc.)

$V_\$$ = Dollar Value of property affected

N_s = Number of Sensitive facilities (schools, hospitals, etc.).

This model incorporates data of interest to the traffic engineer such as L_{tv} and N_{hc} as well as data used by an emergency planner such as D_p and N_s but the result cannot be a true measure of risk because it does not incorporate accident rates in the equation. Its value in assessing relative risk is also questionable because of inconsistencies in units of measurement used, such as the addition of dollars, $V_\$$ and number of buildings, N_s.

Pijawka, et al. [54] assessed the risk of transporting hazardous materials in Arizona. Hazardous material types, volumes and flows were identified. Exposure-miles, defined as the annual mileage traversed by vehicles carrying hazardous materials on a route by route basis, were estimated for each of the major routes in the state. The prevailing accident rate per vehicle mile on each route was estimated and multiplied by the exposure-miles to determine the number of hazardous material carrier accidents per year. Pijawka states that 5% of these accidents result in a release of material (note that others cite values as high as 40% [1]), so the probability of a hazardous materials release is:

$$P_r = .05 \bullet \text{(accident rate/vehicle-mile)} \bullet \text{(exposure-miles)}.$$

A population risk factor was then calculated by multiplying the release probability, P_r, with the population at risk, defined as the population within 3 miles of a route. Note that the population risk factor does not consider the health effects of different materials, a uniform health impact is assumed. Clearly this is an area of future refinement, a chlorine release has a much greater impact than a release of the same volume of diesel fuel. Another refinement might be to calculate P_r based on a unit of measurement smaller than an entire route.

An attempt was made in the article to correct this shortcoming by introducing a Potential Hazard Rating (PHR) into the equation. PHR is a measure of relative hazard of classes of materials, combining the volume of material shipped in each hazard class and the average evacuation distance for each hazard class. This distance depends upon the physical characteristics of the class of materials. So, some degree of incident severity is taken into account, but since PHR is an index rather than an actual measurement of risk, the results are useful only for comparing the rank order of hazards.

Rowe [58] discusses the difficulties inherent in determining "absolute" risk assessments and the resulting reliance upon "relative" risk estimates by many models currently in use. He divides the search for absolute risk into two approaches: bottom-up estimates and top-down estimates. In the bottom-up approach, the analyst begins at the finest detail available, looking at the risks of a given shipment of a particular material on one mode along a specific route segment. The accident probabilities are added for each segment along the route until the desired destination is reached. Rowe's quarrel with this approach is the propagation of errors through the process which can lead to error ranges of orders of magnitude, especially for rare events. In his view, these ruinous errors are introduced through the multiplicative nature of accident probability calculations: risk is usually modeled as the product of a number of factors, each contributing substantial error. For example, risk might be defined as:

$$R = P_i \bullet P_s \bullet P_h \bullet P_m \bullet P_e$$

Where: P_i = the probability of an incident occurring

P_s = the probability of a particular accident severity class

P_h = the probability of release of hazardous material

P_m = the probability of specific meteorological conditions

P_e = the probability of exposure resulting in damage.

Top-down risk estimates use aggregate historic data as the basis for analysis. If data does not exist, models are used to explain causality between accidents and consequences. The major problems with this approach according to Rowe is that either the data is extremely difficult to obtain or the models used as a substitute are not directly testable. Again, this is especially the case for rare events. Rowe's conclusion is that, "More practical analyses have then focused on relative risk estimates for specific situations." [59]

Rowe is disingenuous in his labelling of risk assessment methods as either absolute or relative. Rowe's definition of "absolute" risk is actually a definition of relative risk, that is, a method of measuring risk relative to the conditions present. Altering conditions results in different risk values, introducing a new variable into the equation above results in a new risk measurement. Risk can only be measured in context, it exists only as a relative value. Rather than absolute risk, this category could be better named true risk or actual risk or real risk (or estimated or approximate ...). Rowe's category of "relative" risk could more properly be called ordinal risk or risk indices or normative risk since the best that can be obtained from such analyses are rankings of risks (as with Pijawka's PHR index).

<u>Risk of Shipping Radioactive Material</u>

As noted earlier, the risks associated with transporting radioactive materials have long been recognized if not fully understood. One indication of this was the decision to locate radioactive materials processing facilities, utilization facilities and waste sites near each other. While security was of paramount importance, especially at military sites, eliminating transportation risks was a secondary concern. Still, in 1983, Zeigler, Johnson and Brunn [88] noted that, "The risks of radioactive waste transportation have yet to be adequately assessed, however."

An early study performed by Goodridge [27] summarized transportation accidents involving radioactive materials over a period of fifteen years through 1964 in the United States and the United Kingdom. Two noteworthy observations are made by Goodridge: the first is that during the study period about 1 in 15,000 shipments was involved in an accident, the second is that 28% of these accidents resulted in release of radioactive material and subsequent contamination of surrounding areas. Also noted in the paper is that while there were 27 serious injuries and 10 fatalities in the 153 accidents examined, none of the personal injury was due to the radioactive properties of the materials carried.

Shappert [63] reports 30 incidents involving radioactive materials in transit during the 1968-1970 period in the United States. Half of these accidents resulted in the breach of package integrity, 10 of which involved the release of radioactivity. During this time period there were approximately 900,000 shipments of radioactive materials per year in the U. S.

More recent information on transportation accidents involving radioactive materials in the United States is summarized by Wolff [85]. This report compiles the results of three accident surveys performed by various researchers in 1975, 1980 and 1982 as well as incorporating later accident reports. The time frame covered is from 1971 through 1982. 123 transportation accidents were reported. Of these, 12 accidents or 10% resulted in the release of radioactivity due to failure of the packaging. Seven other accidents resulted in packaging failure but radioactivity was not released. The rate of accidents involving radioactive material was quite low since by 1982, 2 million shipments occurred annually. All packages that failed were classified as DOT Type

A packages or lower. (DOT Type A packaging is not required to withstand accident conditions.)

The potential for and the occurrence of this type of incident led to regulations for the packaging of radioactive materials for shipment, the placarding of vehicles and shipment documentation. The International Atomic Energy Agency prepared guidelines for standardized regulations in these areas [35] which were adopted by many member nations. Further experience with shipping incidents such as those related to the 1979 closure of waste disposal sites and concern for the potential consequences of catastrophic accidents caused regulations to be adopted in the U. S. controlling the physical form of the material shipped [74] and suggesting preferred routes for shipment [76].

Are these regulations warranted? Are more stringent requirements needed? Do the existing regulations address the goal of safely transporting radioactive materials? A computer code designed at Sandia National Laboratories (SNL) has proven useful in answering questions such as these. RADTRAN (version III is the most current) was written by Taylor and Daniel [72] to examine the environmental impact of transporting radioactive materials by air. It has since been used to model consequences for the shipment of materials ranging from spent fuel to radiopharmaceutical sources over a variety of transportation modes.

RADTRAN provides estimates for the expected radiological consequences due to incident-free transportation and accidents [33]. For accident scenarios, order-of-magnitude estimates of decontamination costs are calculated. The approach used is probabilistic. For example, a shipment may or may not be involved in an accident as determined by an imputed accident rate. In the case of no accident, (the most likely occurrence), the radioactive properties of the material being shipped are used to calculate the dose received by the population surrounding the transportation route. A health effects model estimates the latent cancer fatalities caused by the postulated whole body dose, based on the probability of occurrence of such effects. The consequences of an accident are determined by a given distribution of accident severity, the probability of the shipping container being breached, the fractions of material released and aerosolized, the dispersion of the aerosol based on a distribution of meteorological conditions and finally the health effects model to calculate the uptake of the contaminants by the surrounding population and the health effects experienced.

An interesting application of RADTRAN is described by McClure [35]. In this paper, McClure first chooses categories of LLW to ship, then uses RADTRAN to calculate constant unit consequence and unit risk factors for each shipment type. He chose a population distribution of 90% rural, 5% suburban and 5% urban for analysis. The unit consequence factor (UCF) is the exposure received during incident-free transportation of the chosen waste group over the distance of 1 kilometer. Similarly, the unit risk factor (URF) is the exposure per kilometer assuming an accident rate for the transport link. These factors have units of person-rem/kilometer, so multiplying by the distance shipped gives the expected population dose. In this way routes differing in length can be compared on a radiological basis. It seems that a useful extension to this method is to apply it to a detailed network, with measured input parameters of material shipped, accident rates, population density and segment length. This simulation of the flow of radioactive materials could then be used to route the shipments so that potential impacts are lessened.

Integrating Distinct Models or Methods

The goal of this research is to integrate disparate methods of analysis in areas such as routing algorithms, health physics, traffic safety and risk assessment to provide a basis for the selection of a low-level radioactive waste disposal site. While this has not yet been attempted, some examples of integrating analysis methods do exist.

In his overview of the transportation of radioactive materials, Wolff [36] provides values for unit risk and unit consequence factors for the radiological and nonradiological impacts of shipping radioactive waste. The set of radiological factors were calculated with RADTRAN, the nonradiological factors were calculated using a line source pollutant dispersal model and a health effects model.

Cashwell, Joy and McGuire [40] combine the routing models HIGHWAY and INTERLINE with a logistics model. The Nuclear Materials Transportation Logistics Model schedules shipments, optimizes destinations and packaging choices and calculates capital and operating costs. The combined models are used to generate spent fuel flow density maps of the United States under varying assumptions.

The transport of high-level waste (HLW) as studied by Neuhauser, et al. [41] provides an opportunity similar to LLW transportation for the integration of analytical methods. Again, HIGHWAY and INTERLINE were used to route HLW shipments based on minimized travel times. The demand for HLW shipments was calculated using a simulation model, WASTES. Capital and operating costs were modeled for both truck and rail transport modes. Finally, RADTRAN was used to provide unit risk and unit consequence factors for risk analysis. This analysis was performed after the shipping routes had been determined with the routing algorithms.

Voth [42] prepared a dissertation combining existing models to determine optimum LLW disposal site and technology combinations. In this research, candidate disposal sites were chosen throughout Pennsylvania. The environmental impact of each site was modeled with the EPA-PRESTO computer code. Transportation impacts were estimated by first categorizing waste shipments, using RADTRAN to determine unit risk and unit consequence factors for each category and then multiplying the unit factors by the distance between the appropriate generators and disposal site. The distances were estimated by the Pythagorean theorem applied to a Cartesian coordinate system.

Finally, Saccomanno and Chan [43] have studied alternative routing strategies for hazardous materials in Toronto. Three strategies were examined: minimize truck operating cost, minimize accident likelihood and minimize objective risk exposure. The operating costs included only the salaries and out-of-pocket expenses borne by the truck operator. Accident costs were ignored since they rarely occur and so are usually not part of the route decision process. The routes selected to minimize costs were those that would exist in an unregulated environment. They were used as bases for comparison.

Minimizing accident likelihood called for the consideration of two influences upon accident rates: deterministic effects and stochastic effects. The deterministic influences were mainly the geometric design characteristics of a given roadway link. The stochastic influences dealt principally in weather and visibility conditions. It was assumed that these influences were independent and that the probability of truck accident occurrence could be expressed as the joint probability of a truck accident for a given set of deterministic and stochastic influences. The accident probability for a route is the sum of the link probabilities.

The objective risk exposure, or absolute risk exposure, was defined as the product of the accident likelihood and the consequences of an accident. The consequences were determined by an airborne dispersion model for toxic materials, by the size of a flammable vapor cloud for flammable material and the blast effects of explosive material. The risk exposure was estimated for all possible stochastic conditions and the results summed for each route.

The city of Toronto was divided into eleven zones and the minimum path between each zone centroid was generated for each of the routing strategies. Minimizing operating costs resulted in the largest use of arterial roads at the expense of increased risk. Minimizing risk caused the central business district to be avoided and increased the use of expressways. Higher operating costs also resulted. Minimizing accident likelihood resulted in both increased costs and increased risk exposure in almost all cases.

Support for the Current Research

This literature review has shown that:

1. Routing algorithms exist,
2. These algorithms have been applied to shipment of hazardous materials with distance or travel time as the decision variable,
3. Attempts have been made at quantifying transportation risk through either relative or indexed measurements,
4. Some studies have combined routing hazardous or radioactive shipments and risk assessment,
5. No attempt has yet been made to use risk estimates as the decision variable in routing radioactive shipments.

Chapter 3

RISK and PHILOSOPHY

What is risk? Can it be measured? Is a certain level of risk acceptable or tolerable? Who is to bear the risks in life? These questions must be answered (or the attempt made) before proceeding.

Defining Risk

The common meaning of risk is exposure to danger or loss. Webster [82] defines risk as, "the chance of injury, damage, or loss; dangerous chance; hazard," injecting the element of probability into the formal definition. The magnitudes of the chance and the loss are left open for argument. Few of us have an intuitive feel for probabilities, instead events are viewed as black or white, if a risk is accepted we "expect" something to interfere with our plans or conversely we "expect" to succeed completely with the loss confined to "the other guy."

Statisticians have taken risk to a more neutral ground: they define risk as the expected value of all possible outcomes of an event [57]. The risk function is:

$$R = \Sigma p_i \bullet O_i$$

where:

p_i = the probability of occurrence of outcome i

O_i = the magnitude of the consequences of outcome i.

The summation is performed over all possible outcomes i.

This definition includes both positive and negative outcomes, that is, the expected value of a wager would include possible gains as well as losses.

The definition of risk used in the literature dealing with the risk of technology ranges from the popular to the statistical, depending upon the author's point of view and purpose. Langdon Winner [83,84] chooses to view risk strictly in terms of hazards. Nicholas Rescher [57] uses the expected value of all outcomes to define risk. William Lowrance [50] falls in the middle, believing that risk is best defined as a measurement of the probability and severity of the negative or adverse outcomes. How can the literature hold such a broad definition of risk? The answer appears to be two-fold:

1. The definition of risk is limited by the perception of risk.
2. The definition of risk chosen is the one which best supports the author's argument or purpose.

Perceived Risk

Perceiving is Understanding

Decisions are made by weighing alternatives with knowledge and experience as bases. A decision to take a risk is no different. Even impulsive decisions involving risk-taking are based on what we have learned. Darting across a busy street to buy a lottery ticket is not a random, baseless action. Senseless perhaps, but we *knew* that we would not find a parking spot across the street, we *knew* that we would not be struck by a car and though we *knew* we would not win the lottery, "Where else can I turn a buck into 40 million?" The gestalt of this situation is so strong that we recognize it immediately. No overt cognitive process need have taken place and yet, at some level, risks were weighed and a decision made. Imprinted upon our memory is that which we have learned, providing a basis for future behavior. In response to a stimulus, we sift through the memories, searching for a similar situation. More often than not, the decision reached will be based on the analogous experience. The decision-making process is colored by the stimulus received and the image retrieved, that is, our perception of the situation.

Judgments about possible outcomes of a situation are biased by experience. Lack of experience can cloud judgment. Still, experience remains the basis and so a memory may be stimulated which has no actual relation to the perceived situation. An extraordinary event like the explosion of the space shuttle *Challenger* might later be associated with an impending airplane flight, even though the two have almost nothing in common. The lingering image of the fireball hanging in the sky may cause an individual boarding a plane to perceive the risk of flying as much higher than it actually is.

Perceived risk may significantly differ from the "true" risk. Distortion may occur by assigning high probabilities to extremely rare events. Potential loss may be judged as severe when in fact, little is at risk. Any distortion in the perceived risk can lead to behavior which might be called irrational by an observer with a different perspective. (An omniscient observer would of course recognize the limits of human perception.) Whether irrational or not, the behavior follows from the perception of risk and so is justified teleologically if not morally. If there is disagreement between observers, it is the perception of risk and the knowledge base that should be examined for differences rather than the action taken as a result of the risk.

Perception versus reality of risk (defined as hazards of technology) is discussed by Zeigler, Johnson and Brunn [89]. They present a graph similar to figure 3, relating the perception of a hazard to the reality of the situation. In an ideal world, we would all live within the shaded squares along the diagonal, assigning to each risk encountered its "true" value.

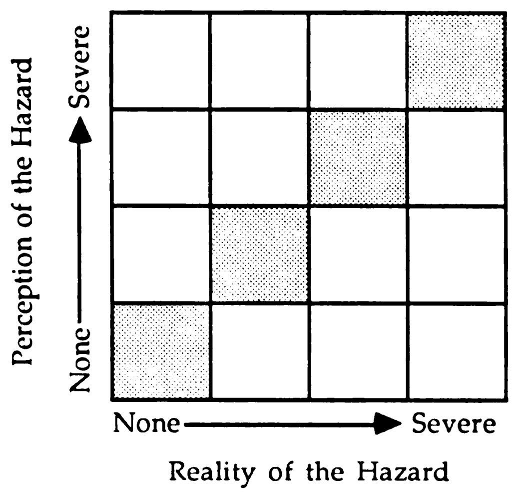

Figure 3. Perception vs. Reality

Of course this is not how the universe operates, some of us exist off the diagonal. Furthermore, the "true" risk may not be objectively knowable, in other words, the perception *is* the reality. The subjectivity inherent in perceiving, that is sensing and interpreting events, colors the reality of the situation even as the reality shapes the perception. Perhaps the graph would better reflect the situation if reality and perception were not depicted as independent (orthogonal) variables.

Nevertheless, instances of perception not matching "reality" do exist. Zeigler, et al. give examples. For the case in which the perception of risk was higher than necessary they mention the supersonic transport (SST) debate:

> The SST's impact on the earth's ozone layer was perceived in the early 1970's to be so severe that the technology was rejected by the U. S. Congress. Some recent evidence suggests, however, that high-flying SSTs may actually encourage the formation of ozone rather than breaking it down.

At the opposite extreme, in which the actual hazard is much worse than perceived, they cite the health effects of the Rocky Flats nuclear weapons plant:

> Johnson [42] used the plutonium content of the soil around the nuclear installation as a measure of cumulative exposure, 1953-1971. ...Exhaust from the plant's smokestack was the primary source of plutonium so that the configuration of the hazard zone is a function of wind direction and distance from the source. ...Johnson calculated the percentage of excess cancer deaths, 1969-1971. He found a higher incidence of all cancers near the plant and a decided distance decay effect with decreasing concentrations of plutonium. ...Had the residents around Rocky Flats recognized the true configuration of the contoured risk surface, measures might have been taken to further reduce the release of radionuclides from the smokestack ...

The authors conclude that public policy should be formulated first to draw risk perception versus reality to the diagonal of their diagram and second to reduce the zones along the diagonal toward the origin. In other words, policy initiatives should align the perception of risk with the actual risk and then the risks of technological ventures should be driven to zero.

My conclusions from this figure deal not with future policy initiatives but with the errors made in current policy decisions due to differences in perception and reality. If the reality of the risk is large where none is seen, the error is that a dangerous venture may be accepted resulting in unwarranted exposure to risk. On the other hand, if a risk is perceived as large when actually it is trivial, the error is that a worthwhile venture might be rejected or that effort is made to reduce an already minute risk. Alternatively, concentration on an overestimated risk can cause us to ignore issues with large inherent risk, especially those existing below the diagonal in Zeigler's diagram. Figure 4 summarizes the conclusions I have drawn from the work of Zeigler, Johnson and Brunn.

In either case the perception of risk has led to an error in judgment. Which area represents the worse error? What is risked by the faulty perception of risk? It seems that being below the diagonal might be a more immediate and perhaps fatal error. Erring above the diagonal appears to result in only economic consequences, but being above the diagonal may also lead to stagnation and stultification which, in terms of the human race, may be the more grievous error.

Perceiving is Sensing

To perceive also has the denotation of becoming aware through the senses and the ability or inability to detect a hazard with the senses certainly affects the perception

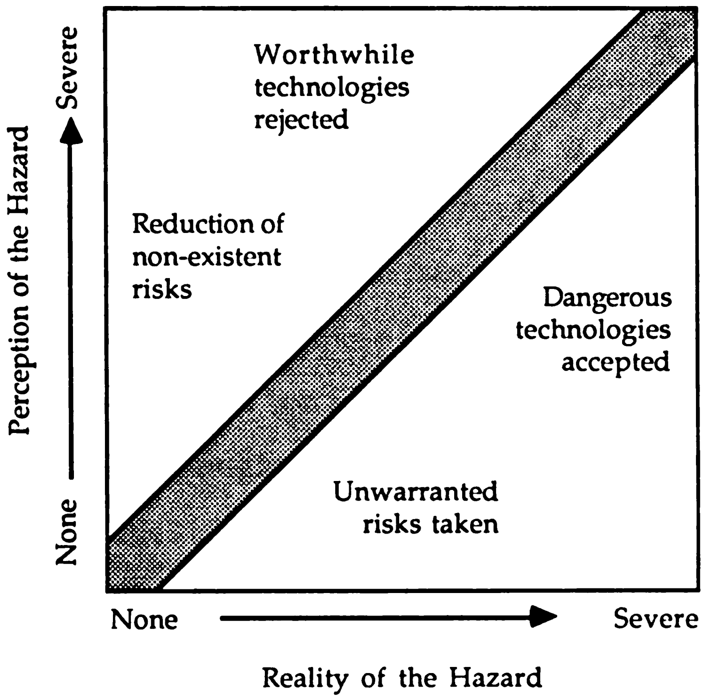

Figure 4. Errors Resulting from Incorrect Evaluation of Risk

of risk. This is one factor keeping any activity involving radiation in the realm of perceived risk exceeding real risk. Because we cannot directly sense the products of radioactive decay, we must rely on technology to provide the senses. The proper tool, properly used, will detect radiation, but are the tool and the technician to be trusted? This is the argument put forth by those perceiving the risk to be great, at least greater than that perceived by the technician. The perceptions here are still marked by experience, the technician deals with radiation and instruments daily and so is familiar if not comfortable with the risk. The nuclear opponent is dealing with a rare event or an abstraction, the only references available are Chernobyl and Three Mile Island.

Radiation is not the only subject leading to distorted perceptions of risk. Each year a number of welders or construction workers die because they entered an area with an oxygen-poor atmosphere. Their senses could not warn them that the oxygen had been displaced by argon (to prevent oxidation during tungsten inert gas welding), incapable of supporting life. Their sensory perceptions had skewed their perception of risk in the opposite direction, the perceived risk was much lower than the actual risk.

(It is this type of error in perception, thinking risk is lower than it really is, that provides the driving force for those who see risks as being greater than they actually are. In reaction to the fear of erring on the side of accepting more risk than originally thought, some individuals will give an event a large risk value where little risk is present. We fear too much the unfamiliar, we fear too little the familiar.)

Culture and Beliefs Determine Risk

To this point I have explained the nebulous nature of risk, how the concept varies with the definition used and the perception experienced. Next we will see how a person's beliefs and role within society form the basis for deciding what is a risk and what is not.

Cultural Perception

Douglas and Wildavsky, in their essay entitled **Risk and Culture** [18], repeatedly make the point that, "The perception of risk is a social process." They state that certain types of social structures stress particular types of fears or risks. Their argument is that society is formed through the organization of social relations. Organization implies choosing. Choice implies prioritization and ordering. Some things are of high rank and stressed, others are ignored because of their unimportance. This applies to all decisions made by a society, including the decision as to what should be considered risky. That is, a society selects the activities to be viewed with collective fear, it chooses its risks.

Douglas and Wildavsky give examples of cultures selecting their risks. For instance, they describe the Lele of Zaire. Although these people were often inflicted with terrible tropical diseases, they focused on the risks of being struck by lightning, suffering from infertility and being afflicted with bronchitis. Illnesses more severe than bronchitis and more likely to occur than lightning strikes are nevertheless regarded with less fear. Cultures choose their demons.

Relativism

The idea that risk or perception of risk depends on one's point of view is, of course, a relativistic approach. Relativism is apparent not only between cultures but also within a culture. To see this, we can employ one of Einstein's favorite techniques when dealing with relativity, the thought experiment.

Within our society, a person's economic or social condition may affect the perception of risk and the likelihood of accepting a risk. Someone living in poverty might accept a risk that would be unthinkable for a person of wealth, even if the two individuals have fundamentally the same beliefs and values. The difference in risk acceptance originates with the viewpoint. Suppose, for example, that an unemployed father of four is offered a job as a coal miner. He accepts the position to provide for his family. Suppose however that the position was first offered to the Chairman of the Board of General Motors. Does he accept the new challenge? Not likely. Interchanging the individuals, however, results in a swapping of risk acceptance behavior. Acceptance is relative to the situation.

The viewpoint also changes according to differences between value systems within a single culture. Douglas and Wildavsky [20] identify two distinct approaches to Western culture: the market and the bureaucracy. The first is populated by individualists, the second by those who are comfortable in a hierarchy. Risk acceptance again flows from the conditions. The bureaucrat's opinion of risk in a given situation may be very different from that of the small businessman.

If any risk acceptance behavior can be rationalized by calling upon relativism, is it possible to set aside a group of activities that may be considered "safe"? Or must we accept the lowest common denominator, that is, no activity is safe if any one person says it is not?

Cultural Consensus

Within a culture it is possible and necessary for a consensus to be reached. Agreement is needed on, at the very least, a range of acceptable risk-bearing activities. This returns us to the process of social organization proposed by Douglas and Wildavsky. Just as a culture can agree on what is to be feared, it can agree on which activities are acceptable. If an individual or

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group engages in activities excessively risky, then those involved can be removed from the culture in one way or another. In **The Calculus of Consent**, Buchanan and Tullock [3] show the mechanisms by which a society of diverse individuals can reach a consensus. They show that unanimous consent need not be reached as long as rules exist which allow social groups to bargain over "externalities" such as risk. Thus risk can be traded against insurance costs or another external cost to allow for agreement.

That agreement can be reached is empirically evident. Both the Lele and our own culture have been able to come to broad agreement within themselves as to the risks to be accepted and those to be avoided. To reach agreement, a wide range of viewpoints (economic, philosophic, social, religious, scientific, politic) need to be accommodated. Choices must be made.

Løvborg: "... and this book deals with the future."
Tesman: "With the future. But, good heavens, we know nothing of the future!"
Løvborg: "No; but there is a thing or two to be said about it just the same."
Henrik Ibsen. **Hedda Gabler**. 1890, Act II.

Choice and the future are inescapably linked, to choose is to decide along which path the future lies. Each of us has a view of the future colored by our beliefs and views. That is why a workable consensus on any topic including risk can follow only from consideration of the viewpoints mentioned above. To ignore any of these viewpoints is to ignore the picture of the future held by part of society, with a resulting lack of support for any decision made. The need to consider a society's collective view of the future before choosing its course may help explain the differences between cultures, our view of the future differs from that of the Lele, and so the risks we choose to worry about differ.

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Cultural Issues to Resolve

A number of issues recur in our intracultural negotiations on risk. These issues spring from the perspective each discipline brings to the negotiation. Control over the acceptance of a risk, distribution of the risk imposed, measurement of risk, the desired socio–political structure and decision–making process, the value of a life, the value of a species, the role of technology in our lives; these are some of the recurring issues to be argued and negotiated. These issues are intricately entwined, woven into a fabric of cultural transactions. The control over risk acceptance, the equity of risk distribution and the role of technology are tied in with the type of socio–political structure employed. The decision–making process influences how risk is measured and what value is to be placed on the outcomes of an activity. The interactions involved are complex and cannot be severed.

Control and Voluntary/Involuntary Risk

The issue of control over the acceptance of a risk follows from the argument that some risks are imposed involuntarily and that these risks are inherently different from those freely accepted. Evidence exists showing that the sense of control over a situation or choice influences the magnitude of risk accepted [61,69,70]. The risk of death or injury due to voluntary activities (smoking, occupation, driving, etc.) are an order of magnitude or more greater than the risks due to involuntary hazards (floods, volcanoes, lightning, etc.). Control of the decision, that is, conscious consent to an activity apparently causes us to be more receptive to risks than if the risk is imposed by an outside force. Seemingly, accepting the authority of the decision leads to acceptance of the responsibility for the outcome. Does this mean that if we were in control of floods and tornadoes we would accept

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greater risk from them? Do we actually accept the possibility of a hazardous outcome from a decision we make? I do not think this is the case. I believe instead that each of us truly feels that no harm will come to us due to our decisions. Only favorable outcomes are acceptable to us, even if we are fully aware of the hazards before we decide. Unfavorable outcomes are unacceptable and are the responsibility of others (e.g. government, a corporation, another individual).

Judith Jarvis Thomson [73] supports this argument through an example she gives in "Imposing Risks." Imagine there are two routes home from work. One is a long, safe walk through a brightly lit middle-class shopping area. The other is a short walk along Unpleasant Way, through a poorly lit warehouse district known to be infested with muggers and other assorted reprobates. Thomson places herself in the example and knowing the risks involved, decides to walk through the warehouses because the longer walk would be too tiring. No duress, compulsion or coercion is felt while deciding. Of course, upon entering Unpleasant Way she is immediately mugged. She asks if she should not have grounds for complaint if not against the city then at least against the mugger. She holds that she did not consent to being mugged by an individual or to the imposition of risk of mugging by such a person. She contends that she did not consent to the dangerous nature of Unpleasant Way at night nor did she consent to the case that if she walks Unpleasant Way at night she is placed in risk of being mugged. Thomson instead says that she consented only to walking Unpleasant Way at night, even though she knew its danger. In other words, she is willing to accept the responsibility for the outcome only if it is favorable, if she gets mugged then it is proper to blame the mugger or the city.

This is precisely the behavior I referred to earlier, denial of responsibility if the untoward happens, acceptance of responsibility if and only if the outcome is what we wanted. This behavior is exhibited by both individuals and bureaucracies. A cigarette smoker wonders, "Why me?" when the diagnosis is terminal lung cancer. A gambler asks why he wasn't stopped by management before losing his life savings at the Las Vegas craps table. A speeding driver spends the rest of his life in a wheelchair because the road commission did not install a guard rail to keep him from hitting the bridge at 90 miles per hour. This type of behavior is not rare and isolated, it is the order of the day. In **Catch–22**, Yossarian vowed to live forever or die trying [29]. It is all any of us can hope to do. None of us truly accept our mortality, a few perhaps are resigned to it. The issues of control, voluntary risk or involuntary risk are merely constructs enabling us to rationalize away our own responsibility for our losses. My conclusion is that the debate over control, voluntary versus involuntary only touches the surface and draws attention away from deeper, more productive discussion.

Douglas and Wildavsky [19] also regard the debate over control as specious: "Voluntary/involuntary is a movable boundary, capable of turning every constraint on choice into injustice." That is, the person, the culture and the person's situation within the culture determine what is regarded as a voluntary or involuntary risk. The rich might consider air pollution an involuntary risk but the poor may find industrial pollution more acceptable than being unemployed. Douglas and Wildavsky find that, "Either involuntary risk is an empty logical category, or it has to be a complaint against the particular social system which gives some people a harder life."

Douglas and Wildavsky hold that the distinction between voluntary and involuntary risk can be made only if the cultural structure is stagnant, frozen for all time. If that is the case then all activities, risk-generating or not, are predetermined by the structure and so every activity is involuntary. Douglas and Wildavsky reduce this argument to its absurd conclusion using a society modeled after ours, but possessing a petrified social system. Any risk that is involuntary and unjust would be relieved by law. Because all risks could be regarded as involuntary, all responsibility would be treated this way until all losses are compensated by the society's institutions. The culture is responsible for all actions, the individuals are not.

I disagree with Douglas and Wildavsky's interpretation that all risk is voluntary within a culture's set of rules in only one particular case. Hazards that are greatly displaced in time from the initiating event seem to fall into the involuntary category whether or not society tries to represent the views of future generations in social transactions. Recall Løvborg's statement in **Hedda Gabler** bear in mind however that the future cannot disagree with what we say about it. The decisions of today present future generations with a *fait accompli* and we have no way of knowing whether our interpretation of their wants and needs is correct. Will they judge as we do conditions that we believe are acceptable? Or will they find our decisions to be totally wrong? Future generations cannot represent themselves today in our cultural negotiations and have no way of correcting our mistakes. As an example, perhaps we should have taken the opportunity presented by OPEC to eliminate the use of petroleum products as fuel, reserving those products for petrochemical production now and in the future. Not doing this may place future generations at risk with respect to materials necessary to support their lives in exchange for an economical means of supporting our lives.

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Distribution of Risk

The distribution of risk is closely tied to both the social structure and the chosen boundary between voluntary and involuntary risks. Zeigler, et al. [90] show the geographical distributions of some risk-bearing activities. One set of maps show that hazardous material incidents are highly correlated ($r = 0.83$) with population distribution on national and state levels. On the surface this appears to be an equitable distribution of "involuntary" risk. An individual's exposure to this risk is roughly uniform, independent of location. Categorizing the incidents by type reveals another factor for consideration, low population areas were more likely to see transportation incidents while high population areas were exposed to a higher rate of handling and processing incidents. So, policies designed to lower the rate of industrial incidents while ignoring transportation would cause the distribution of risk to skew to lower population areas. Public policy affects the distribution of risk.

At the local level, the incidents were strongly correlated ($r = 0.73$) with the location of industry. The risk passes from involuntary to voluntary at this level of detail, industrial workers "choose" to accept the risk as part of the job whereas a member of the general populace probably did not choose to live near a hazardous stretch of railroad track involved in a derailment of chlorine tank cars. Working at the local level, it might be decided that nothing should be done to reduce the number of incidents because the risk is borne by those gaining the benefits of the associated activities.

Another map reproduced by Zeigler, et al. projects the distribution of fallout in the United States following a nuclear war. The low population density region of the Plains States is subjected to a disproportionate risk of fallout because of the prevailing winds and the concentration of strategic military bases in the region, that is to say, targets. The ultimate price of defense appears not to fall equally upon the citizens of this country. The socio-political structure has placed the residents of the Plains States at risk in return for greater security for the country.

A final diagram illustrates how technological hazards can be displaced in time as well as space. Figure 5 is derived from Zeigler, et al. [91]. Technology A is displaced in both time and space from the hazard it generates. Technology B is displaced in time only, while technology C is displaced in space only from its hazards. Technology D exhibits displacement in time and space by varying degrees. The hazard associated with technology E is experienced at the same place and time occupied by that technology. Displacements of either type can lead to conflict. As mentioned earlier, temporal dislocation can place unwarranted burdens on future generations. Spatial displacement leads to the issue of risk distribution.

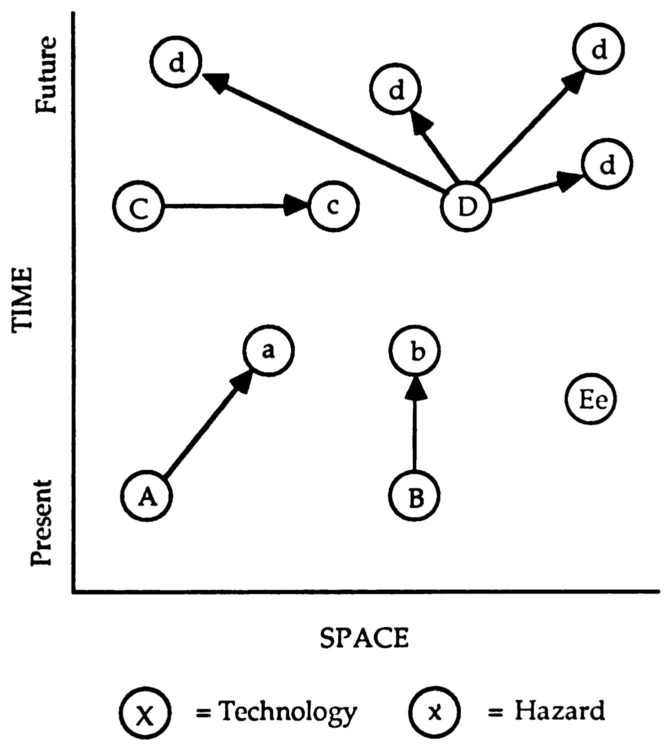

Figure 5. Displacement of Hazards in Space and Time

These examples show the interaction among the various disciplines (political science, engineering, philosophy, ...) needed to resolve the issue of risk distribution. The social imperative draws people together into communities. Economics causes industries to be clustered near the population served, just as those industries act as magnets drawing people to them. Science gives us the techniques to build the industries and mitigate accidents. Politics and economics close some paths opened by science while allowing others to remain open. Political pressure places hazardous activities in areas of low population because they are far removed from the coasts or simply because the population is low or to attract industry and population to the area. Enumerating the interactions might take forever and still leave the questions of how, why and to whom risk is distributed unanswered. To deal with these questions it is necessary to place them in a cultural context.

Just as voluntary/involuntary is a movable boundary, the equity/inequity boundary varies with the circumstances. In fact the question of equal distribution of risk depends upon the boundary set for voluntary/involuntary risk. It makes no sense to speak of the equal distribution of voluntary risk, equity presupposes involuntary risk. An individual exposed to what he would consider an involuntary risk does not want to be singled out for exposure. Better still would be no exposure, whether his neighbor's exposure is relieved or not. (In other words, he would like to be a "free rider" and not be exposed to the risk while still gaining any benefits associated with the risk–generating activity. "Not in my back yard!" is the slogan of the free rider.) As an example, a wealthy individual might find a vacation home on Florida's Gulf coast enjoyable, that is until a hurricane destroys it. Not as enjoyable would be rebuilding it with his own funds, federal disaster relief would be a much better system of paying for repairs. Of course, if his investment position allowed him to escape taxes, then so much the better, as long as the factory line–workers in the north continue to pay theirs. Clearly the situation is asymmetric, the vacationer's judgment on equity of risk distribution would undoubtedly reverse if the situation was reversed and it is unlikely that the northern factory worker would ever say that the risk was distributed equally if any relief program is established. Once again, the culture, the person and the person's status within the culture determine what is or is not an equitable distribution of risk.

The Desire to Shape Society

Arguments over the voluntary versus involuntary nature of risk or over the distribution of risk throughout society are merely smoke screens. The real issue is this: who decides; who shapes the future; who wins. Behind every risk debate, on any side of the debate, is a hidden agenda. The arguments put forth by each side of the debate are molded by the beliefs of that side, by their desire to see society fit those beliefs and by their vision of the path leading them to this promised land.

Are there no neutral observers of life? No dispassionate jurors waiting to decide our fate? No indifferent and aloof navigators charting the course to the future? Quite simply, there are not. As Wordsworth [86] said, "The Child is father of the Man," and so each of us brings to the debate on risk our acquired learnings and beliefs. The arguments we put forth reflect these beliefs, the decisions we make support our beliefs. Like Heisenberg, we are forced to realize that no neutral observer exists, the very act of observing affects the system being observed. Societal values and our own values for society affect our perception of risk which, in turn, affects societal values. How risk is to be measured and the units of measurement to be used are also affected. The viewpoints taken in the risk debate are not pure and absolute, instead they are infected by the debators' beliefs about the past and their desires for the future. The desire to create a society attuned with our beliefs fixes the stand each of us takes in the debate on risk.

Vivid examples of this assertion exist. During the 1970's, in the midst of the energy crisis, a vituperative debate on the future of energy sources ran between proponents of coal and nuclear power and proponents of renewable energy sources. Lovins [48,49] coined the term "soft energy" for renewable energy sources, painting the technology as warm and cuddly, easy to build, use and maintain. His future world was decentralized, with people living near their food supplies and jobs, using little energy, staying at home and being perfectly happy. In his analysis of the risks of this lifestyle he not surprisingly found the major risks to be from the technologies and lifestyles currently practiced. In his studies however, Lovins chose to ignore some sources of risk and uncertainty, such as the use of toxic materials in photoelectric cells or the risk due to frequent interruption of power, issues that would not support his claims. Coal and nuclear proponents were quick to pick up the gauntlet, Inhaber [33,34] recalculated the risks of renewable and conventional energy sources and found that renewable energy sources had risks that were orders of magnitude greater than almost all conventional sources. Inhaber reached this conclusion by including in his analysis the materials used for construction of energy sources, labor and transportation accidents and an allowance for the loss of power due to the intermittent nature of renewable sources. Inhaber, then an employee of the Atomic Energy Control Board of Canada and later with Oak Ridge National Laboratory, concluded that centralized energy production and distribution systems were to be favored. Holdren et al. [31,32] responded by claiming that

Inhaber placed too much emphasis on the risk of losing power and that Inhaber's solution of having coal backup systems for the renewable sources created most of the risk due to renewables. The debate continued with both sides choosing to ignore risks or methods injurious to their cause. No one ever suggested that perhaps a combination of technologies would produce both lowered energy use and reduced risk. Such an idea would have been antithetical to both sides, a hybrid social and technological structure was unacceptable.

Winner [83] would have advised Lovins and Holdren, ". . . to think twice before allowing the concept [of risk assessment] to play an important role in their positions on public issues." Winner prefers to speak in terms of hazards rather than risks since hazards can be agreed upon [84]. By way of example, he states that New Englanders, "are under no obligation to begin analyzing the risks of acid rain; they might . . . confound the experts by talking about 'that destructive acid rain' and what's to be done about it." Since his beliefs do not support the type of risk analysis performed by Lovins, Inhaber and Holdren, that is the weighing of costs versus benefits of an activity, Winner is able to eliminate an entire side of an issue. In Winner's version of the world, the hazard of unemployment for people in the Ohio Valley is not an issue of concern to New Englanders being rained upon.

Lowrance [50], Rescher [57], Shrader–Frechette [64] and Fischhoff, et al. [25] all believe that risk assessment in one form or another is useful. The form of risk assessment generally supported in the literature is cost-benefit analysis or risk-benefit analysis. As alluded to earlier, this formal analysis weighs the benefits of an activity against the costs of that activity. The sources of conflict are immediately apparent, the benefits and costs must be defined, units of measurement agreed upon, weighting factors determined, methodologies confirmed, models calibrated and on and on. The scope of this task is an endorsement for Winner's argument, for the sake of simplicity if for no other reason. Furthermore, no amount of calculation will assuage the anxieties of those biased against the questioned activity in the first place. Another bias which can not be overcome is that held against the group performing the assessment, whether that group is a bureaucracy or a business. Yet, for all of this, risk assessment has become widely accepted and practiced within our technological culture. This is because risk assessment as practiced today tends to support the status quo, just as Winner states [83]. The hand sculpting society seeks tools which will complete the work as envisioned by the sculptor, not as envisioned by the critic.

Is it possible for risk assessment (or any technical method) to be neutral and objective? Invoking Einstein and Heisenberg again, we realize that just as there are no neutral observers, there are no neutral analysts. Fischhoff, Lichtenstein and Slovic [24] address this question indirectly while searching for "acceptable" risk:

> That choice depends upon the alternatives, values, and beliefs that are considered. As a result, there is no single all-purpose number that expresses "acceptable risk" for a society.
>
> Values and uncertainties are an integral part of every acceptable risk problem. As a result, there are no value-free processes for choosing between risky alternatives. The search for an "objective method" is doomed to failure and may blind the searchers to the value-laden assumptions they are making ...
>
> Not only does each approach fail to give a definitive answer, but it is predisposed to representing particular interests and recommending particular solutions. Hence, choice of a method is a political decision with a distinct message about who should rule and what should matter.

Shrader–Frechette [65] examines the ethical and philosophical aspects of positivism (i.e. complete objectivity and neutrality) and concludes that such behavior is not only impossible but that it is not desirable in risk assessment and so should not even be attempted.

Where Does All of This Lead?

If objectivity and neutrality do not exist, if the definition of risk depends on who is doing the defining, if our beliefs and desires shape our evaluation of risk, is there any point in dealing with risk and risk assessment as research methods? Can meaningful research be performed with risk assessment as its basis? I think the answer to both questions is yes.

To clarify the issues surrounding the use of risk and risk assessment, Shrader–Frechette [65] recommends that four elements be added to risk or technology assessment methods:

1. Explicit admission of the methodological, ethical, factual, and theoretical assumptions upon which the technology assessment (TA) or environmental-impact analysis (EIA) conclusions are contingent;
2. Use of much broader and much more varied social indices;
3. Employment of an adversary system of TA and EIA;
4. Evaluation of alternative philosophical positions on various policy options.

When dealing with risk and risk assessment, the basis for decision must be kept in mind. Following Shrader–Frechette's first recommendation, this basis should be stated directly, as with any other assumptions affecting the results of an analysis. No apologies need be made for the basis used.

When confronted with work in the area of risk in which assumptions are not explicitly stated, it is not unreasonable to be skeptical, to search for the hidden agenda behind the results. This is not to say that such results should be ignored or discounted, only that the path leading to the results may be as important as the results themselves.

Guidance concerning the use of risk assessment may be obtained from Douglas and Wildavsky [18]. They view risk as the "joint product of *knowledge* about the future and *consent* about the most desired prospects." (Italics in original.) From this they derive a matrix (figure 6) outlining four problems associated with risk and the avenues to solving the problems.

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CONSENT	KNOWLEDGE: Certain	KNOWLEDGE: Uncertain
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Contested	Problem: **Disagreement** Solution: **Coercion or Discussion**	Problem: **Knowledge and Consent** Solution: **?**

Figure 6. Four Problems of Risk

If consent exists, then risk assessment appears to be a viable and appropriate tool, within the limits of knowledge. It is when consent does not exist that risk assessment fails as a tool and instead becomes an issue of debate, part of the problem rather than part of the solution.

Following the course set by Shrader–Frechette and Douglas and Wildavsky, the use of risk assessment techniques to site LLW repositories is appropriate. The final section of this chapter lists the basis for this conclusion.

Basis for the Current Research

This research is based on the premise that consent has been reached concerning both the need to dispose of LLW and the need to maintain industries and facilities that generate the waste. This consent springs from the Congress of the United States as seen in the Atomic Energy Act of 1954 and the Low Level Waste Policy Act of 1980.

Consent has also been reached on the risks of radioactivity. The International Commission on Radiological Protection and the National Academy of Sciences provide methods for assessing those risks [12,26,35,36,37,38,39,40,66,79].

The assumption is made that the risks due to contact with radioactive material and the costs of transporting such material can be stated in terms that will allow the risks and costs to be combined.

Finally, the philosophical framework for this research is utilitarianism–to seek and choose the course of action that promises the greatest good for the greatest number.

Chapter 4

RESEARCH METHODS

Overview

The method to be used in assessing the risks and costs of transporting LLW consists of four major subcomponents: a LLW shipment inventory, a transportation network description, a radiological risk assessment model and the optimization algorithm. The first two subcomponents are data sets. This chapter gives in general terms the parameters needed to describe the LLW shipment inventory and the transportation network. Data specific to the Midwest Interstate Low Level Radioactive Waste Compact (MILLRWC) are contained in appendices. The second pair of subcomponents are analytical methods, using the data contained in the LLW inventory and the transportation network. The risk assessment model and optimization algorithm are described in detail in this chapter.

Low-Level Waste Shipment Inventory

The parameters needed to describe LLW shipments in a region are largely dictated by the requirements of the risk assessment model and the optimization algorithm. These parameters are:

1. Generator Location: The geographical location of the LLW generators in the region.

2. Waste Form: The form of the waste generated at each site (e.g. irradiated reactor components, immobilized scintillation liquid, compactible waste, etc.) and shipped for disposal. The packaging requirements are useful for distinguishing between waste forms (e.g. shielded cask, LSA box, etc.).

3. Isotopes Shipped: The isotopes contained in each waste form listed above.

4. Volume Shipped: The volume of each waste form shipped annually.

5. Annual Shipments: The number of annual shipments of each type of waste form or package.

6. Curie Content: The quantity of Curies of each isotope per shipment by waste form.

This data can best be obtained through a survey of the generators in a region. Some broad surveys have been performed in the past by various federal or state government agencies, but generally these do not provide the level of detail needed. These surveys also do not usually reflect the volume reduction programs implemented or planned by many generators. Surveys performed by the regional compacts will be more likely to contain current data and the level of detail needed by the optimization method described in this chapter.

Some of the necessary waste shipment parameters may be derived from others. The number of annual shipments may be obtained from the annual volume by using the average truckload for each shipment type. The

Curie content per shipment may be estimated by the average shipment content of each waste form, or perhaps based on another factor, such as the greatest quantity expected to be in a single shipment.

The risk analysis model requires the identification of the waste forms (package types) and isotopes shipped. The optimization algorithm uses the results of the risk assessment model in conjunction with the generator location, the Curies shipped and the number of annual shipments in the routing of shipments.

Appendix A presents the LLW shipment inventory for the MILLRWC as obtained through a survey conducted by ERM-Midwest, Inc.

Transportation Network

As with the shipment inventory, the parameters necessary to describe the transportation network are primarily dictated by the risk assessment model or the optimization algorithm. The network parameters required are:

1. Node Identification: Identify and geographically locate each node on the network.

2. Link Identification: Identify connections between nodes.

3. Link Length: Distance between linked nodes.

4. Population Density: The population density surrounding each link. The area within 5 kilometers of each link is used to calculate the density.

5. Population Density Classification: Classify link as urban, suburban or rural. The risk assessment model makes use of this system of classification as well as requiring a representative value of population density (mean, mode, etc.) for each class.

6. Commercial Vehicle Accident Rate: The rate of accidents involving commercial vehicles on each link expressed as number per commercial vehicle per unit length.

Nodes, links and link lengths can be obtained from maps. The most likely source for the remaining information is the Department of Transportation in each of the states spanned by the network. If necessary, commercial vehicle accident rates can be estimated using average daily traffic counts, total accident rate and the percentage of commercial vehicles on each link. Population density can be obtained through the Census if it is not available from the state department of transportation although some interpretation of the data may be needed since Census tracts as a rule do not match the 5 kilometer boundary around the routes.

All of these parameters are used by the route optimization algorithm. The values for population density in the three classifications are used by the risk assessment model as is the commercial vehicle accident rate.

The data used to model the MILLRWC are contained in appendices B and C; appendix B holds the node data, appendix C the link data.

Radiological Risk Assessment Model

The model used in this research to assess radiological risk is derived in large measure from RADTRAN III [51] which has been developed over the last decade by Sandia National Laboratories. Some of the techniques used in RADTRAN III are duplicated in the following model while other of RADTRAN's methods have been rejected in favor of alternatives. Techniques developed elsewhere are appropriately referenced.

To accurately model radiological risk requires detailed knowledge about specific situations and exposures, a condition that is impractical if not impossible to deal with on even a limited basis. Accordingly, a number of assumptions have been made to simplify the risk assessment problem, these are noted as they occur. These simplifications cause an increase in the unc

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uncertainty of risk magnitudes but the basis for comparison between risk measurements remains.

Risk Modeled by Exposure

The assessment of radiological risk is based upon the exposure of individuals in a population to a radiation source. The source may be outside the body resulting in an external dose (in the case of gamma radiation this is called the whole-body dose) or the radiation source may be ingested or inhaled resulting in an internal exposure. The frequency of health effects (somatic or genetic) caused by either type of exposure is generally accepted to be proportional to the dose received [12], that is, the probability of a particular health effect is a linear function of the exposure. The precise relationship depends on the source and type of exposure and the particular health effect to be measured, but in general, the risk of incurring an undesirable health effect due to radiation can be estimated by knowing the radiation dose received. Dose or exposure is a surrogate measure for risk when dealing with the health effects of radiation.

Risk as measured by exposure can be applied on an individual or population basis. Individual response to a given exposure varies, there is a distribution of responses if the same dose is received by a number of persons, especially if each exposure is small. As a result, dealing with individual exposures leads to significant risk uncertainties. The population dose response (the sum of the individual doses) is less subject to these uncertainties, even when the individual exposures are small. So, population dose (in units of person-rem) will be the parameter used to model radiological risk in this method.

Overview of the Radiation Exposure Model

To estimate the population exposure and thus the risk due to the transportation of LLW, unit risk factors (URF) will be developed for each of the isotopes noted in the LLW shipment inventory as described above. The dimensions of URF are person-rem per unit distance. Only the isotopes shipped in large quantities need be considered and of those, only the strong gamma emitters (> 10 KeV per disintegration), the internal-dose-significant beta emitters (^{90}Sr), and the alpha emitters will produce significant exposures. As in RADTRAN, two transportation situations will be modeled, accident-free transportation and shipment involving an accident. To simplify the process, only three shipment package types (casks, drums and boxes) will be modeled. Each shipment will be assumed to consist of one truckload of the particular package type. The volumes per truckload are: cask, 5 m^3; 55 gallon drums, 16 m^3 and LSA boxes, 27.5 m^3. Constant and uniform population densities will be assumed for each of the three types of population zones.

As seen in figure 7, each combination of isotope, package type and population density will be analyzed by two exposure models: accident-free exposures and accident exposures.

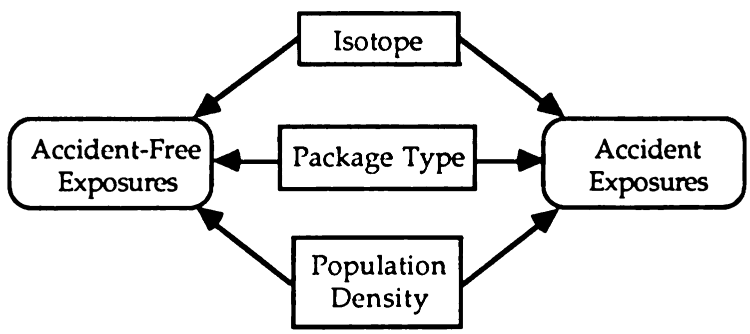

Figure 7. Model Outline

The accident-free portion will examine the exposure to three population segments: persons along the shipment path, the vehicle crew and those persons sharing the transportation link with the shipment. Figure 8 provides a summary of the accident-free model.

The accident exposure section calculates the exposure for two cases: accidents in which the radioactive material is contained within its Type B package and accidents in which the containment provided by a Type A package fails and the material is dispersed to the atmosphere (figure 9).

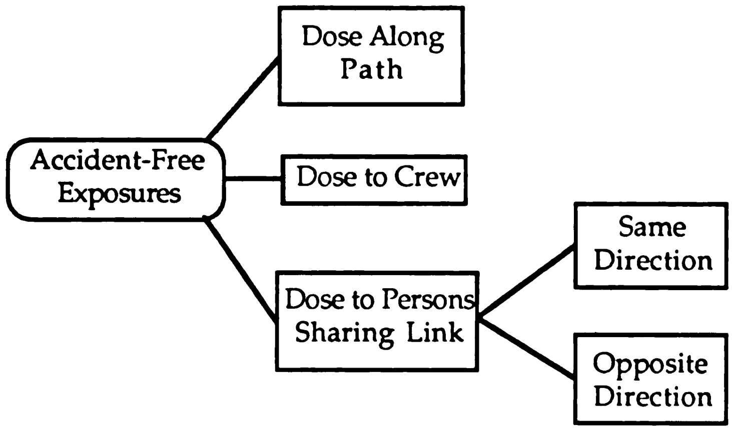

Figure 8. Accident-Free Exposures

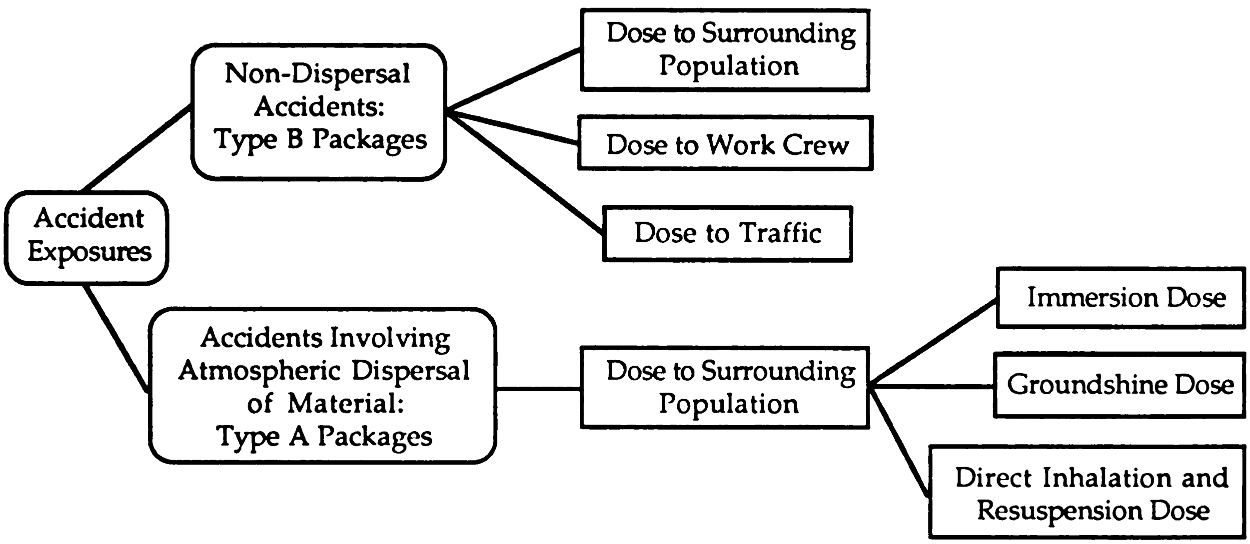

Figure 9. Accident Exposures

For the non-dispersal accident, the dose is calculated for the surrounding population, the recovery crew and persons in vehicles passing the accident scene. In the case of an accident involving dispersal of material, the dose to the downwind population is estimated by modeling the whole body dose due to immersion in a radioactive cloud, the whole body dose caused by radioactivity deposited from the cloud onto the ground and the internal dose from inhaling the material in the initial cloud and the material resuspended by wind or other means. Since the material is assumed to be completely dispersed and only relatively small quantities of LLW will be modeled, the dose to a recovery or decontamination crew has been neglected in the dispersal accident dose estimation.

Both models will be described in detail in the following sections.

Accident-Free Exposure

As in RADTRAN, accident-free exposure will be estimated by representing each shipment as a point source. All exposures in the accident-free case will be external, so only gamma emitting isotopes are studied. The dose rate at distance r from a point gamma source is given by the inverse-square law:

$$DR(r) = \frac{S_p}{4\pi r^2} \bullet e^{-\mu r} \bullet B(\mu r) \bullet \frac{1}{\varphi_E} \quad (1)$$

Where: $DR(r)$ = Dose Rate at distance r from source

S_p = Source photon emission rate

$S_p/4\pi r^2$ = Flux at distance r

μ = Attenuation coefficient for intervening medium

$e^{-\mu r}$ = Attenuation factor for thickness r of medium

$B(\mu r)$ = Dose-rate buildup factor in medium at distance r

φ_E = Flux to dose rate conversion factor for γ energy E.

The product of the attenuation and buildup factors, $e^{-\mu r} \bullet B(\mu r)$, is a function of the energy of the photon, the medium through which the photon passes and the distance to the receptor. In this research, the intervening medium will be limited to air. Appendix D shows that in air, $e^{-\mu r} \bullet B(\mu r)$ is approximately 1 to a distance of 50 m for 0.5 MeV and 1 MeV photons. These factors can be ignored when calculating dose rates at distances of 50 meters or less. At distances greater than 50 m, the effect of attenuation and buildup can be represented by $K_E(r)$, defined as the ratio of the dose rate with attenuation and buildup to the dose rate neglecting these factors. $K_E(r)$ values are calculated in appendix D for distances from 100 to 800 meters at 0.5 and 1.0 MeV. The dose calculations in this research fall into two categories: receptors less than 50 m from the source for which $K_E(r) = 1$ and receptors out to a distance of 800 m. Since r = 800 meters, it will be unambiguous to refer to the attenuation and buildup factor as simply K_E. From appendix D, $K_{E<0.75} = 0.21$, $K_{E\geq 0.75} = 0.30$.

With this simplification equation (1) becomes:

$$DR(r) = \frac{S_p}{4\pi r^2} \bullet \frac{K_E}{\varphi_E} \qquad (1a)$$

or, letting the constant $k = S_p K_E / 4\pi\varphi_E$:

$$DR(r) = k/r^2 \qquad (1b)$$

Dose Along Path

The dose to persons along the transportation path is modeled by the point source traveling at a speed v by a person located at a perpendicular distance x from the path. References 51 and 78 give the dose at distance x along the path as:

$$D(x) = \frac{2k}{v} \bullet I(x) \qquad (2)$$

Where: $k = S_p K_E / 4\pi\varphi_E$

$$I(x) = \int_x^\infty \frac{dr}{r \bullet (r^2 - x^2)^{0.5}} = \frac{\pi}{2x}$$

I(x) is integrated from the shortest perpendicular distance to the source, x, to the longest, ∞, representing the dose received at x during the approach of the source. The factor of 2 accounts for the source returning to an infinite distance. Substituting for I(x) equation (2) becomes:

$$D(x) = \frac{k \bullet \pi}{v \bullet x} = \frac{S_p \bullet K_E}{4 \bullet \varphi_E \bullet v \bullet x} \tag{2a}$$

The total dose along the path is calculated by integrating D(x) over the range of distances of concern, that is from a distance to be considered the minimum reasonable value for x to that distance at which the inverse-square law causes the dose rate to become negligible. The minimum distance d_{min}, from a roadway at which an individual might be found probably depends on the population density classification; in an urban area, 5 meters seems reasonable while in rural areas 50 meters may be a better estimate. Since the method will be used for all population zones, I will use the smaller value, 5 meters, for d_{min}. The maximum distance d_{max}, will be 800 meters (0.5 miles) at which the dose rate is about 10^{-6} times its value at 1 meter.

The definite integral then must be multiplied by a factor of 2 to account for both sides of the road, by the population density PD_i, of the area surrounding the link and by a units conversion factor Z. The total dose along the path is expressed as:

$$D_{path} = 2 \bullet Z \bullet PD_i \bullet \int_{d_{min}}^{d_{max}} D(x)\, dx \tag{3}$$

$$D_{path} = 2 \bullet Z \bullet PD_i \bullet \frac{S_p \bullet K_E}{4 \bullet \varphi_E \bullet v_i} \int_{5m}^{800m} \frac{dx}{x} \tag{4}$$

$$D_{path} = \frac{Z \bullet PD_i \bullet S_p \bullet K_E}{2 \bullet \varphi_E \bullet v_i} \bullet \ln\left(\frac{800m}{5m}\right) \tag{5}$$

$$D_{path} = \frac{2.54 \bullet Z \bullet PD_i \bullet S_p \bullet K_E}{\varphi_E \bullet v_i} \quad (6)$$

Note that the shipment velocity has been given the subscript i to allow the speed to vary with population density class i. (Three types of population density zones are used: urban, suburban and rural.) To complete the derivation, the conversion constant Z needs to be defined by unit analysis. D_{path} will actually be used to estimate unit risk factors and so the desired units are person-rem/km. PD_i has units of persons/km^2. S_p is given in photons/second. φ_E has units of rem/hr per photon/sec-cm^2. The shipment velocity v, is in km/hr. Combining these factors results in:

$$\frac{\text{person-rem}}{\text{km}} = \frac{\frac{\text{persons}}{\text{km}^2} \bullet \frac{\text{photons}}{\text{sec}} \bullet \frac{\text{rem}}{\text{hr}}}{\frac{\text{km}}{\text{hr}} \bullet \frac{\text{photons}}{\text{sec} \bullet \text{cm}^2}} \bullet Z \quad (7)$$

Z must have units of km^2/cm^2, and so $Z = 10^{-10}$ km^2/cm^2.

Since URF's are being estimated, it seems reasonable to assume that the source S_p has a strength of 1 Curie = 3.7×10^{10} disintegrations/second. By also assuming that the energy of decay for the isotopes in question can be represented by 1 photon of the appropriate energy per disintegration then $S_p = 3.7 \times 10^{10}$ photons/sec. The energy E, used to look up the flux to dose rate conversion factor φ_E, is the total energy per disintegration. D_{path} for a URF simplifies to:

$$D_{path} = \frac{2.54 \bullet 10^{-10} \bullet PD_i \bullet 3.7 \bullet 10^{10} \bullet K_E}{\varphi_E \bullet v_i} \quad (8)$$

$$D_{path} = 9.4 \bullet \frac{PD_i \bullet K_E}{\varphi_E \bullet v_i} \quad (9)$$

Finally, a correction factor needs to be applied to D_{path} to account for the differences in shielding and source geometry among the types of packages modeled. For example, the dose rate due to 1 Curie of a 1 MeV-photon emitting isotope at a given distance from the source would depend on whether the package is a steel box, a drum of asphalt-solidified material or a lead-shielded cask. The shielding provided by the cask and the self-shielding provided by a large, solid source must be considered. Also to be considered is the energy dependence of the shielding correction factor. As seen earlier, the attenuation and buildup factors are energy dependent. These arguments lead to a correction factor, C_{Eh}, that varies with isotope energy E and package type h. Table 1 lists the correction factors C_{Eh} for LSA boxes, 55 gallon drums filled with solidified waste and shielded casks over photon energies ranging from 0.1 MeV to 1 MeV and greater. The final form of D_{path} is:

$$D_{path} = 9.4 \bullet \frac{C_{Eh} \bullet PD_i \bullet K_E}{\varphi_E \bullet v_i} \tag{10}$$

This is the first component of the total accident-free exposure model.

Table 1. Values of C_{Eh}

Energy(MeV)	LSA Box	55 gal Drum	Cask
0.1	1	0.05	0.001
0.5	1	0.1	0.005
≥1.0	1	0.5	0.01

Table 2 lists the values for the parameters speed (v_i), population density (PD_i) and traffic count (TC_i) (which will be encountered in a later section) by the population density class i.

Table 2. Parameters Specific to Population Density Class

i	Classification	v (km/hr)	PD (persons/km^2)	TC (vehicles/hr)
1	Rural	88	50	470
2	Suburban	88	1000	1200
3	Urban	64	3500	2800

Dose to Crew

The vehicle's crew compartment must have a dose rate less than 2 mrem/hr by Federal law (49 **CFR** 173.441b(2)). Assuming a crew of two and a dose rate (DR) in the cab of 1 mrem/hr = 0.001 rem/hr, the dose to the crew while travelling at speed v_i is:

$$D_{crew} = \frac{2 \bullet DR}{v_i} = \frac{0.002}{v_i} \tag{11}$$

Dose to Those Sharing Transportation Link

Vehicles Travelling in the Opposite Direction

Dose models for persons sharing the transportation link have been derived from RADTRAN III [51]. The dose model for persons travelling in the direction opposite the LLW shipment is similar to the model for dose received along the path. Some changes are in order though. The speed of passage is $2 \bullet v_i$ since each vehicle has speed v_i. d_{min} and d_{max} must cover the opposing lanes of traffic, so d_{min} = 3m and d_{max} = 10m. The final difference is that the population density is the product of the vehicle density and the number of persons per vehicle (PPV). The vehicle density in units of vehicles/km can be calculated by dividing the traffic count in the population density zone i, TC_i (units of vehicles/hr), by the vehicular speed in zone i, v_i (units of km/hr). PPV is assumed to be 2 persons per vehicle for all PD classes. S_p is again assumed to be 3.7×10^{10} photons/sec and Z is again 10^{-10} km^2/cm^2. Correction factor C_{Eh} remains applicable. D_{opp} is:

$$D_{opp} = \frac{Z \bullet S_p \bullet C_{Eh}}{2 \bullet \varphi_E \bullet 2v_i} \bullet \frac{PPV \bullet TC_i}{v_i} \bullet \ln\left(\frac{10m}{3m}\right) \tag{12}$$

$$D_{opp} = \frac{1.2 \bullet 3.7 \bullet 2 \bullet TC_i \bullet C_{Eh}}{4 \bullet \varphi_E \bullet {v_i}^2} \tag{13}$$

$$D_{opp} = 2.2 \bullet \frac{TC_i \bullet C_{Eh}}{\varphi_E \bullet v_i^2} \qquad (14)$$

Vehicles Travelling in the Same Direction

To model vehicles travelling in the same direction, the assumption is made that all vehicles travel at the same speed. This implies that the LLW shipment travels in an unchanging platoon of vehicles, that is, the other vehicles are at rest with respect to the shipment. The exposure received by the occupants of other vehicles is analogous to a case of a stationary point source and stationary receptors. Equation (1b) gives the dose rate as a function of distance for a point source. The dose at distance r is the product of the dose rate and the exposure time, t. Since a URF is to be calculated, the exposure time will be the time necessary to travel a unit distance. If the speed v_i is in km/hr, then t in hr/km is the inverse of v_i.

$$D_{same}(r) = DR(r) \bullet t \qquad (15)$$

$$D_{same}(r) = \frac{k \bullet t}{r^2} \qquad (16)$$

$$D_{same}(r) = \frac{k}{r^2 \bullet v_i} \qquad (17)$$

Integrating the dose over r gives the total dose for those travelling in the same direction as the shipment. The range of r is from some minimum distance to ∞. The minimum distance is assumed to be the distance travelled in 2 seconds (following safe driving rules). This distance, d_{min}, in meters is $2 \bullet 0.278 \frac{\text{m-hr}}{\text{sec-km}} \bullet v_i \frac{\text{km}}{\text{hr}}$. Assuming the lanes of travel can be represented at distances greater than d_{min} by a line, the differential element is just an increment of the line, dr. As in the previous section, the population density along the direction of travel is the persons per vehicle times the traffic count divided by the speed. A factor of 2 is needed to account for persons ahead of and behind the shipment. The constants Z and C_{Eh} are also required for units conversion and shielding effects. The integrated D_{same} becomes:

$$D_{same} = \frac{2 \bullet k \bullet Z \bullet C_{Eh} \bullet TC_i \bullet PPV}{v_i^2} \bullet \int_{d_{min}}^{\infty} \frac{dr}{r^2} \qquad (18)$$

$$D_{same} = \frac{2 \bullet k \bullet Z \bullet C_{Eh} \bullet TC_i \bullet PPV}{v_i^2} \bullet \left(\frac{-1}{\infty} + \frac{1}{0.56 \bullet v_i}\right) \qquad (19)$$

$$D_{same} = \frac{2 \bullet k \bullet Z \bullet C_{Eh} \bullet TC_i \bullet PPV}{0.56 \bullet v_i^3} \qquad (20)$$

Substituting PPV = 2, $Z = 10^{-10}$ and $S_p = 3.7 \times 10^{10}$ gives:

$$D_{same} = 2.1 \bullet \frac{TC_i \bullet C_{Eh} \bullet K_E}{\varphi_E \bullet v_i^3} \qquad (21)$$

Notice that D_{same} will always be less than D_{opp} due to the extra factor of v_i in the denominator. On the surface this may seem unreasonable, the dose received passing a source at speed $2v_i$ having a value greater than the dose received from a source which is stationary relative to the receptor. The explanation is that the distance from the source has been assumed to be 3 to 10 meters for opposing traffic while the closest approach for traffic travelling in the same direction is assumed to be $0.56v_i$. At a speed of 88 km/hr, d_{min} is 49 meters.

Total Dose (URF) for Accident-Free Situations

The total dose in accident-free situations is given by:

$$AFD_{Total} = D_{path} + D_{crew} + D_{opp} + D_{same} \qquad (22)$$

$$AFD_{Total} = \frac{9.4 \bullet C_{Eh} \bullet PD_i \bullet K_E}{\varphi_E \bullet v_i} + \frac{0.002}{v_i} + \frac{2.2 \bullet TC_i \bullet C_{Eh}}{\varphi_E \bullet v_i^2} + \frac{2.1 \bullet TC_i \bullet C_{Eh} \bullet K_E}{\varphi_E \bullet v_i^3} \quad (23)$$

AFD_{Total} as expressed above is actually the consequence per kilometer of shipping LLW, that is the unit consequence factor (UCF). To generate URF's, AFD_{Total} is multiplied by the probability that no accident occurs. A base commercial vehicle accident rate of 1 x 10^{-7} per kilometer per year has been assumed in these calculations. So, the probability of no accident is (1 - 0.0000001) = 0.999999 ≈ 1. For the accident-free case then, URF = UCF.

Exposure from Accidents

Two types of accidents are to be modeled (as seen in figure 9), non-dispersal accidents in which the radioactivity is contained within the shipping package and atmospheric dispersion accidents in which the radioactive material is carried away from the accident site by the atmosphere. The non-dispersal model simulates an accident involving a Type B package. No Type B package has ever been breached in an accident. The dispersal model simulates a worst case accident involving a Type A package which bursts upon impact, its contents completely dispersed to the atmosphere. The driving forces behind the release of the material are assumed to be the vehicular impact plus an ensuing fire of sufficient intensity and duration to consume all the LLW contained in the shipment. To calculate URF's, each shipment is assumed to be 1 Curie of material and a base accident rate is assumed to be 1 x 10^{-7} per kilometer per year. Later, during network optimization, the actual Curie content and accident rates will be used.

Non-Dispersal Accidents

Dose to Surrounding Population

Following an accident in which package containment is not breached, the shipment can be modeled as a stationary point source. The exposure at distance r is the product of the exposure time t and $DR(r) = k/r^2$:

$$D_{area}(r) = \frac{k \bullet t}{r^2} \tag{24}$$

Integrating $D_{area}(r)$ over the inhabited area surrounding the accident site leads to an estimate of the population dose. The element of integration for the area is an annulus with circumference $2 \pi r$ and differential thickness dr (figure 10).

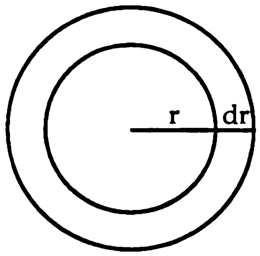

Figure 10. Annular Element

The lower limit of integration is assumed to be d_{min} = 10 m, that is, a recovery work crew could be expected to keep the public at least 10 meters from the accident scene. The upper limit of integration is as used in determining the dose along the path, d_{max} = 800 m. Again, the constants Z and C_{Eh} are required for unit conversion and shielding considerations. The population density PD_i converts the units of exposure to person-rem. The dose to the surrounding area is:

$$D_{area} = \frac{t \bullet Z \bullet C_{Eh} \bullet PD_i \bullet S_p \bullet K_E}{4 \bullet \pi \bullet \varphi_E} \bullet \int_{d_{min}}^{d_{max}} \frac{2 \bullet \pi \bullet r}{r^2} dr \tag{25}$$

$$D_{area} = \frac{t \bullet Z \bullet C_{Eh} \bullet PD_i \bullet S_p \bullet K_E}{2 \bullet \varphi_E} \bullet \int_{10m}^{800m} \frac{dr}{r} \tag{26}$$

$$D_{area} = \frac{t \bullet Z \bullet C_{Eh} \bullet PD_i \bullet S_p \bullet K_E}{2 \bullet \varphi_E} \bullet \ln\left(\frac{800m}{10m}\right) \tag{27}$$

Assuming an exposure time of 8 hours (while the recovery crew arrives and completes their work) and with S_p set equal to 3.7 x 10^{10} and Z equal to 10^{-10} km^2/cm^2, the exposure simplifies to:

$$D_{area} = \frac{8 \bullet C_{Eh} \bullet PD_i \bullet K_E \bullet 3.7}{2 \bullet \varphi_E} \bullet 4.4 \tag{28}$$

$$D_{area} = 65 \bullet \frac{C_{Eh} \bullet PD_i \bullet K_E}{\varphi_E} \tag{29}$$

Dose to Passing Vehicles

The dose to passing vehicles following a non-dispersal accident is analogous to the dose along the path for accident-free situations. In the accident-free case, the source moved with speed v_i while the receptors were stationary, in this case the source is stationary while the vehicles pass by at v_i km/hr. The relative speed is the same in both cases. To simplify the model, assume the vehicles move along a line located x kilometers from the source. The population exposed is 2 • PPV • TC_i • t where the factor of 2 takes into consideration both directions along the line. The dose along the line using the form suggested by equation (2) is:

$$D_{veh} = \frac{2 \bullet k \bullet Z \bullet C_{Eh} \bullet 2 \bullet PPV \bullet TC_i \bullet t}{v_i} \bullet \int_x^{\infty} \frac{dr}{r \bullet (r^2 - x^2)^{0.5}} \tag{30}$$

$$D_{veh} = \frac{2 \bullet S_p \bullet Z \bullet C_{Eh} \bullet 2 \bullet PPV \bullet TC_i \bullet t \bullet \pi}{v_i \bullet 4 \bullet \pi \bullet \varphi_E \bullet 2 \bullet x} \tag{31}$$

Assuming t = 8 hours, PPV = 2 persons per vehicle, S_p = 3.7 x 10^{10} γ per second, Z = 10^{-10} km^2/cm^2 and x = 30 meters = 0.03 km, D_{veh} reduces to:

$$D_{veh} = 987 \bullet \frac{C_{Eh} \bullet TC_i}{v_i \bullet \varphi_E} \tag{32}$$

Dose to Work Crew

The dose to the work crew assigned to recover a shipment from an accident can be modeled by a point source at distance r. Assuming an average distance of r = 10 meters, the source strength $S_p = 3.7 \times 10^{10}$, the exposure time t = 4 hours and the work crew consists of P = 10 people, the dose to the crew is:

$$D_{work} = \frac{P \bullet t \bullet S_p \bullet C_{Eh}}{4 \bullet \pi \bullet \varphi_E \bullet r^2} \tag{33}$$

$$D_{work} = \frac{10 \bullet 4 \bullet 3.7 \times 10^{10} \bullet C_{Eh}}{4 \bullet \pi \bullet \varphi_E \bullet 10^6} \tag{34}$$

$$D_{work} = 1.18 \times 10^5 \bullet \frac{C_{Eh}}{\varphi_E} \tag{35}$$

Total Dose (URF's) due to Non-Dispersal Accidents

The total dose from non-dispersal accidents is:

$$NDAD_{Total} = D_{area} + D_{veh} + D_{work} \tag{36}$$

$$NDAD_{Total} = \frac{65 \bullet C_{Eh} \bullet PD_i \bullet K_E}{\varphi_E} + \frac{987 \bullet C_{Eh} \bullet TC_i}{v_i \bullet \varphi_E} + \frac{1.18 \times 10^5 \bullet C_{Eh}}{\varphi_E} \tag{37}$$

$NDAD_{Total}$ is actually the consequence of a non-dispersal accident. URF's are the product of $NDAD_{Total}$ and the probability of a commercial vehicle accident. As stated earlier, a base accident rate of 1×10^{-7} per kilometer per year has been assumed. A unit risk factor for isotope E, in package type h, in population density zone i is then:

$$URF_{Ehi} = (NDAD_{Total})_{Ehi} \bullet 10^{-7} \tag{38}$$

Atmospheric Dispersal Accident

The second type of accident modeled is one in which radioactive material is released to the atmosphere. For this to happen certain conditions must be present (figure 11). The first condition is the occurrence of an accident involving LLW. The second condition is that the accident is severe enough to cause the package to lose integrity. The final condition is that the type of package shipped must be susceptible to rupture (Type A package).

Each of these conditions can be expressed as conditional probability distributions: the accident rate if a commercial vehicle is involved, the severity distribution given an accident occurs, the failure rate for a certain package type and severity of accident. Three simplifying assumptions will be made to compute URF's: the base accident rate is 10^{-7} per kilometer per year, all accidents are of the highest severity, all packages fail completely. In the optimization algorithm the URF's will be corrected for the actual accident rate on each link. The remaining assumptions will not be dealt with further.

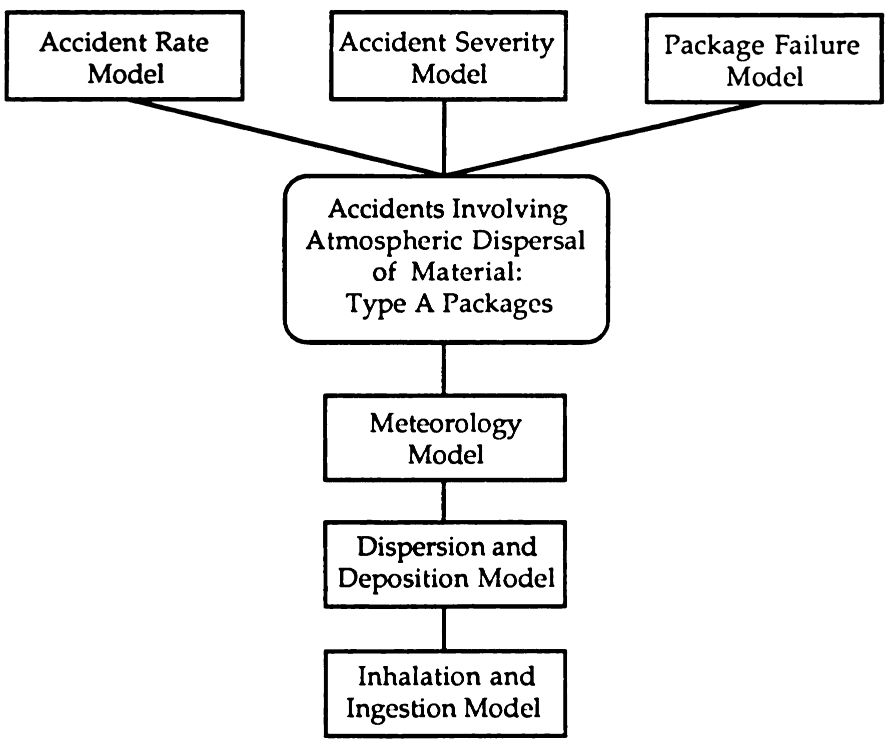

Figure 11. Dispersal Accident Methodology

If the initiating conditions are met and an atmospheric release occurs, the released material is carried downwind and dispersed by atmospheric turbulence. Dispersal implies that the material is spread over an ever-increasing area with a corresponding decrease in the concentration of the airborne material. Most of the impacts of the radioactivity are dependent on this concentration, which generally has the notation χ. For example, the exposure received from immersion in a cloud of radioactive material is dependent on the concentration of material in the cloud. The amount of material inhaled or deposited on the ground downwind of the source of release are also dependent upon χ.

A number of methods are available to estimate χ downwind from the point of release. Two key parameters are the meteorological conditions at the time of the release and the topography near the release site [66]. (Thermal gradients and topographical features are the primary driving forces of atmospheric turbulence and dispersion.) **Meteorology and Atomic Energy 1968** [66] contains measurements or estimates for the airborne concentration χ normalized by the material release rate Q (χ/Q) for many meteorological and topographical conditions at downwind locations both on and off the axis of wind direction.

RADTRAN III [51] provides a method for estimating downwind concentration for average conditions. In RADTRAN, lines of equal χ (isopleths or iso-dose lines) are drawn, each line enclosing an elliptical area. The areas form a series of nested ellipses originating at the release point, 18 elliptical areas in total. Values of χ/Q are tabulated at each area boundary for six meteorological conditions (Pasquill stability categories). Pasquill stability is a measure of atmospheric turbulence or mixing. The Pasquill stability categories range from A = unstable to F = extremely stable. Knowing the fraction of time each Pasquill category occurs, the χ/Q values can be weighted accordingly and an average value for each area calculated. This method will be incorporated into the present research using only the first 11 elliptical areas, with the fractions of occurrence for each category given in table 3. These values are typical for the Great Lakes region.

Table 3. Pasquill Category–Fraction of Occurrence

Category	Fraction
A	0.10
B	0.05
C	0.10
D	0.40
E	0.25
F	0.10

Having the values of χ, the amount of material deposited on the ground can be calculated as well as the depleted concentration χ_D. The average depleted concentration $\bar{\chi}_D$ will also prove useful. These calculations and results are presented in appendix E.

Whole Body Dose

The exposure resulting from atmospheric dispersal accidents can be divided into three components as shown by figure 9. Whole body dose is the exposure received by being immersed in a cloud of radioactive material. **Meteorology and Atomic Energy 1968** [68] gives the dose rate in rad/sec (≈ rem/sec for γ radiation) for the case of a receptor at ground level in an infinite cloud of γ emitting isotopes as:

$$DR(x,y,0,t) = 0.25 \bullet \bar{E} \bullet \chi(x,y,0,t) \qquad (39)$$

$\bar{E}$ is the average gamma energy of the cloud components. By previous definition, a URF will be defined for each isotope shipped, so DR and $\bar{E}$ are specific to a particular isotope. Since isopleths of concentration have been defined and deposition has been considered in appendix E, the dose rate within an elliptical area n, can be estimated using the $\bar{\chi}_D$ for the nth area:

$$DR_n(t) = 0.25 \bullet \bar{E} \bullet \bar{\chi}_{Dn}(t) \tag{40}$$

The population dose in elliptical area n can be calculated by multiplying $DR_n(t)$ by the area of the nth ellipse A_n, the zonal population density PD_i, the exposure time t, and a conversion factor of 10^{-6} km^2/m^2 correcting the unit differences between A_n and PD_i. To simplify, assume that t = 8 hr = 2.88×10^4 seconds and that PD_i does not vary within the downwind area, that is, the subscript i is constant over the area affected by the release. The total population exposure is the summation of the area doses over all 11 ellipses:

$$D_{WB} = \sum_{n=1}^{11} DR_n(t) \bullet t \bullet A_n \bullet PD_i \bullet 10^{-6} \tag{41}$$

$$D_{WB} = t \bullet PD_i \bullet 10^{-6} \bullet \sum_{n=1}^{11} DR_n(t) \bullet A_n \tag{42}$$

$$D_{WB} = 2.88 \times 10^{-2} \bullet PD_i \bullet \sum_{n=1}^{11} DR_n(t) \bullet A_n \tag{43}$$

Inhalation Dose

The second dose component is the internal dose which results from inhaling the radioactive material suspended in the air. There are two sources of suspended material, the original release and material which is initially deposited on the ground and then resuspended by wind or other mechanical means. The total inhalation dose D_{inh} is the sum of the initial release dose D_{init} and the dose resulting from resuspension of the material D_{res}:

$$D_{inh} = D_{init} + D_{res} \tag{44}$$

$$D_{inh} = D_{init} \bullet \left(1 + \frac{D_{res}}{D_{init}}\right) \tag{45}$$

$$D_{inh} = D_{init} \bullet RDF \tag{46}$$

Where: $RDF = 1 + \frac{D_{res}}{D_{init}}$ (47)

The resuspension dose factor or RDF for an individual isotope as given in RADTRAN III [51] was originally derived in the **Reactor Safety Study** [79]:

$$RDF = 1 + v_d \bullet 8.6 \times 10^4 \bullet \left(\frac{10^{-5}}{\eta} \bullet (1 - e^{-18250\eta}) + \frac{10^{-9}}{\lambda} \bullet (1 - e^{-18250\lambda}) \right) \quad (48)$$

Where: v_d = Deposition velocity (assumed to be 0.005 m/sec)

$$\eta = 0.693 \bullet \left(\frac{1}{RT_{1/2}} + \frac{1}{t_{1/2}} \right) \quad (49)$$

$\lambda = \frac{0.693}{t_{1/2}}$ = Radioactive decay constant

$RT_{1/2}$ = Resuspension half-life (assumed to be 365 days)

$t_{1/2}$ = Radioactive half-life in days

8.6×10^4 = Seconds per day

18250 = Days in 50 years

The deposition velocity (0.005 m/sec) used to calculate RDF and $\bar{\chi}_D$ is a value representative of field test results on fission product particulates as reported in reference 67. As defined by equation (48), RDF typically has values in the range of 1.5 to 3.

With RDF quantified, only D_{init} remains to be defined in order to calculate the inhalation dose. The formulation of D_{init} used here will be adapted from that used in RADTRAN III [51]. The RADTRAN model gives the dose for an individual within elliptical area A_n as a function of a number of factors which have been assumed to be unity for the case of a URF. These factors include the Curies per package, the packages per shipment, the fraction of material released, the fraction of material which becomes airborne and the fraction of airborne material of respirable size. Eliminating these factors leaves:

$$ID_{init,m,n,o} = RPC_{m,o} \bullet \bar{\chi}_{Dn} \bullet BR \qquad (50)$$

Where: ID = Individual dose

$RPC_{m,o}$ = Radiotoxicity factor for material m, organ o

$\bar{\chi}_{Dn}$ = Depleted concentration of airborne material

BR = Breathing rate

For use in this research the subscript m can be eliminated since URF's are isotope specific. Radiotoxicity factors have been estimated for individual isotopes by the International Commission on Radiological Protection and can be calculated from data presented in **Permissible Dose for Internal Radiation,** Table 1 [36]. These factors have units of rem per Curie inhaled. Rather than use the organ specific values used by RADTRAN, the model employed in this research will use the values for the total body found in reference 36. The breathing rate used is found in **Report of the Task Group on Reference Man** [39] and has a value of 3.3×10^{-4} m^3/sec. The population dose in area n is found by multiplying equation (50) by the population density PD_i and the area A_n. This introduces a unit conversion factor of 10^{-6} km^2/m^2. Summing over *all* areas n gives the complete initial dose:

$$D_{init,n} = 10^{-6} \bullet RPC \bullet \bar{\chi}_{Dn} \bullet BR \bullet A_n \bullet PD_i \qquad (51)$$

$$D_{init} = \sum_{n=1}^{11} \bar{\chi}_{Dn} \bullet A_n \bullet RPC \bullet PD_i \bullet BR \bullet 10^{-6} \qquad (52)$$

$$D_{init} = RPC \bullet PD_i \bullet 3.3 \times 10^{-4} \bullet 10^{-6} \bullet \sum_{n=1}^{11} \bar{\chi}_{Dn} \bullet A_n \qquad (53)$$

$$D_{init} = 3.3 \times 10^{-10} \bullet RPC \bullet PD_i \bullet \sum_{n=1}^{11} \bar{\chi}_{Dn} \bullet A_n \qquad (54)$$

The total inhalation dose due to initial release and resuspension is thus:

$$D_{inh} = RDF \bullet 3.3 \times 10^{-10} \bullet RPC \bullet PD_i \bullet \sum_{n=1}^{11} \bar{\chi}_{Dn} \bullet A_n \qquad (55)$$

Groundshine Dose

The final component of dose due to atmospheric dispersal accidents is that caused by radioactive material deposited on the ground by the initial release plume. The deposited material creates a plane source of exposure to persons entering the area. Within each elliptical isodose area the source can be regarded as an infinite plane. This is the model used by RADTRAN III [51] to estimate groundshine exposure and will also be used here.

The dose rate from an infinite plane source depends on the surface density of the contaminant (Curie/area) and the decay energy of the contaminant. The contamination level can be determined if the undepleted χ/Q values and the depleted χ_D/Q_D values are known. Appendix E provides estimates for χ_D/Q_D taken from reference 68, the incremental and cumulative amounts deposited in each ellipse and the surface density of the deposition. The equation for the population dose rate due to the deposition of a given isotope within area n is:

$$DR_{gnd,n}(t) = Z_2 \bullet \frac{Dep_n}{A_n} \bullet E_\gamma \bullet Pop_i \bullet e^{-\lambda t} \bullet (0.63e^{-.0031t} + 0.37e^{-.000021t}) \qquad (56)$$

Where: $Z_2 = 3.04 \times 10^{-4} \dfrac{\text{rem-m}^2}{\text{day-Ci-MeV}}$ = conversion constant

Dep_n = Material deposited in elliptical area n (Ci)

$Pop_i = A_n \bullet PD_i \bullet 10^{-6} \dfrac{\text{km}^2}{\text{m}^2}$ = Population in PD zone i

E_γ = Gamma decay energy (MeV)

$\lambda = \dfrac{0.693}{t_{1/2}}$ = Radioactive decay constant

t = time since release (days)

The first exponential term decreases the source strength through radioactive decay. The exponential terms in parentheses decrease the source strength via soil uptake, wind dispersion, weathering or other processes. Combining the constants and exponential terms leaves:

$$DR_{gnd,\,n}(t) = Z_3 \bullet Dep_n \bullet E_\gamma \bullet PD_i \bullet (0.63e^{-(.0031+\lambda)t} + 0.37e^{-(.000021+\lambda)t}) \quad (57)$$

Where: $Z_3 = 3.04 \times 10^{-10} \dfrac{\text{person-rem}}{\text{day-Ci-MeV}}$ = conversion constant

At this point the method to be used departs from that used in RADTRAN III. Where RADTRAN continued by determining if the contamination level was high enough to require interdiction of the land of decontamination, the method used here will assume that the contamination levels are of a magnitude which would not require decontamination or interdiction. So the resident population would receive a low intensity yet chronic exposure during the remainder of their lives. That exposure is quantified by the definite integral of $DR_n(t)$ from the release at $t = 0$ through t = lifetime. Assume the average life after exposure is 50 years and set $\kappa = 0.0031 + \lambda$ and $\omega = 0.000021 + \lambda$. Integrating equation (57) results in:

$$D_{gnd,\,n} = Z_3 \bullet Dep_n \bullet E_\gamma \bullet PD_i \bullet \int_0^{50y} (0.63e^{-\kappa t} + 0.37e^{-\omega t})\, dt \quad (58)$$

$$D_{gnd,\,n} = Z_3 \bullet Dep_n \bullet E_\gamma \bullet PD_i \bullet \left(\frac{-0.63}{\kappa} \bullet (e^{-\kappa T} - 1) + \frac{-0.37}{\omega} \bullet (e^{-\omega T} - 1) \right) \quad (59)$$

$$D_{gnd,\,n} = Z_3 \bullet Dep_n \bullet E_\gamma \bullet PD_i \bullet \left(\frac{0.63}{\kappa} \bullet (1 - e^{-\kappa T}) + \frac{0.37}{\omega} \bullet (1 - e^{-\omega T}) \right) \quad (60)$$

Where: $\kappa = 0.0031 + \lambda$

$\omega = 0.000021 + \lambda$

T = 50 years = 18250 days

With the exception of Dep_n, all the terms in equation (60) are independent of the elliptical area n. The total groundshine exposure is simply the summation over n of Dep_n multiplied by the remaining terms, which are specific to the isotope in question or the population density class:

$$D_{gnd} = Z_3 \bullet E_\gamma \bullet PD_i \bullet \left(\frac{0.63}{\kappa} \bullet (1 - e^{-\kappa T}) + \frac{0.37}{\omega} \bullet (1 - e^{-\omega T}) \right) \bullet \sum_{n=1}^{11} Dep_n \qquad (61)$$

Total Dose (URF's) due to an Atmospheric Dispersal Accident

The total dose from an accident involving dispersal of radioactive material is the sum of the whole body or cloudshine dose, the inhalation dose and the groundshine dose. This again is the consequence of an assumed accident so the unit risk factor is the total dose multiplied by the base probability of 1 x 10^{-7} accidents per kilometer per year:

$$ADAD_{Total} = D_{WB} + D_{inh} + D_{gnd} \qquad (62)$$

$$URF_{Ehi} = (ADAD_{Total})_{Ehi} \bullet 10^{-7} \qquad (63)$$

Table 4 gives examples of the dose components for accident-free as well as non-dispersal and atmospheric dispersal accident situations, appendix F presents the complete list of estimates of dose components for the isotopes shipped in quantity in the MILLRWC. Appendix G gives the Unit Risk Factors for those same isotopes.

Network Optimization Model

Three components make up the network optimization computer model: input and initialization module, weight or optimization function and optimization algorithm, and output module. The input and initialization module loads network and shipment data into memory, allows the user

Table 4. Dose Component Examples

Accident-Free Dose Components

Isotope & Package	D_{path}	D_{crew}	D_{opp}	D_{same}	AFD_{Total}
			RURAL		
^{60}Co Cask	1.98E-07	2.27E-05	5.01E-09	5.36E-11	2.29E-05
^{60}Co LSA	1.98E-05	2.27E-05	5.01E-07	5.36E-09	4.30E-05
^{226}Ra LSA	1.41E-05	2.27E-05	3.56E-07	3.81E-09	3.71E-05
			SUBURBAN		
^{60}Co Cask	3.96E-06	2.27E-05	1.28E-08	1.37E-10	2.67E-05
^{60}Co LSA	3.96E-04	2.27E-05	1.28E-06	1.37E-08	4.20E-04
^{226}Ra LSA	2.81E-04	2.27E-05	9.09E-07	9.73E-09	3.05E-04
			URBAN		
^{60}Co Cask	1.90E-05	3.13E-05	5.65E-08	8.31E-10	5.03E-05
^{60}Co LSA	1.90E-03	3.13E-05	5.65E-06	8.31E-08	1.94E-03
^{226}Ra LSA	1.35E-03	3.13E-05	4.01E-06	5.90E-08	1.39E-03

Non-Dispersal Accident Dose Components (Cask Shipments)

Isotope	D_{area}	D_{veh}	D_{work}	$NDAD_T$	$Prob \cdot NDAD_T$
			RURAL		
^{60}Co	1.20E-04	1.95E-04	4.37E-03	4.69E-03	4.69E-10
			SUBURBAN		
^{60}Co	2.40E-03	4.98E-04	4.37E-03	7.27E-03	7.27E-10
			URBAN		
^{60}Co	8.41E-03	1.60E-03	4.37E-03	1.44E-02	1.44E-09

Dispersal Accident Dose Components (LSA & Drum Shipments)

Isotope	D_{WB}	D_{inh}	D_{gnd}	$ADAD_T$	$Prob \cdot ADAD_T$
			RURAL		
^{60}Co	7.64E+01	1.92E-02	2.90E-05	7.64E+01	7.64E-06
^{226}Ra	4.71E+01	1.75E+02	8.94E-05	2.22E+02	2.22E-05
			SUBURBAN		
^{60}Co	1.53E+03	3.85E-01	5.79E-04	1.53E+03	1.53E-04
^{226}Ra	9.41E+02	3.50E+03	1.79E-03	4.44E+03	4.44E-04
			URBAN		
^{60}Co	5.35E+03	1.35E+00	2.03E-03	5.35E+03	5.35E-04
^{226}Ra	3.30E+03	1.23E+04	6.26E-03	1.56E+04	1.56E-03

to choose the destination point for the shipments, permits the user to choose the desired optimization function (minimize cost or risk) and allows the user to specify the output mode. The output module displays or prints the optimal route for each shipment and the cost (or total weight) of each shipment. Alternatively, the routing information can be suppressed and only the cost results displayed. The heart of the program is the analysis module containing the optimization algorithm and the weight function.

Optimization Algorithm

The optimization algorithm is an adaptation of the Dijkstra algorithm found on pages 234-5 of **Discrete Optimization Algorithms with Pascal Programs** by Syslo, Deo and Kowalik [71]. This algorithm solves for the shortest path between two nodes on a network with links having nonnegative weights. The algorithm fails if any segment is negatively weighted but this constraint should not pose a problem for a transportation network where weights always parameters possess positive values such as distance, travel time or economic cost.

The algorithm works by first naming an origin node, S, and a destination node, T. All nodes on the network are initially given a *temporary* label of ∞, with the exception of node S which is given a *permanent* label of 0. The algorithm then searches for all nodes with temporary labels connected to S (at this stage all nodes connected to S have temporary labels). Each node connected to S is given a new temporary label equal to the sum of the permanent label of S (0) and the weight to the connecting node, in other words, the new temporary label for each node connected to S is the weight of the connecting link. Also recorded is the designation of the preceding node, in this case node S. Next, the smallest temporary label is found. This will be a node adjacent to S since all other nodes are labelled ∞. This node, call it A, is permanently assigned a label equal to the weight of its link with S. If A is the destination node T, then the algorithm stops and the final weight total is the value of the permanent label. If A is not T, then the algorithm continues by searching through all temporarily labelled nodes for those connected to A. New temporary labels are calculated for these nodes by adding the weights of their links to A with the permanent label for A. The new set of temporary labels are compared with the existing temporary labels for these nodes, if the new value for a node is less than the previous value, the new value becomes the temporary label otherwise the previous value is retained. If a new temporary label is installed, A is recorded as the predecessor node. Once the new set of temporary labels is in place, the smallest label is found and made permanent for that node. If the last permanently labelled node is not the destination node T then the process of:

1. Searching for connections to the node most recently given a permanent label,
2. Determining new temporary labels, and
3. Selecting the smallest temporary label and making it permanent,

continues until T is assigned a permanent label. Once this happens, the label of T equals the total weight from S to T. (The weight parameter can of course be any variable associated with network links such as cost or distance.) The path from S to T can be traced back from T by looking at the predecessor nodes. The predecessor of T leads to another node and so on until eventually the path leads to a node with A as its predecessor which in turn has the origin S as its predecessor.

As noted in chapter 2, this algorithm is considered efficient by Syslo, Deo and Kowalik for solving the path between two points. For the type of problem addressed here however (that is, a large number of origins and one destination), the algorithm becomes even more efficient if it is run from the destination to each origin under certain conditions. Two network conditions are possible, one is a network in which the link weights are independent of the choice of endpoints, the other is a network in which the endpoints chosen affect the weight calculations. For the case of weights independent of the choice of endpoints, if the permanent labels established for the first destination-origin pair are not reset to ∞, then all origins having weight less than the first origin have already been solved and the algorithm only need refer to the permanent label to report the solution. If the second origin chosen has a weight greater than the first, the algorithm can proceed from the first origin, building the network outward from the destination. The expected solution time for an origin becomes less as more of the network is solved because it becomes more and more likely that any particular node has been permanently labelled. In the case where link weights are dependent upon the choice of endpoints, the permanent labels must be reset for each origin-destination pair and the calculational savings are not realized. Figure 12 is a flow diagram of the optimization algorithm, graphically depicting the steps described in this section for the case of endpoint-independent link weights.

Verification of Algorithm

The operation and accuracy of the optimization algorithm was verified using a simple network. This verification process is described in appendix H.

Weight Functions

The function used to determine the weight of each link on the network is critical to the selection of succeeding nodes by the optimization algorithm

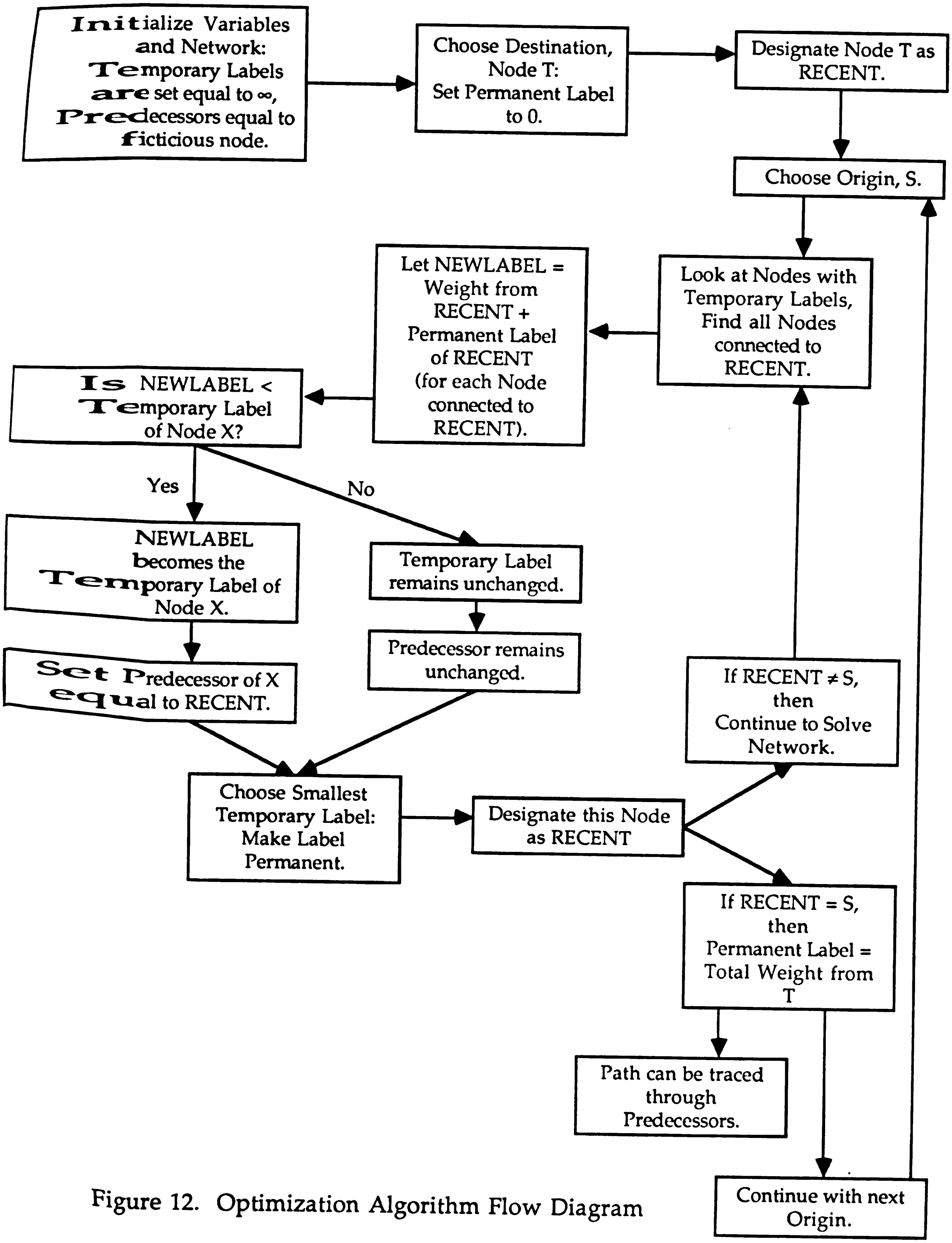

Figure 12. Optimization Algorithm Flow Diagram

since the choice is made by adding the weight of each link to the permanent label (or total weight from the initial node) of the predecessor node. A link weight may be an easily measured physical property such as distance or travel time or it may be an economic function based on such properties, as in the cost per mile multiplied by the distance. The weight function need not be dependent upon obvious geometric properties like distance. For example, the ratio of flow volume on a link to the flow capacity of that link might be used to examine the best paths for an additional increment of flow. This is analogous to the resistance offered by a component in a circuit. The weight function used to model the economic cost of transporting LLW in this research is a straightforward function of link length while the function used to model risk is only partially dependent upon the network's geometry.

Cost Function

The function used to estimate the economic cost of shipping LLW is based on the commodity rates charged by Tri-State Motor Transit Company [77] of Joplin, Missouri, a major carrier of LLW shipments in the Midwest. The rates in cents per mile are given in table 5.

Using regression analysis, analytical models of these rates (in cents per mile) can be determined:

Round Trip:

One Way Mileage < 100 miles:

Rate = 338

100 miles < One Way Mileage < 600 miles:

$$\text{Rate} = 3140 \bullet (\text{One Way Mileage})^{-0.484} \qquad r^2 = 0.98 \qquad (64)$$

One Way Mileage > 600 miles:

Rate = 142

One Way Trip:

One Way Mileage < 100 miles:
Rate = 471

100 miles < One Way Mileage < 1000 miles:
$$\text{Rate} = 4290 \bullet (\text{One Way Mileage})^{-0.4799} \qquad r^2 = 0.99 \qquad (65)$$

One Way Mileage > 1000 miles:
Rate = 156

Table 5. LLW Rates in Cents per Mile

One Way Mileage	One Way	Round Trip	One Way Mileage	One Way	Round Trip
100	471	338	450	207	158
125	433	313	475	202	155
150	396	289	500	194	152
175	362	268	550	190	149
200	313	245	600	185	142
225	296	233	650	179	142
250	284	217	700	176	142
275	271	204	750	173	142
300	259	194	800	165	142
325	252	183	850	164	142
350	244	177	900	162	142
375	235	171	950	159	142
400	224	165	≥1000	156	142
425	217	162			

Notes: 1. For a rate to apply, mileage cannot exceed one way mileage value.
2. Trips less than 100 miles are charged 100 mile rate.

The round trip rate equation is used to calculate the cost of cask shipments since the shielding casks are returned and reused rather than disposed after each trip. Shipments of 55 gallon drums or LSA boxes use the one way trip rate equation since the empty vehicle may be used for other commodities after unloading the LLW.

Since both rate functions monotonically decrease as total mileage increases, the length of each link can be used as the link weights. This reduces the number of calculations performed by the algorithm since link lengths are part of the data describing the network. Thus the labels and weights calculated by the algorithm represent the distances from the destination, the economic cost is computed after the optimal path and weight are determined rather than during each iteration of the algorithm. So in the case of economic cost, the weight function is the link length. Since the length of a link is independent of the origin-destination pair, the form of the algorithm may be used which does not require resetting the permanent labels after each solution. After the distance between the destination and an origin is optimized, the shipping rates are calculated using equations (64) and (65), then the annual cost (in cents) of shipment from the origin is calculated with the following cost functions:

Cask shipments:

$$\text{Cost} = (\#\text{ of annual shipments}) \bullet [(\text{Rate} \bullet 2 \bullet \text{distance}) + 200000 + (100000 \bullet 2 \bullet \text{distance}/500)] \quad (66)$$

Drum or Box shipments:

$$\text{Cost} = (\#\text{ of annual shipments}) \bullet \text{Rate} \bullet \text{distance} \quad (67)$$

The factors of (2 • distance) in the cask function reflect the round trips needed to return the cask. The cask function also includes two factors representing the cask rental fee charged by the operator of the LLW repository. The fees used are representative of those charged by Chem-Nuclear Systems Incorporated [6], which operates the LLW repository site at Barnwell, South Carolina. The fees include a flat rental charge of $2,000 for use of the shielding cask plus an additional $1,000 per day, with the assumption that 500 miles are travelled each day.

Risk Function

The risk function uses link statistics, shipment data and URF information to assess the risk of shipment from the generating sites to the destination. The risk function produces a weight specific to each link for each origin. This means that the weights must be reset after each origin-destination solution.

As the algorithm proceeds after initialization, an origin is designated for evaluation. A reference is established to the shipment data for that origin. The data required for the risk function are the waste forms (package types), the isotopes shipped, the Curie content of each isotope per shipment and the annual number of shipments. The next step, weighing links connected to the destination node T, requires the use of link data such as population density, accident rate and length. Two components of risk are calculated for each link, the accident-free consequence and the accident consequence. The probability of a commercial vehicle accident normalizes these two factors. The weight functions used to estimate risk are:

Accident-Free Consequence:

$$AFConseq = \sum_{k} \sum_{j} [Ci_{ij} \bullet NURF_{kjl} \bullet L_n \bullet S_{ij} \bullet (1-P_n)] \quad (68)$$

Accident Consequence:

$$AccConseq = \sum_{k} \sum_{j} [Ci_{ij} \bullet AURF_{kjl} \bullet L_n \bullet S_{ij} \bullet P_n] \quad (69)$$

Total Consequence :

$$Conseq = AFConseq + AccConseq \quad (70)$$

Where: C_{ij} = Curies from origin i in package type j shipped annually

$NURF_{kjl}$ = Non-accident Unit Risk Factor for isotope k in package type j in population density zone l (person-rem per mile)

$AURF_{kjl}$ = Accident Unit Risk Factor for isotope k in package type j in population density zone l (person-rem per mile)

L_n = Length of link n

S_{ij} = Number of annual shipments from origin i of package type j

P_n = Accident rate for commercial vehicles per mile per year on link n.

Combining Cost and Risk

To this point cost and risk have been dealt with independently, the algorithm minimizes cost exclusive of the risk imparted upon the populace while risk is minimized without thought of the expense imposed on the waste generators. Policy based on either case alone suffers from lack of perspective. The goal of this research is to shed light on the issue, not cast it into shadow, so a way to combine cost and risk is needed.

One approach to combining cost and risk is to define a common unit of measurement. The two parameters could then be combined prior to optimization resulting in a solution which minimizes the combination. For example, shipment distance is the cost measurement which is minimized while risk is minimized through an estimate of radiological exposure. As noted earlier, distance is easily converted to an economic unit such as dollars giving an estimate of the minimum economic cost in units dealt with on an everyday basis. If risk can be expressed in terms of dollars then it can be easily combined with cost. While the conversion of exposure to dollars is possible, the procedure is not as straight-forward as with distance and raises additional complications for policy makers.

The units of exposure are person-rem. **Title 10, Code of Federal Regulation** states that if exposure can be reduced by one person-rem at a cost of $1,000 or less, then it must be done. This provides a basis for equivalency between risk and dollars:

$$1 \text{ person-rem} = \$1{,}000 \qquad (71)$$

With this equation and equations (66) and (67) cost and risk estimates can be combined for each shipment and link during the optimization process to produce a solution which minimizes the combination. If a great deal of confidence is placed in the cost and risk estimates then the optimization of the network with respect to the combined parameters is the preferred method of evaluation. From a practical point of view though such a method forces the algorithm to perform a large number of calculations at each step and so slows the algorithm considerably. The extra time needed to optimize the network may not be warranted if low levels of confidence exist for either the cost or risk estimates.

Alternatively, equation (71) is a basis for trading risk against cost. If the cost and risk of shipping LLW to a number of potential repository sites are known a graph can be generated showing the relationship between the two parameters. If a correlation between the variables exists, equation (71) suggests that a potential repository should be rejected if an alternative exists which would reduce risk at a cost less than or equal to $1,000 per person-rem. (Should is used rather than must because of the uncertainty inherent in the risk estimates.) So, if the relationship between risk and cost is such that risk can be reduced at a cost of $500 per person-rem for all sites then the most expensive site is acceptable and should probably be recommended as the repository. If on the other hand the cost of risk reduction is greater than $1,000 per person-rem then the lowest cost site may be justified.

On the surface either method seems reasonable, the equivalence between risk and economic value is mandated by the federal government (Nuclear Regulatory Commission) which is a persuasive argument for both methods. Taking the equivalence a step further though brings some inconsistencies to light. Previously it was noted that the radiological risk has been quantified by the Committee on the Biological Effects of Ionizing Radiation [12]. One of the primary conclusions of their studies is that a population exposure of 8225 person-rem can be expected to generate 1 excess cancer fatality in the exposed population. In other words, 1 life equals 8225 person-rem. Since by law 1 person-rem equals $1,000 then it follows that:

$$\text{1 life saved} = \text{8225 person-rem} \bullet \frac{\$1000}{\text{person-rem}} = \$8.2 \times 10^{6} \qquad (72)$$

The act of equating risk and dollars places a dollar value on a life. There is nothing inherently wrong with placing a value on a life, it is done daily in decisions made deliberately or instantaneously (compare the values weighed in deciding to run a yellow light and in deciding which hospital receives the latest diagnostic tool). The problem arises in trying to choose a value to place on a life. Clearly the NRC equates one life with about $8 million. The value endorsed by the Federal Highway Administration in weighing alternative highway improvement projects is about $250,000 per life saved. Here is a second unit of the federal government using a value for a life 1/32 of that used by the first. Which is right? A traffic fatality is immediate and the average life expectancy lost is on the order of decades. A cancer generated by exposure to radioactivity has a latency period of about 5 years for leukemia to nearly 30 years for lung cancer. As a result the average life expectancy lost is more likely on the order of years rather than decades yet the value of a life saved from radiation induced cancer is held to be 32 times as valuable as a life saved from a highway accident. The question is further complicated by the subject of this research. If an accident occurs which results in one highway fatality and a substantial release of radioactive material causing one excess cancer fatality, are the two lives to be valued differently by society and policy makers?

To sidestep conflict or controversy over the monetary value of life the measures of both risk and cost can be normalized to produce risk and cost indices for potential repository sites. The values obtained for risk and cost through the optimization algorithm may be normalized to any standard but perhaps the most easily interpreted standard of comparison is the minimum value for each parameter. An index can thus be produced by simply taking the ratio of a risk or cost value at a site to the lowest value obtained for the network. Since the indices are dimensionless indicators of rank, they can be combined into a composite index. The composite can be calculated in any manner deemed reasonable by policy makers, for example the two indices may be weighted equally or cost may represent 90% of the final composite or perhaps the cube of the risk index is to be added to cost index. In any event the lowest composite index will represent the choice within the imposed framework. This will be the method used to evaluate the MILLRWC.

Model Implementation

The four components of the model are brought together in a computer program listed in appendix I. This program, written in ZBasic (a compiled Basic language with versions available for many different types of personal computers), contains the shipment data for the MILLRWC and the URF data for isotopes shipped within the MILLRWC. It accesses a file containing the network data for the Midwest. Two network analysis options are provided based upon the weight functions defined in the previous section: minimize cost or minimize risk. The program was verified with the simple network used in appendix H before it was applied to the MILLRWC data. The results from the network analysis of the MILLRWC will be discussed in Chapter 5.

Chapter 5

MODELLING THE MILLRWC

Results

The Midwest Interstate Low-Level Radioactive Waste Compact was modeled using the data contained in appendices A, B, C and G. A number of nodes were tested as potential repository sites by simulating the shipment of waste to those nodes and estimating the cost and risk of the shipments. The most illustrative way to display the results is to place the cost (or risk or combined) estimate for each node on a map of the region and then connect the points of equal cost. The resulting iso-cost (iso-risk, etc.) map shows at a glance the area of lowest cost and the variation in cost with respect to location. This technique will be used to examine cost and risk separately and also the combination of the two parameters. All values used to generate the maps are contained in appendix J.

Cost

Annual costs of waste shipment in millions of dollars are shown in figure 13. The cost at each site is based on the shortest distance between each waste generator and that site. As seen by the map, shipment cost is relatively insensitive to location in the region. The lowest annual shipment cost is $860,000 to Gary, IN, the highest is to the Minnesota border near Fargo, ND at $1,500,000 or about 1.8 times the lowest cost. Note that the center-of-mass of LLW shipments as calculated by the MILLRWC is designated C on the map. The lowest cost site does not coincide with the center-of-mass because Lake Michigan prevents straight-line shipments from generators in Michigan and Ohio to the center-of-mass. The displacement of the lowest cost repository site from the center-of-mass in southeastern Wisconsin to north-central Indiana is due to the higher connectivity of the network in the three eastern states relative to the four western states. This is especially true with regard to the major generators, that is nuclear power plants, in Michigan and Ohio which are located very close to the I-80 corridor across northern Indiana and Ohio. These power plants, representing the three largest volume generators in Michigan and the two largest in Ohio, are all within 40 miles of I-80 which in turn provides direct east-west access across the entire region. In contrast, the power plants in the four western states, with the exception of the plant located near Cedar Rapids, Iowa, are situated 200 miles or more off the I-80 axis. The importance of I-80 to minimal distance transportation routes in the region is seen in figure 13. The iso-cost lines form concentric ellipses with major axes along the I-80 corridor. The cost gradient perpendicular to I-80 is much steeper than along I-80 so that locating a site anywhere between Gary, IN and Toledo, OH, a distance of 200 miles, does not change the transportation cost while the cost at Grayling, MI, 200 miles north of I-80, is 20% higher.

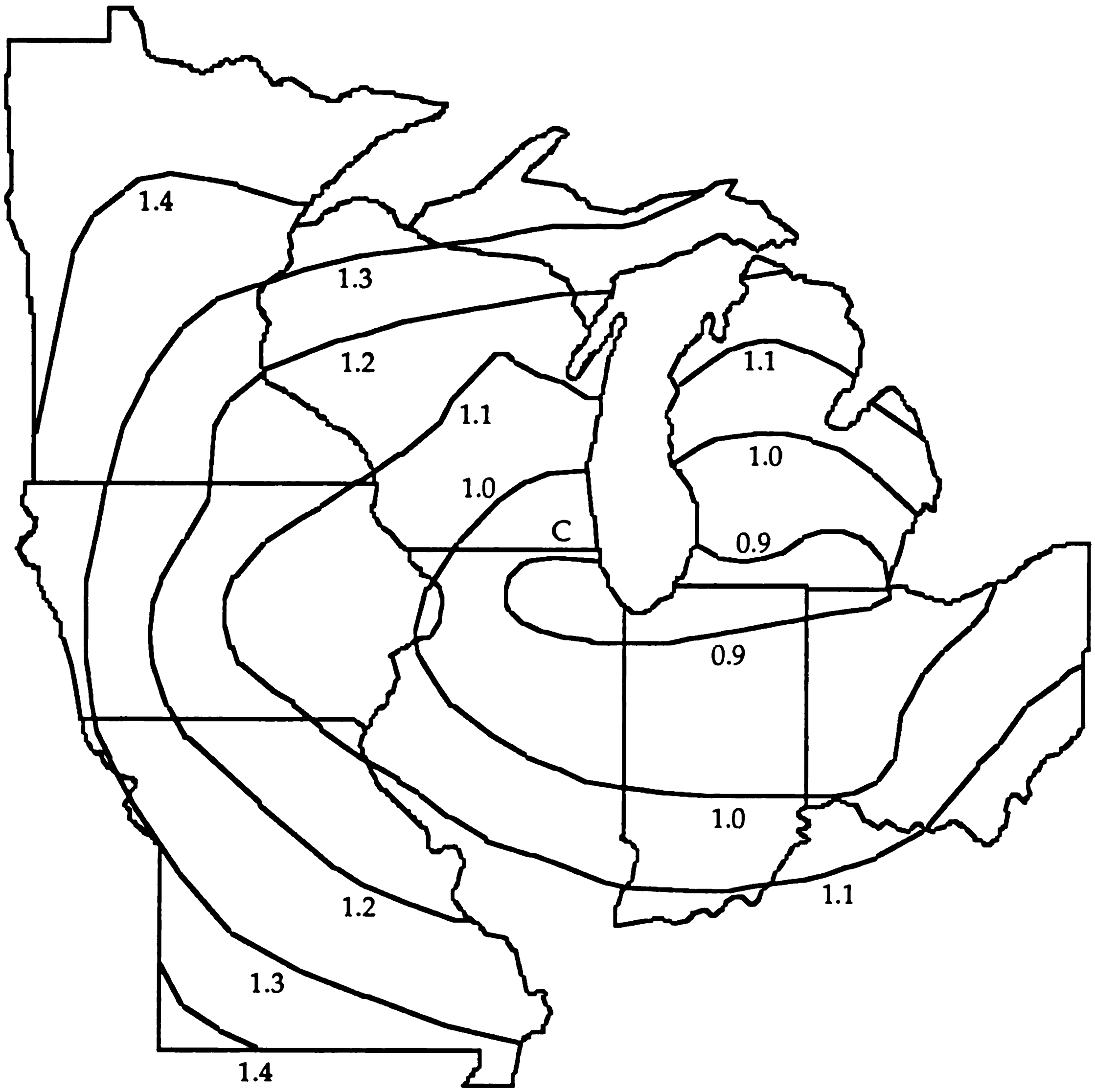

Figure 13. Iso-Cost Lines (in Millions of Dollars per Year)

Risk

The risk of shipping LLW in thousands of person-rem per year (calculated using the assumptions stated in Chapter 4) is shown in figure 14. Risk is somewhat more sensitive than cost, ranging from a low of 5500 person-rem near Iowa City, IA to 12,100 person-rem at Sault Ste. Marie, MI, a factor of 2.2 larger. Since risk is primarily determined by the population exposed and the distance travelled, the point of lowest risk occurs in a low

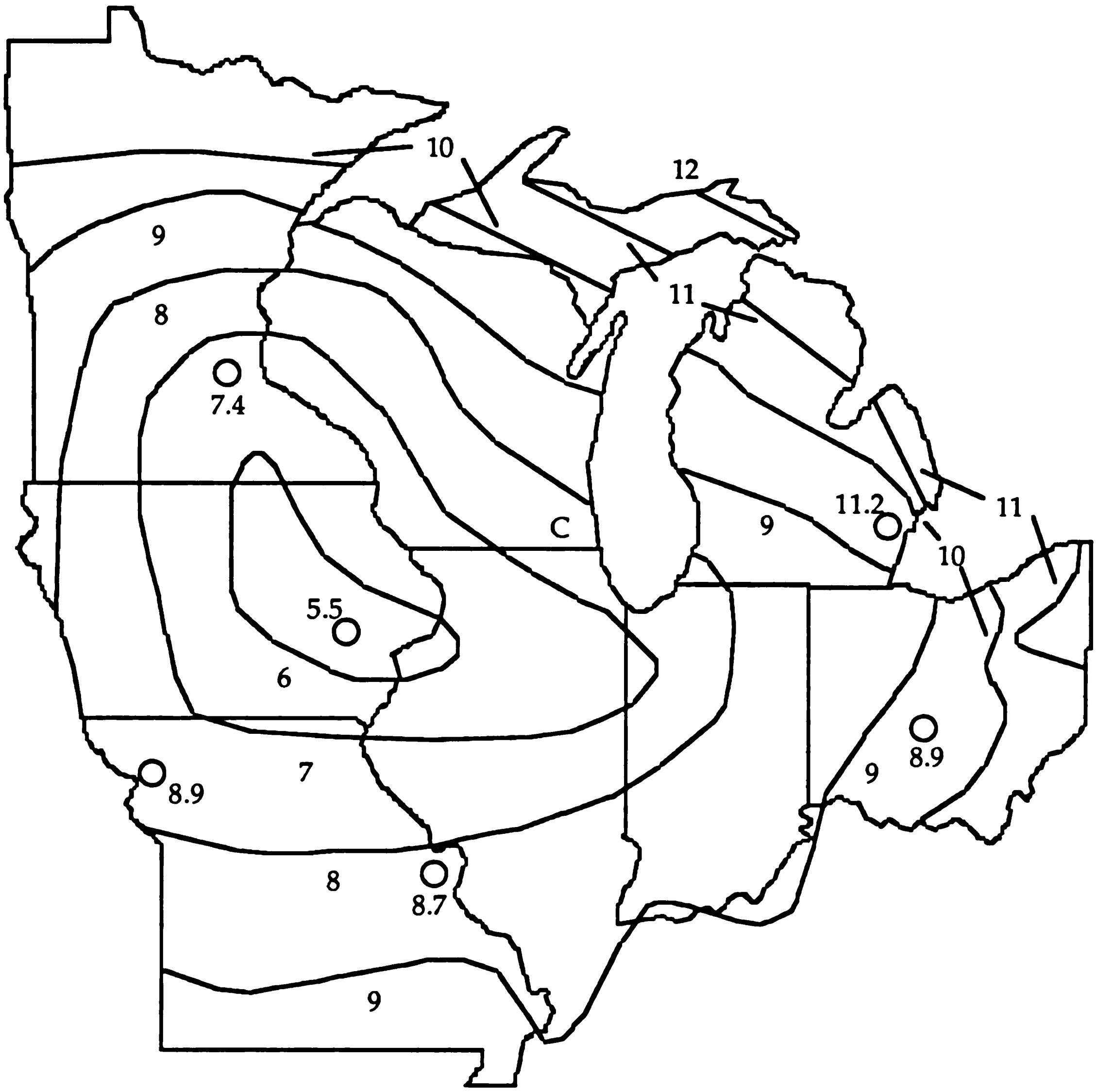

Figure 14. Iso-Risk Lines (in Thousands of Person-Rem per Year)

population density area within the I-80 corridor. The region of low risk extends along I-80 and I-35 forming a boomerang shaped area in Iowa. Metropolitan areas such as Minneapolis–St. Paul, MN and St. Louis, MO form local maxima within regions of lower risk. High population density along the Lake Erie shore in Ohio and along I-94 in Michigan cause the risk gradient to steepen in these areas. Some aberrations in the results such as high values for St. Joseph, MO and Akron, OH and the low value for Springfield, OH may be caused by abnormal accident rates assigned to links in these areas. In general, areas of low risk are areas with low population density and good accessibility along I-80 and I-35.

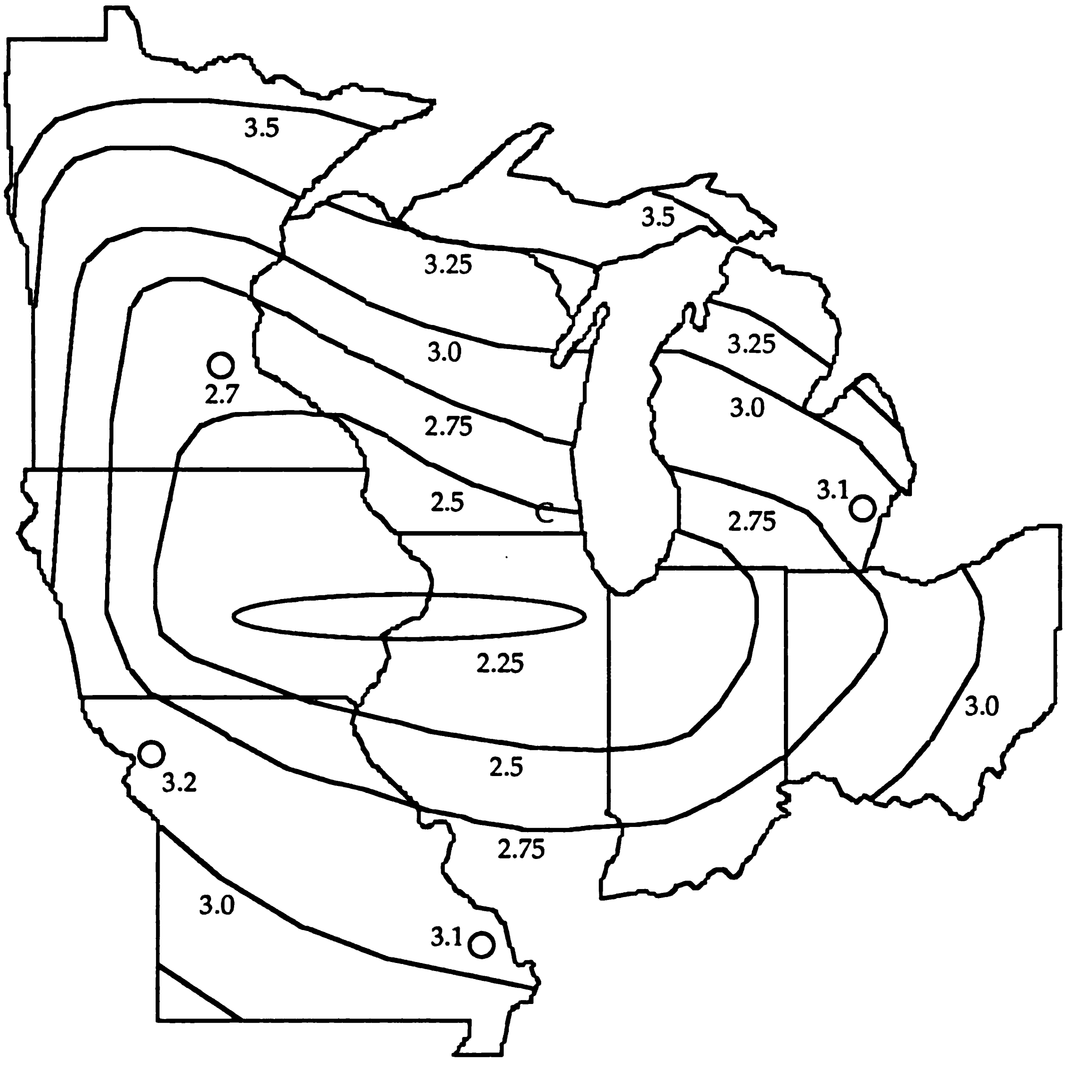

Figure 15. Normalized Cost + Normalized Risk (Arbitrary Units)

Combined Cost and Risk

To produce figure 15, the cost estimates were normalized to the minimum value of $860,000 at Gary, IN while the risk estimates were normalized to the minimum value of 5500 person-rem at Tiffin, IA. The resulting cost and risk indices were then added to create the combined index displayed in figure 15. This map is a superposition of the two previous maps and reflects its origin. The area of lowest combined cost and risk is confined to a narrow ellipse along I-80 from Iowa City, IA to the Illinois-Indiana border. Regions of successively higher cost and risk are bounded by ellipses with major axes skewed off the I-80 axis reflecting the influence of low risk values along I-35 in Iowa and Minnesota. The combined index ranges from 2.2 at Tiffin, IA to 3.7 at Sault Ste. Marie, MI, 1.7 times greater than the low value. This is a smaller range than either cost or risk alone because the low cost values for sites in the eastern states are balanced by higher risk estimates while the opposite situation prevails in the western group of states. As a result, the profile of the combined cost and risk index is relatively flat across the entire region.

Figure 15 assumes equal weight is given to the cost and risk indices. Other linear combinations are of course possible, however, all other such combinations will be bounded by figures 13 and 14. Figure 15 represents a transition state in passing from a condition in which all weight is on cost and none on risk (figure 13) to the opposite condition where risk receives 100% of the weight and cost none (figure 14).

Cost–Risk Correlations

The relationship between cost and risk for the nodes tested as potential repositories is exhibited in figure 16. Evidently there is no correlation when the data is taken over the whole region, the F ratio of 0.123 indicates that the null hypothesis of slope equal to 0 cannot be rejected.

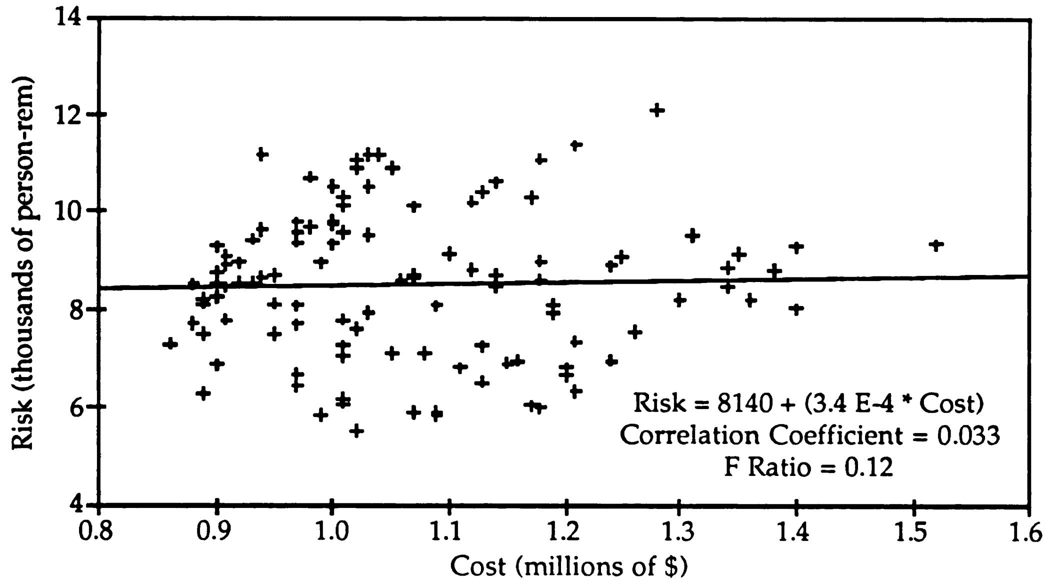

Figure 16. Regression of All Data Points

Stratifying the data by geographical region highlights a relationship between cost and risk which was not apparent for the entire region. This correlation is interesting in that it is positive in both geographical regions, that is, increasing the transportation cost to reach a non-optimal site will generally be associated with an increase in the population risk.

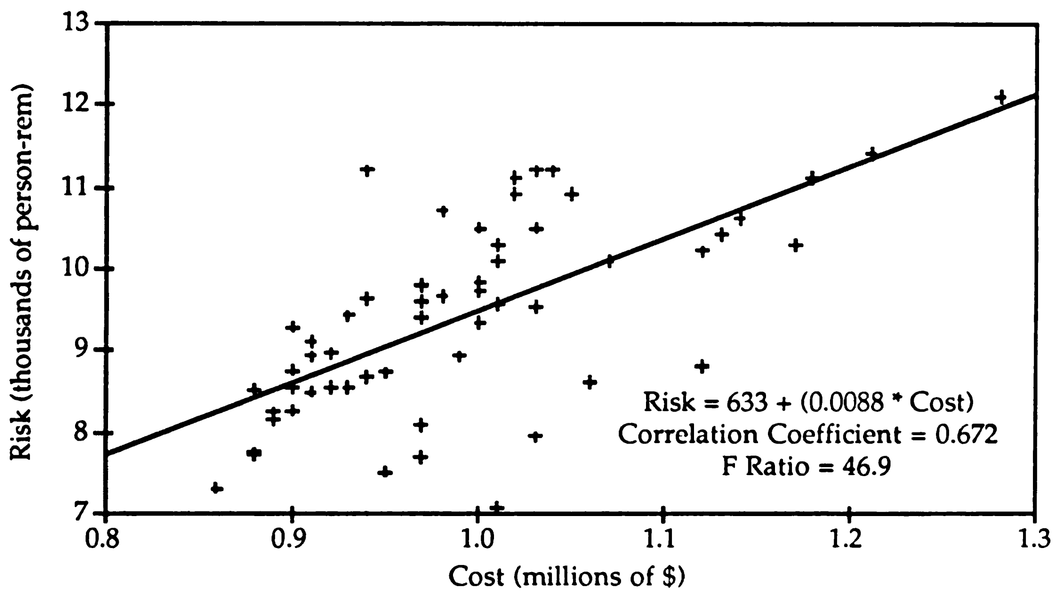

Figure 17. Regression of Eastern Data Points

In the eastern group of states (Indiana, Michigan and Ohio) this relationship is somewhat stronger than in the western group (Iowa, Minnesota, Missouri and Wisconsin). The correlation coefficient for the eastern group is 0.67, for the western group it is 0.57. In both cases though the F ratios suggest that the slope is not equal to 0 at the 0.01 confidence level. Figures 17 and 18 contain the graphs of cost versus risk for the eastern and western groups of states.

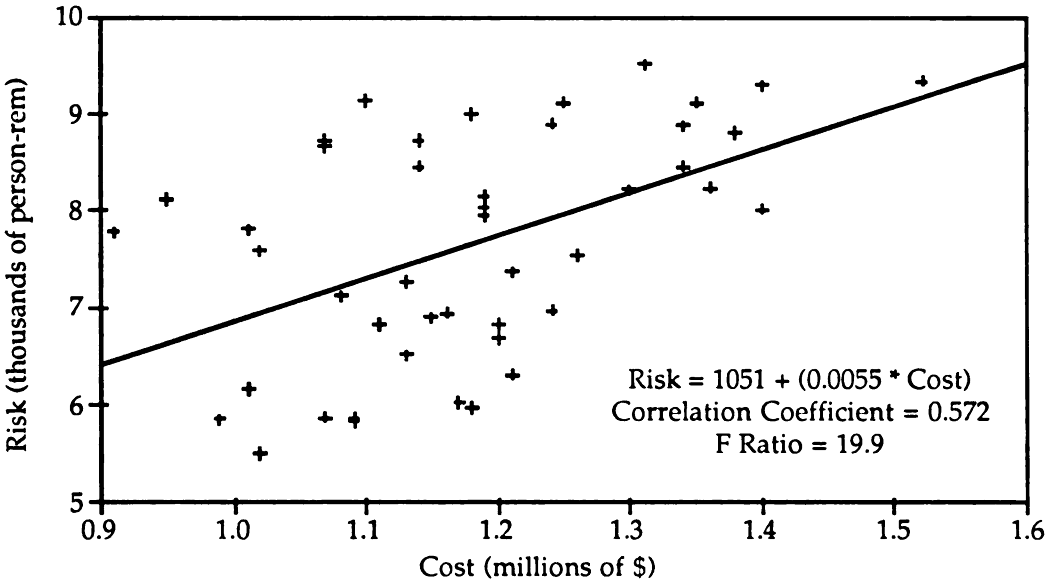

Figure 18. Regression of Western Data Points

Sensitivity Analyses

Four sensitivity analyses were performed on the model to test its behavior under extreme conditions. The first analysis tested the effects of withdrawal of one state from the MILLRWC. The three states producing the largest volumes of LLW, Michigan, Minnesota and Ohio were removed in turn from the model. Subsequent analyses examined the effects of accident rates, shipment volume and packaging type. Each analysis was performed for five nodes, the four nodes with the largest or smallest estimates for cost or risk, and one node with average cost and risk estimates. (In the analysis of a state removed from the Compact, nodes within that state were not tested.) Comparisons are provided between the results of each sensitivity analysis and the base results presented earlier.

One State Withdraws from MILLRWC

To test the effect of a state withdrawing from the Compact, all shipments generated in one state were set to zero and estimates made of the cost and risk of shipments from the remaining six states. Michigan, Minnesota and Ohio were individually removed from the model. These three states produce the largest volumes of LLW in the Compact and represent the geographical extremes.

Withdrawal of a state from the Compact reduces the total number of shipments and so results in lower transportation cost and risk. To place the results of the sensitivity analysis in the proper context for comparison with the results from the complete Compact, the cost and risk estimates are normalized within this analysis. These normalized values are then compared to the normalized base values obtained in the analysis of the complete MILLRWC. The cost values are normalized to Gary, IN and the risk values are normalized to Tiffin, IA.

Table 6. Michigan Withdraws

	Normalized Cost		Normalized Risk	
Node	**Base**	**Test**	**Base**	**Test**
Tiffin, IA	1.19	1.06	1.00	1.00
Gary, IN	1.00	1.00	1.32	2.00
Moorhead, MN	1.77	1.52	1.70	1.67

Table 7. Minnesota Withdraws

Node	Normalized Cost		Normalized Risk	
	Base	Test	Base	Test
Tiffin, IA	1.19	1.25	1.00	1.00
Sault Ste. Marie, MI	1.49	1.47	2.18	1.67
Gary, IN	1.00	1.00	1.32	0.99
East Lansing, MI	1.07	1.04	1.62	1.15

Table 8. Ohio Withdraws

Node	Normalized Cost		Normalized Risk	
	Base	Test	Base	Test
Tiffin, IA	1.19	1.15	1.00	1.00
Sault Ste. Marie, MI	1.49	1.54	2.18	2.54
Gary, IN	1.00	1.00	1.32	1.51
Moorhead, MN	1.77	1.69	1.70	1.72
East Lansing, MI	1.07	1.12	1.62	1.90

The results of this test are as expected, removal of Michigan lowers the relative cost at western sites in the Compact region and increases the relative risk at eastern sites. Similar results are shown when Ohio is removed from the model. This behavior flows from the relative redistribution of LLW generators within the region. In both of these cases, shipments from the western states take on a greater role in determining the cost and risk relative to the base case. These shipments travel short distances to repository sites in the west, lowering the relative cost. Shipments to eastern sites have greater relative risk because of the greater weight given to the long distances travelled by shipments from the western generators.

Conversely, removing Minnesota from the model produces lower cost and risk for eastern sites and higher cost and risk for western sites.

Accident Rate Reduction

Accident rates and population density are two important parameters in the estimation of exposures. To test the effect of accident rates on the risk estimates, the accident rates were reduced by a factor of 10 for three cases: rural links only, urban links only and all links. The results are presented in tables 9 and 10:

Table 9. Risk Estimates (person-rem) with Accidents Reduced by a Factor of 10

Node	Base Data	Rural Only	Urban Only	All Links
Tiffin, IA	5517	5516	4176	3499
Sault Ste. Marie, MI	12050	12050	9786	8500
Gary, IN	7302	7302	5292	4216
Moorhead, MN	9354	9353	7161	6128
East Lansing, MI	8964	8963	6973	5754

Table 10. Fraction of Base

Node	Rural Only	Urban Only	All Links
Tiffin, IA	1.0	0.76	0.63
Sault Ste. Marie, MI	1.0	0.81	0.71
Gary, IN	1.0	0.72	0.58
Moorhead, MN	1.0	0.77	0.66
East Lansing, MI	1.0	0.78	0.64
Mean	1.0	0.77	0.64
Standard Deviation	0.0	0.03	0.05

Reducing accident rates in rural areas has little effect because the population density and accident rates are already low in rural areas (relative to urban areas) and so the dose component along the rural section of a route is small relative to the urban component. A ten-fold decrease in the urban accident rates returns a decrease in the population exposure of nearly 1/4. If the preventive measures were extended to suburban areas, the dose reduction is more than 1/3. Policies intended to reduce risk through reduction of accident rates should recognize that risk will be reduced only by a factor 1/6 to 1/8 the magnitude of the reduction in accident rates.

Volume Reduction

Many generators are practicing or planning waste volume reduction measures to reduce waste shipping and disposal costs. All such procedures do not reduce the amount of radioactivity in the waste but in fact may increase the concentration of the radioactivity. To examine the effect of volume reduction and increased concentration on transportation cost and risk, the volume shipped by each generator was halved except for those generators currently requiring only one truckload per year. It was assumed that concentrating the waste in this manner would not result in the requirement of shielding casks for shipments currently unshielded. Tables 11 and 12 contain the results:

Table 11. Cost and Risk with Volume Reduced 50%

Node	Base $ (millions)	$ (millions)	Base Person-rem	Person-rem
Tiffin, IA	1.02	0.56	5517	5721
Sault Ste. Marie, MI	1.28	0.70	12050	12450
Gary, IN	0.86	0.47	7302	7581
Moorhead, MN	1.52	0.82	9354	9801
East Lansing, MI	0.92	0.51	8964	9262

Table 12. Fraction of Base

Node	Cost	Risk
Tiffin, IA	0.54	1.04
Sault Ste. Marie, MI	0.55	1.03
Gary, IN	0.54	1.04
Moorhead, MN	0.54	1.05
East Lansing, MI	0.55	1.03
Mean	0.54	1.04
Standard Deviation	0.003	0.007

As expected, the cost is nearly halved since the number of shipments is nearly halved. The risk increases, also as expected since the concentration of radioactivity in each shipment has increased. The interesting point is the trade-off between cost and risk, risk increases by 4% while cost decreases by 50%. This indicates that an effective volume reduction program could save a substantial fraction of the annual shipping costs at the expense of only a minor increase in the risk.

Improved Package Integrity

The atmospheric dispersal accident dose ($ADAD_{Total}$) is a major contributor to population exposures in the model. Elimination of this component would reduce the expected health effects due to radiation exposure. Noting that a cask or Type B container has never been breached in an accident, the dispersal accident component could effectively be removed by requiring all shipments to be in Type B or similar high integrity containers. This scenario was tested by assuming that:

1. Present cask shipments remain the same,

2. Material currently shipped in drums, barrels or boxes will be shipped in "casks" of 10 m^3 capacity. Since current drum shipments are assumed to be 16 m^3 and LSA box shipments are assumed to be 27.5 m^3, the new containers will require more shipments, those shipments will be two-way to return the cask and a cask rental fee will be charged.

3. Accident consequence factors can be neglected since they are approximately 1×10^{-5} the magnitude of the accident-free consequence factors which are in person-rem per mile:

Rural zones =	3.65×10^{-5}
Suburban zones =	3.73×10^{-5}
Urban zones =	5.45×10^{-5}

As shown in tables 13 and 14, requiring casks for all shipments would triple the annual costs while reducing the exposures by a factor of 3.

Table 13. Cost and Risk if Casks are Required

Node	$ (millions)	Person-rem
Tiffin, IA	3.14	2044
Sault Ste. Marie, MI	4.00	5181
Gary, IN	2.62	2438
Moorhead, MN	4.56	3643
East Lansing, MI	2.87	3352

Table 14. Fraction of Base

Node	Cost	Risk
Tiffin, IA	3.08	0.37
Sault Ste. Marie, MI	3.13	0.43
Gary, IN	3.05	0.33
Moorhead, MN	3.00	0.39
East Lansing, MI	3.12	0.37
Mean	3.08	0.38
Standard Deviation	0.05	0.04

Model Applied to Single State

The final exercise performed with the model was to apply it to a single state, representing the case in which a state chooses to dispose of its waste independently. This tested the effect of reducing the scale of the network. Michigan was chosen for this test, all generators located outside of Michigan were eliminated from the data set. The cost and risk of shipping LLW within Michigan was estimated by the model. The results were then normalized and combined.

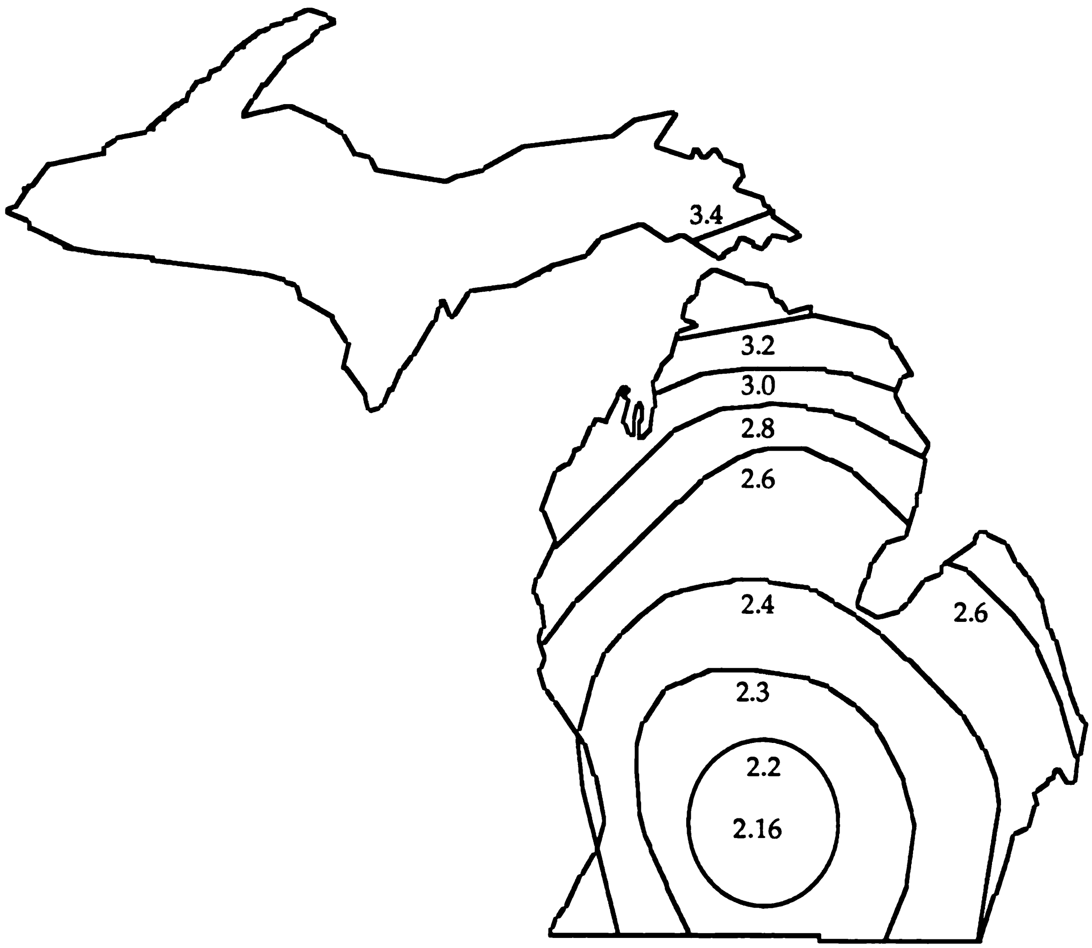

Figure 19. Iso-Cost Lines if Michigan Goes Alone
(in Hundred Thousand Dollars per Year)

Figure 19 shows the cost of shipping LLW generated within Michigan to repository sites in Michigan. The site with the lowest transportation cost ($216,000 per year) is near Marshall, MI. The variation in cost is small, the highest cost node on the network, Sault Ste. Marie, is only 1.6 times as costly as the least expensive site. These costs are about 25% of the costs incurred when the MILLRWC is modeled. Interestingly, modelling the MILLRWC produces a transportation cost ratio between Sault Ste. Marie and Marshall of 1.4 : 1. This is approximately the same as when Michigan is modeled alone. This can be explained by the geography of the state, shipments originating outside of Michigan have a limited number of routes to any site within the state due to the peninsulas defined by the Great Lakes. Thus shipments originating outside of Michigan will take roughly the same route to any potential repository site within Michigan when the object is to minimize distance.

The risk of shipping LLW in Michigan is shown in figure 20. The sites with the lowest risk are along I-275 between I-94 and I-75, close to the Fermi II nuclear power plant. Risk increases slowly westward along I-94 due to the influence of the Palisades and Cook nuclear power plants. Northeast of the area of lowest risk, risk increases rapidly as a result of the high population density and accident rates encountered in the Detroit metropolitan area.

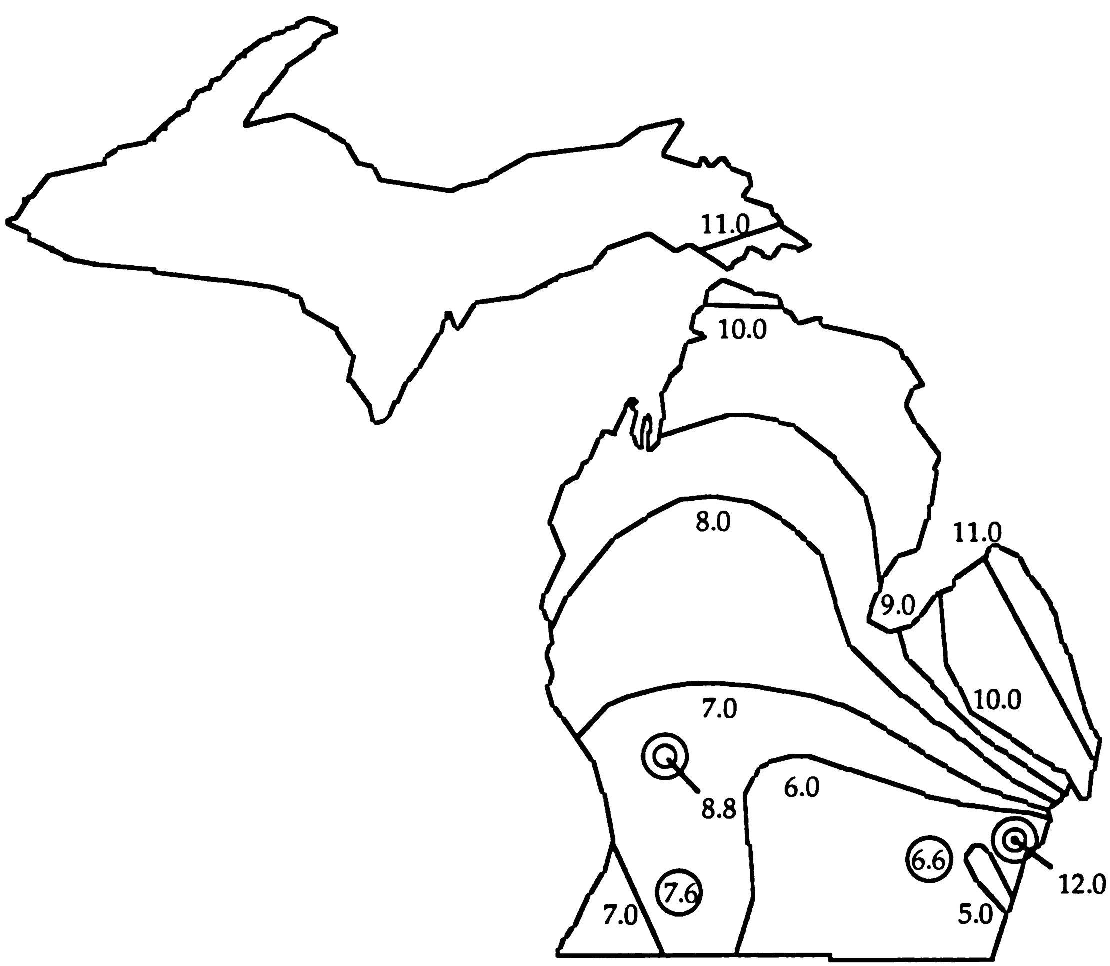

Figure 20. Iso-Risk Lines if Michigan Goes Alone
(in Hundreds of Person-Rem per Year)

Risk values range by a factor of 2.6 from lowest to highest. These areas are adjacent to one another, unlike the other analyses performed thus far which generally show a smooth transition from minima to maxima.

Where the cost results were a factor of four lower for Michigan alone versus the entire MILLRWC, risk estimated by analyzing Michigan separately is lower by a factor of 10 to 20.

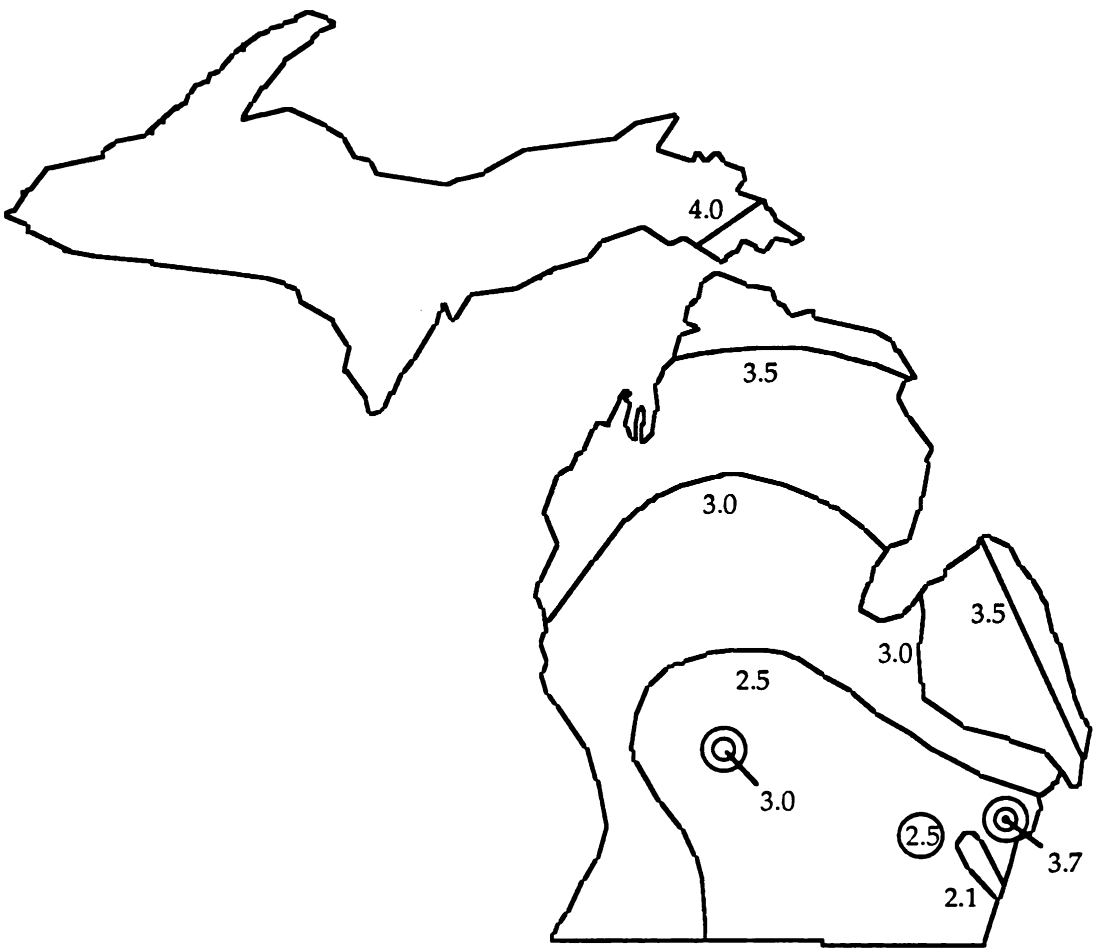

Figure 21. Normalized Cost + Normalized Risk if Michigan Goes Alone (Arbitrary Units)

Figure 21 shows the results of normalizing the cost and risk values to their respective minima and then combining the normalized values. Equal weight was given to both the cost and risk components. Figure 21 reflects the structural relief imposed by the risk estimates smoothed by the slowly varying cost estimates. The maximum value is approximately twice the minimum. A broad region of the Lower Peninsula varies by less than 20% from the I-275 corridor containing the area of lowest cost and risk.

A final note to these analyses is that St. Ignace, MI was the westernmost site tested in the Upper Peninsula. Sites west of St. Ignace can be expected to have cost and risk values greater than those at St. Ignace or Sault Ste. Marie because the western Upper Peninsula is further removed from the LLW generators in the state which are concentrated in the southern Lower Peninsula.

This application of the model shows that it works well with small or large networks. In terms of computation time a small network is desirable since the time needed to calculate the shortest path increases by the square of the number of nodes. To be weighed against the computation time is the level of detail required for confidence in the conclusions. The level of detail increases with the number of nodes on the network, a large number of nodes produces fine structural details. The model is capable of providing reliable cost and risk estimates for the shipment of LLW and by judicious choice of nodes, can do so in a reasonable amount of time. Appendix K contains the complete results of modelling Michigan alone.

Summary

Applying the model and assumptions to the Midwest Low-Level Radioactive Waste Compact produces these results:

1. The region of lowest shipping cost is northern Indiana and Ohio and southern Michigan. This region is centered by I-80 and extends approximately 30 miles on either side of this route. The highest cost in the MILLRWC is 1.8 times greater than the lowest cost.

2. The region of lowest radiological consequence is in Iowa along the axes formed by I-80 and I-35. The greatest consequence is 2.2 times larger than the lowest consequence.

3. Combining normalized cost and risk values on an equal basis produces minimum values in a narrow region along I-80 in eastern Iowa. The largest value of the combined index is 1.7 times greater than the smallest.

4. Locating a repository in a region with higher cost will tend to increase the risk. Similarly, locating in areas of higher risk will typically result in increased costs.

5. Withdrawal of a state from the compact tends to shift the regions of low cost and risk away from that state.

6. Reducing urban accidents by a factor of 10 reduces the radiological consequences by nearly 25%. Reducing all accidents by a factor of 10 reduces the consequences by 35%.

7. Volume reduction (or shipment reduction) of 50% results in a 50% cost reduction and a 5% increase in risk.

8. Requiring Type B containers for all shipments will triple the cost while reducing the risk by a factor of three.

9. The model is effective in analyzing single states if the network is defined to the appropriate level of detail.

Applying the model to Michigan alone results in:

10. The region of lowest transportation cost is in the south central Lower Peninsula. Of the sites tested, the highest cost is in the eastern Upper Peninsula, 160% greater than the lowest cost.

11. The transportation cost to a repository site when Michigan is modeled separately is about 25% of the cost to that site if the entire MILLRWC is modeled.

12. The area of lowest risk is the I-275 corridor between I-94 and I-75 in southeastern Michigan. The highest risk estimated is in downtown Detroit, 2.6 times greater than the lowest risk.

13. The consequence of shipping LLW to a site in Michigan is 10 to 20 times less if Michigan is modeled alone than if the MILLRWC is modeled.

14. The region of lowest combined cost and risk is in the I-275 corridor between I-94 and I-75. The region of highest combined cost and risk is in the Upper Peninsula, Sault Ste. Marie has a combined index about twice the minimum index.

Chapter 6

CONCLUSION

Some broad conclusions may be drawn from this research in addition to the results specific to the Midwest region given in Chapter 5. Some of the conclusions are applicable in general to the topics of risk and transportation while the remaining conclusions are specific to the model developed for this research. Before stating these conclusions however, the assumptions critical to the conclusions will be restated.

Assumptions Upon Which the Results Are Based

The assumptions used in each of the four components of the model will be listed in turn.

Low-Level Waste Shipment Inventory

1. Full truckloads are shipped whenever possible.
2. Packaging is one of three types: casks for high-activity wastes, 55

gallon drums for immobilized reactor wastes and LSA boxes for other waste. Packaging is assigned to waste based on the isotope and quantity of radioactivity.

3. Shipments are modeled as the annual averages of each of the three package types from each generator.

Transportation Network

1. The population density for each link in Michigan was calculated as the weighted average of the population density within 5 kilometers of each link. The values fell within three ranges: rural (0-600 persons per km^2), suburban (601-1600 persons per km^2) and urban (>1600 persons per km^2). Segments outside Michigan were assigned population density categories based on their geographic location and then randomly assigned a population density from the ranges defined above.
2. Commercial vehicle accident rates were calculated for each link in Michigan using 1983 and 1984 traffic volumes (including percentage of commercial vehicles) and the commercial vehicle accident records from the same years. When grouped by the population density category of the link, these accident rates have a log-normal distribution. Segments outside Michigan were randomly assigned an accident rate based on the population density category of the link and the accident rate distribution for that category.

Radiological Risk Assessment Model

1. Radiological risk is estimated by external and internal exposure models.
2. Unit risk factors can be defined for a unit distance and unit quantity of material (1 Curie) based on the isotope, the package type, the population density and the presence or absence of an accident. A base accident rate of 1×10^{-7} per kilometer per year is assumed.

Accident-Free Exposure

1. A point source model, modified by attenuation and buildup in air and package shielding is used as the basis for estimating exposure in accident-free situations.
2. The dose to the population along the path is calculated from a minimum distance of 5 meters to a maximum distance of 800 meters.
3. The dose to the crew is based on a dose rate in the crew compartment of 1 millirem per hour.
4. The dose to vehicles travelling in the direction opposite the shipment's direction is calculated between 3 meters and 10 meters.
5. The dose to vehicles travelling in the same direction as the shipment is based on a minimum distance of approach equal to the distance travelled by the vehicles in 2 seconds.

Non-Dispersal Accident Exposure

1. All accidents involving casks (Type B containers) are non-dispersal accidents.
2. A point source model is used for non-dispersal accident situations. Exposure time is assumed to be 8 hours except for the work crew which is exposed for 4 hours.
3. The dose to the surrounding population is calculated from 10 meters to 800 meters. The population density is assumed to be constant over this area.
4. Vehicles are assumed to pass no closer than 30 meters from the accident site.
5. The dose to the work crew is calculated based on an average distance of 10 meters from the source over a period of 4 hours. The work crew consists of 10 people.

Atmospheric Dispersal Accident Exposure

1. All accidents involving packages other than casks are atmospheric dispersal accidents.
2. In an atmospheric dispersal accident, the assumptions are that all material shipped is released to the atmosphere and all material

released is respirable.

3. Meteorological conditions typical of the Great Lakes region are assumed.
4. The deposition velocity of all material is assumed to be 0.005 m/sec.
5. Radiotoxicity factors are calculated from the MPC values for total body as presented in **Permissible Dose for Internal Radiation** [36].
6. The breathing rate for internal exposure is 3.3×10^{-4} m^3/sec as found in **Report of the Task Group on Reference Man** [39].

Network Optimization Model

1. Cask rental charges are a flat fee of $2,000 plus $1,000 per day.
2. For a given repository site, the risk estimates are linearly additive for all shipments from all generators.

The conclusions which follow are based upon these assumptions as they were applied in their respective model components.

Conclusions Applicable to Risk and Transportation

The first broad conclusion is that it is possible to estimate and quantify the risk of shipping radioactive material. Although this has been demonstrated previously by RADTRAN and other models, the method used in this research, derived in large measure independent of RADTRAN, serves to confirm the ability to estimate risk. The methods to estimate risk used in this research may be more accessible than mainframe models such as RADTRAN because they can be easily adapted to any spreadsheet program available for personal computers. The ability to estimate transportation risk is now in the hands of transportation and emergency response planners or policy makers rather than confined to federal research laboratories. Furthermore, the process used here should be useful as guidance for methods of estimating risk in transporting other hazardous materials.

Another conclusion to be drawn is that risk can be used as the criterion for selecting routes. Minimizing risk will not, in general, produce the same routes as minimizing distance. It is therefore appropriate to consider risk as a route selection parameter when analyzing or establishing public policy affecting the transportation of hazardous materials.

It can also be concluded that parameters with quite different units of measurement such as cost and risk may be combined through the use of indices. The resultant index describes the value of a chosen point relative to others within the framework of the combination. In other words, indices provide both a means to combine dissimilar parameters and a basis for comparison among the results of the combination. A benefit of this method is that issues such as the monetary value of a life can be avoided because all comparisons are on relative terms. So any value for a life can be used as long as it is consistent within the calculations for each parameter.

Finally, the overall method used in this research should be applicable to the shipment of materials other than LLW. Hazardous material such as gasoline, explosives or chemicals are candidates for further examination. Application of the method to these materials is dependent upon formulating a risk model for the material in question. Choosing the proper network will allow routing shipments within a city or in multi-state regions. While some work has been done in the past [60] on minimizing the risk of hazardous material shipments, the body of knowledge is by no means complete. Use of a method such as the one presented here makes risk assessment accessible to anyone with a personal computer and the expertise necessary to design a risk model.

Conclusions Specific to the Model Used in this Research

The conclusion which stands out is that the radiological risk of shipping LLW as calculated by this model is small compared with other transportation risks. With the heroic assumptions that all accidents are of the most severe type resulting in release of all material from Type A shipments and that all of the material is respirable produces Unit Consequence Factors on the order of 1×10^{-4} person-rem per Curie per kilometer in urban areas if the accident rate is 1×10^{-7} per kilometer per year. At the rate of about 1 latent cancer fatality per 8200 person-rem, the average UCF represents 1×10^{-8} fatalities per Curie per kilometer. Trucks cause about 3×10^{-8} fatalities per kilometer directly and another 10×10^{-8} fatalities per kilometer due to environmental pollution [85]. The radiological risk per Curie is an order of magnitude less than the non-radiological risk without taking the assumptions into consideration. Doing so further reduces the magnitude of the radiological risk. For example, about 60% of the shipments in the MILLRWC carry less than 1 Curie. Another consideration is that less than 1% of all truck accidents exceed the conditions established as design specifications for Type B packages [85]. These factors as well as others cause the radiological risk of transporting LLW to be much less than other risks involved in truck transportation.

A further conclusion drawn from this research is that the dose consequences of shipping LLW is sensitive to the population density along the route. The region of lowest risk (figure 14) falls in the region of lowest population density nearest the center of the region. In selecting routes to all sites, the model chose routes through rural areas almost exclusively, entering urban areas only if no alternative routes existed. Because the population density assumed for urban areas was 70 times greater than rural areas, the model was willing to trade substantial distances through rural areas to avoid exposing urban populations.

Increasing the requirements for packaging LLW to the level of Type B containers for all shipments is an effective way to reduce the risk due to transportation but at a substantial cost. With the assumptions made in Chapter 5, this policy would reduce the consequences by a factor of 3 while increasing the costs by a factor of 3.

Reducing the accident rates for LLW shipments will result in lowered consequences but this appears to be an inefficient method of reducing risks. Lowering accident rates by a factor of 10 on all links lowers the risks by about 1/3. Accident rates would have to be lowered by a factor of 100 to approach the risk reduction resulting from the use of Type B containers on all shipments. No attempt has been made to estimate the cost required to reduce the accident rates for LLW shipments.

Finally, waste volume reduction appears to be a useful practice in lowering the costs of transporting LLW. Reducing the volume by half reduces the shipments by half while doubling the Curie content of each shipment. The result is to cut shipping costs by 50% in exchange for increasing the risk by about 5%.

"Wisdom is ... the goal of knowledge."

J. D. Salinger. **Franny and Zooey**. 1961.

APPENDICES

Appendix A

ANNUAL INVENTORY
OF LOW-LEVEL WASTE SHIPMENTS
IN THE MILLRWC

Appendix A

Annual Inventory of Low-Level Waste Shipments in the MILLRWC

Location	Generator Type	Volume (ft^3) Cask	Volume (ft^3) Drum	Volume (ft^3) LSA Box	Annual Shipments Cask	Annual Shipments Drum	Annual Shipments LSA Box	Isotope	Curies
Two Rivers, WI	PWR	371	3513	6109	3	8	7	C-14	5.2E-2
Total Volume = 9993 cu. ft.	Curie Total = 7.5							Co-60	5.1E 1
								Cs-137	1.2E 1
								H-3	1.4E 0
								I-129	1.3E-3
								Ni-59	3.1E-2
								Ni-63	9.7E 0
								Pu-241	1.1E 0
								Sr-90	1.0E-1
Genoa, WI	BWR	339	219	395	3	1	1	C-14	1.9E-2
Total Volume = 953 cu. ft.	Curie Total = 6.9							Co-60	3.5E 1
								Cs-137	3.3E 1
								H-3	1.5E-1
								I-129	3.3E-3
								Ni-59	2.1E-2
								Ni-63	4.7E-1
								Pu-241	1.3E-1
								Sr-90	5.9E-2
North Perry, OH	BWR	2719	24011	3531	28	34	4	C-14	3.0E-1
Total Volume = 30261 cu. ft.	Curie Total = 1269							Co-60	7.3E 2
								Cs-137	5.2E 2
								H-3	3.6E 0
								I-129	5.2E-2
								Ni-63	9.9E 0
								Pu-241	4.5E 0
								Sr-90	9.3E-1
Kewaunee, WI	PWR	194	480	953	2	2	2	C-14	2.7E-1
Total Volume = 1628 cu. ft.	Curie Total = 4023							Co-60	1.6E 3
								Cs-137	1.8E 0
								H-3	2.2E-1
								I-129	3.3E-3
								Nb-94	8.4E-3
								Ni-59	1.4E 0
								Ni-63	2.1E 2
								Pu-241	1.7E-1
								Sr-90	1.6E-2
Oak Harbor, OH	PWR	742	2987	0	5	7	0	Co-60	8.9E 0
Total Volume = 3729 cu. ft.	Curie Total = 191							Cs-134	4.3E 1
								Cs-137	1.3E 2
								Ni-63	9.1E 0

Location	Generator Type	Volume (ft^3) Cask	Drum	LSA Box	Annual Shipments Cask	Drum	LSA Box	Isotope	Curies
Charlevoix, MI	BWR	1236	2648	1236	7	5	2	C-14	6.6E-2
Total Volume = 5120 cu. ft.	Curie Total = 223							Co-60	1.1E 2
								Cs-137	1.1E 2
								H-3	4.5E-1
								I-129	1.1E-2
								Nb-94	2.2E-3
								Ni-59	7.0E-2
								Ni-63	1.5E 0
								Pu-241	4.1E-1
								Sr-90	2.0E-1
Fulton, MO	PWR	3496	3037	494	20	6	1	C-14	1.4E-2
Total Volume = 7027 cu. ft.	Curie Total = 30							Co-60	2.2E 1
								Cs-137	3.2E 0
								H-3	3.9E-1
								Ni-59	1.3E-2
								Ni-63	4.1E 0
								Pu-241	4.2E-1
								Sr-90	2.9E-2
Palo, IA	BWR	1624	15289	2966	17	23	4	C-14	9.7E-1
Total Volume = 19880 cu. ft.	Curie Total = 12937							Co-60	5.3E 3
								Cs-137	3.3E 2
								Fe-55	6.7E 3
								H-3	2.3E 0
								I-129	3.3E-2
								Nb-94	3.4E-2
								Ni-59	4.4E 0
								Ni-63	6.4E 2
								Pu-241	2.1E 0
								Sr-90	5.8E-1
Bridgman, MI	PWR	1342	22598	3037	8	44	4	C-14	8.0E-2
Total Volume = 26977 cu. ft.	Curie Total = 1044							Co-58	7.5E 1
								Co-60	2.9E 1
								Cs-134	4.0E 2
								Cs-137	5.0E 2
								H-3	3.0E 1
								I-129	2.0E-3
								Ni-59	2.8E-2
								Ni-63	8.7E 0
								Pu-241	1.2E 0
								Sr-90	1.6E-1

Location	Generator Type	Volume (ft^3) Cask	Drum	LSA Box	Annual Shipments Cask	Drum	LSA Box	Isotope	Curies
Newport, MI	BWR	3213	12464	4237	33	11	5	C-14	3.6E-1
Total Volume = 19915 cu. ft.	Curie Total = 1524							Co-60	8.8E 2
								Cs-137	6.2E 2
								H-3	4.3E 0
								I-129	6.2E-2
								Nb-94	1.7E-2
								Ni-59	5.5E-1
								Ni-63	1.2E 1
								Pu-241	5.4E 0
								Sr-90	1.1E 0
Covert, MI	PWR	547	5296	11299	4	10	13	C-14	2.2E-1
Total Volume = 17143 cu. ft.	Curie Total = 2136							Co-60	8.9E 2
								Cs-137	2.1E 1
								Fe-55	1.1E 3
								H-3	2.5E 0
								I-129	2.3E-3
								Nb-94	5.9E-3
								Ni-59	7.6E-1
								Ni-63	1.2E 2
								Pu-241	2.0E 0
								Sr-90	1.9E-1
Monticello, MN	BWR	777	6003	3143	8	10	4	C-14	1.1E 0
Total Volume = 9922 cu. ft.	Curie Total = 8004							Co-60	6.8E 3
								Cs-137	2.0E 2
								Fe-55	1.7E 2
								H-3	1.6E 0
								I-129	2.0E-2
								Nb-94	3.8E-2
								Ni-59	5.8E 0
								Ni-63	8.4E 2
								Pu-241	1.6E 0
								Sr-90	3.5E-1
Red Wing, MN	PWR	530	671	3037	4	1	4	C-14	2.6E-2
Total Volume = 4237 cu. ft.	Curie Total = 40							Co-60	2.8E 1
								Cs-137	5.8E 0
								H-3	7.1E-1
								Ni-59	1.7E-2
								Ni-63	5.3E 0
								Pu-241	5.6E-1
								Sr-90	5.2E-2
Charlotte, MI	Medical	0	0	35	0	0	1	S-35	8.0E-3
Total Volume = 35 cu. ft.	Curie Total = 0.008								
Canton, OH	Medical	35	0	0	2	0	0	Co-60	7.0E 1
Total Volume = 35 cu. ft.	Curie Total = 70.5							Ir-192	5.0E-1

Location	Generator Type	Volume (ft^3) Cask	Volume (ft^3) Drum	Volume (ft^3) LSA Box	Annual Shipments Cask	Annual Shipments Drum	Annual Shipments LSA Box	Isotope	Curies
Cleveland, OH	Medical	0	0	632	0	0	2	C-14	2.0E-3
Total Volume = 632 cu. ft.	Curie Total = 0.179							Cr-51	5.4E-2
								H-3	5.6E-2
								I-125	3.4E-2
								P-32	1.4E-2
								S-35	4.5E-3
River Falls, WI	Medical	0	0	21	0	0	1	H-3	2.6E-2
Total Volume = 21 cu. ft.	Curie Total = 0.043							P-32	7.2E-3
								S-35	9.6E-3
Iowa City, IA	Medical	0	0	300	0	0	1	C-14	2.0E-1
Total Volume = 300 cu. ft.	Curie Total = 0.44							H-3	2.0E-1
								I-125	4.0E-2
Toledo, OH	Medical	0	0	388	0	0	1	C-14	3.6E-1
Total Volume = 388 cu. ft.	Curie Total = 1.67							H-3	1.0E-2
								I-125	1.3E 0
Kansas City, MO	Medical	0	0	88	0	0	1	Cr-51	5.8E-6
Total Volume = 88 cu. ft.	Curie Total = 3.2E-5							H-3	2.6E-5
Stillwater, MN	Medical	0	0	124	0	0	1	C-14	1.0E-3
Total Volume = 124 cu. ft.	Curie Total = 0.044							Cr-51	4.4E-4
								H-3	5.7E-3
								I-125	9.3E-4
								S-35	2.3E-2
Appleton, WI	Medical	0	0	56	0	0	1	H-3	3.3E-3
Total Volume = 56 cu. ft.	Curie Total = 0.003								
Rochester, MN	Medical	0	0	272	0	0	1	C-14	3.8E-5
Total Volume = 272 cu. ft.	Curie Total = 0.03							Cr-51	1.3E-4
								H-3	3.2E-3
								I-125	2.2E-2
								P-32	4.2E-3
								S-35	1.3E-5
Detroit, MI	Medical	0	0	1222	0	0	3	C-14	3.0E-2
Total Volume = 1222 cu. ft.	Curie Total = 3.76							Cl-36	8.7E-4
								Cr-51	8.1E-2
								H-3	2.3E 0
								I-125	2.6E-1
								P-32	7.9E-1
								S-35	2.8E-1
Lacrosse, WI	Medical	0	0	39	0	0	1	C-14	1.3E-4
Total Volume = 39 cu. ft.	Curie Total = 0.008							Cr-51	2.4E-3
								H-3	4.8E-3
								I-125	1.1E-3

Location	Generator Type	Volume (ft^3) Cask	Drum	LSA Box	Annual Shipments Cask	Drum	LSA Box	Isotope	Curies
Milwaukee, WI	University	163	0	402	1	0	1	C-14	1.1E 0
Total Volume = 565 cu. ft.	Curie Total = 519							Cl-36	9.5E 0
								H-3	6.3E 1
								I-125	3.5E 0
								P-32	4.1E 2
								S-35	3.0E 1
								Sr-85	1.7E 0
Cincinnati, OH	University	0	0	1543	0	0	3	C-14	6.7E-2
Total Volume = 1543 cu. ft.	Curie Total = 0.887							Co-60	1.3E-3
								Cr-51	5.2E-1
								Cs-137	1.1E-3
								H-3	2.8E-1
								I-125	7.3E-3
								Ni-63	3.8E-5
								P-32	4.1E 2
St. Louis, MO	University	163	0	7641	1	0	14	C-14	1.1E 0
Total Volume = 7804 cu. ft.	Curie Total = 24.8							Co-60	2.5E 0
								Cs-137	1.2E 0
								H-3	1.9E 1
								Sr-90	9.6E-1
W. Lafayette, IN	University	0	0	191	0	0	1	C-14	5.2E-2
Total Volume = 191 cu. ft.	Curie Total = 1.28							Cl-36	1.7E-4
								H-3	1.2E 0
								I-125	1.7E-2
								P-32	1.6E-3
								S-35	9.5E-3
Madison, WI	University	0	0	148	0	0	1	C-14	1.1E-2
Total Volume = 148 cu. ft.	Curie Total = 0.076							Cl-36	2.8E-5
								Cs-137	6.0E-6
								H-3	6.5E-2
Stevens Point, WI	University	0	0	4	0	0	1	C-14	1.0E-4
Total Volume = 4 cu. ft.	Curie Total = 1.0E-4								
Ames, IA	University	0	0	134	0	0	1	C-14	3.8E-3
Total Volume = 134 cu. ft.	Curie Total = 0.305							Co-60	5.0E-6
								Cs-137	2.0E-4
								Fe-55	4.0E-2
								H-3	2.6E-1
								Ra-226	7.0E-5
								Th-232	9E-6
Bloomington, IN	University	0	0	343	0	0	1	C-14	9.5E-2
Total Volume = 343 cu. ft.	Curie Total = 1.92							Co-60	8.5E-2
								H-3	1.6E 0
								Sr-90	7.4E-2

Location	Generator Type	Volume (ft³) Cask	Drum	LSA Box	Annual Shipments Cask	Drum	LSA Box	Isotope	Curies
Duluth, MN	University	0	0	388	0	0	1	C-14	2.6E-2
Total Volume = 388 cu. ft.	Curie Total = 0.486							H-3	4.6E-1
Columbus, OH	University	0	0	1306	0	0	3	C-14	8.5E-2
Total Volume = 1306 cu. ft.	Curie Total = 0.875							Cr-51	1.4E-1
								H-3	3.9E-1
								I-125	2.4E-1
								P-32	1.1E-2
								S-35	9.2E-3
Columbia, MO	University	18	0	325	1	0	1	C-14	1.6E-2
Total Volume = 343 cu. ft.	Curie Total = 19.2							Co-60	5.3E 0
								Cs-137	3.8E 0
								H-3	1.0E 1
								I-129	3.8E-4
								Nb-94	1.0E-4
								Ni-59	3.3E-3
								Ni-63	7.2E-2
								Pu-241	3.2E-2
								Sr-90	1.8E-2
Ann Arbor, MI	University	0	0	989	0	0	2	C-14	5.6E-2
Total Volume = 989 cu. ft.	Curie Total = 0.435							Cr-51	1.5E-3
								H-3	2.2E-1
								I-125	1.2E-1
								P-32	5.3E-3
								S-35	4.8E-3
Minneapolis, MN	University	0	0	7133	0	0	13	C-14	2.0E-1
Total Volume = 7133 cu. ft.	Curie Total = 7.98							Cr-51	1.5E 0
								H-3	2.6E 0
								I-125	9.5E-1
								P-32	2.0E 0
								S-35	8.0E-1
E. Lansing, MI	University	0	0	3513	0	0	7	C-14	1.0E-1
Total Volume = 3513 cu. ft.	Curie Total = 1.52							H-3	8.6E-1
								I-125	2.0E-1
								P-32	3.4E-1
								S-35	1.6E-3
								Sr-85	1.8E-4
Dayton, OH	University	0	0	148	0	0	1	C-14	1.1E-1
Total Volume = 148 cu. ft.	Curie Total = 0.875							Cl-36	7.8E-4
								Co-60	3.1E-2
								Cs-137	2.3E-5
								Fe-55	2.4E-2
								H-3	8.6E-2
								Kr-85	3.9E-4
								S-35	3.4E-4
								U-238	1.1E-5

Location	Generator Type	Volume (ft³) Cask	Drum	LSA Box	Annual Shipments Cask	Drum	LSA Box	Isotope	Curies
Muskegon, MI	Industrial	0	0	300	0	0	1	C-14	3.8E-2
Total Volume = 300 cu. ft.	Curie Total = 0.113							Cr-51	2.3E-5
								H-3	4.5E-2
								I-125	9.0E-3
								P-32	2.1E-3
Centerville, OH	Industrial	0	0	148	0	0	1	C-14	4.0E-3
Total Volume = 148 cu. ft.	Curie Total = 0.004								
Mattawan, MI	Industrial	99	0	0	3	0	0	Am-241	4.1E 1
Total Volume = 99 cu. ft.	Curie Total = 92.0							Cs-137	2.0E 1
								Pu-239	3.1E 1
								Ra-226	1.2E-2
South Bend, IN	Industrial	0	0	501	0	0	1	Co-60	1.0E-3
Total Volume = 501 cu. ft.	Curie Total = 0.645							Cs-137	1.2E-3
								H-3	4.0E-1
								Ra-226	5.0E-4
								Th-232	2.3E-1
								U-235	1.2E-2
Elkhart, IN	Industrial	0	0	71	0	0	1	C-14	1.6E 0
Total Volume = 71 cu. ft.	Curie Total = 1.6								
Minneapolis, MN	Industrial	681	0	5650	5	0	11	C-14	1.0E-1
Total Volume = 6331 cu. ft.	Curie Total = 1620							Cs-137	1.0E 3
								I-125	2.5E 1
								Kr-85	1.0E 1
								Pm-147	5.0E 0
								Po-210	6.0E 2
								Ra-226	2.0E 0
								Sr-90	4.0E-1
Athens, OH	Industrial	0	0	399	0	0	1	C-14	1.1E-2
Total Volume = 399 cu.ft.	Curie Total = 0.202							H-3	8.1E-2
								I-125	1.1E-1
Warren, MI	Industrial	150	0	58	4	0	1	Am-241	4.4E 0
Total Volume = 208 cu.ft.	Curie Total = 94.7							Co-60	4.0E 0
								Cs-137	8.0E 1
								Fe-55	8.0E-2
								Kr-85	6.0E 0
								Ra-226	8.0E-3
								Sr-90	1.6E-1
Minneapolis, MN	Industrial	0	0	9357	0	0	17	Am-241	3.3E-2
Total Volume = 9357 cu. ft.	Curie Total = 5.23							H-3	2.0E-1
								U-238	5.0E 0

Location	Generator Type	Volume (ft^3) Cask	Volume (ft^3) Drum	Volume (ft^3) LSA Box	Annual Shipments Cask	Annual Shipments Drum	Annual Shipments LSA Box	Isotope	Curies
Indianapolis, IN	Industrial	0	0	2984	0	0	6	C-14	1.1E 0
Total Volume = 2984 cu. ft.	Curie Total = 13.8							Cl-36	1.6E-3
								Cr-51	1.3E-1
								H-3	8.0E 0
								I-125	4.0E 0
								P-32	5.3E-1
								S-35	1.9E-2
								Sr-85	1.6E-3
Akron, OH	Industrial	0	0	201	0	0	1	I-125	3.3E-1
Total Volume = 201 cu. ft.	Curie Total = 0.33								
Des Moines, IA	Industrial	109	0	0	1	0	0	Co-60	2.1E 2
Total Volume = 109 cu. ft.	Curie Total = 210								
Clinton, IA	Industrial	0	0	14	0	0	1	Sr-90	6.1E 0
Total Volume = 14 cu. ft.	Curie Total = 6.1								
Atlantic, IA	Industrial	0	0	4	0	0	1	C-14	5.0E-6
Total Volume = 4 cu. ft.	Curie Total = 5.0E-6								
Chaska, MN	Industrial	0	0	56	0	0	1	C-14	1.5E-3
Total Volume = 56 cu. ft.	Curie Total = 0.266							H-3	2.6E-1
								I-125	3.9E-4
								Ni-63	3.1E-3
								P-32	5.5E-5
								S-35	7.7E-4
Southfield, MI	Industrial	0	0	60	0	0	1	C-14	1.0E-5
Total Volume = 60 cu. ft.	Curie Total = 1.0E-5								
Indianapolis, IN	Industrial	0	0	900	0	0	2	C-14	7.8E-1
Total Volume = 900 cu. ft.	Curie Total = 1.04							H-3	2.3E-1
								I-125	3.3E-2
								P-32	5.9E-4
Mt. Vernon, IA	Industrial	0	0	11	0	0	1	C-14	5.0E-4
Total Volume = 11 cu. ft.	Curie Total = 7.5E-4								
Kalamazoo, MI	Industrial	0	0	7	0	0	1	C-14	2.5E-2
Total Volume = 7 cu. ft.	Curie Total = 0.084							Cs-137	1.0E-3
								H-3	5.6E-2
								Ni-63	5.0E-4
Solon, OH	Government	0	0	39	0	0	1	C-14	4.3E-3
Total Volume = 39 cu. ft.	Curie Total = 0.016							H-3	1.1E-2
								Ni-63	2.4E-4
								Sr-90	1.2E-6

Location	Generator Type	Volume (ft³) Cask	Drum	LSA Box	Annual Shipments Cask	Drum	LSA Box	Isotope	Curies
Yellow Springs, OH	Government	0	0	11	0	0	1	C-14	1.8E-1
Total Volume = 11 cu. ft.	Curie Total = 0.18								
Charles City, IA	Government	0	0	60	0	0	1	C-14	1.0E-4
Total Volume = 60 cu. ft.	Curie Total = 4.8E-4							H-3	3.8E-4

Appendix B

NODE DATA FOR THE MILLRWC TRANSPORTATION NETWORK

Appendix B

Node Data for the MILLRWC Transportation Network

Node	Location	Intersection	Node	Location	Intersection
3	Fargo, ND	I-29, I-94	80	Fidelity, MO	I-44, US-71
12	E Sioux Falls, SD	I-90, I-229	81	Springfield, MO	I-44, US-65
14	Sioux City, IA	I-29, US-75	82	Kirkwood, MO	I-44, I-270
15	Missouri Valley, IA	I-680, I-29	83	Mehlville, MO	I-55, I-270
16	N Council Bluffs, IA	I-680, I-29	84	Crystal City, MO	I-55, US-67
17	Council Bluffs, IA	I-80, I-29	85	Cape Girardeau, MO	I-55, MO-146
24	Neola, IA	I-80, I-680	86	Miner, MO	I-55, I-57
25	St. Joseph, MO	I-29, US-36	87	Hayti, MO	I-55, I-155
26	N Kansas City, MO	I-29, I-635	88	Cooter, MO	I-55, US-61
27	N Kansas City, MO	I-29, I-35	89	Caruthersville, MO	I-155, Co-J
28	N Kansas City, MO	I-35, I-435	90	Charlestown, MO	I-57, US-60
29	Kansas City, MO	I-70, I-435	91	Bridgeton, MO	I-70, I-270
30	Kansas City, MO	I-435, I-70, US-71	92	St. Louis, MO	I-55, I-70
31	Kansas City, MO	I-29, I-35, I-70	93	Columbia, MO	I-70, US-63
48	NW Minneapolis, MN	I-94, I-494	94	Elk Mound, WI	I-94, WI-29
49	SW Minneapolis, MN	I-494, US-169	95	Rice Lake, WI	US-53, WI-48
50	Bloomington, MN	I-35, I-494	96	Chippewa Falls, WI	US-53, WI-29
51	S St. Paul, MN	I-494, MN-3	97	Eau Claire, WI	I-94, US-53
52	SE St. Paul, MN	I-494, US-10	98	East St. Louis, IL	I-55, I-64
53	N Minneapolis, MN	I-694, I-35W	99	Tomah, WI	I-90, I-94
54	N St. Paul, MN	I-694, I-35E	100	Portage, WI	I-90, I-94, US-51
55	NE St. Paul, MN	I-694, MN-36	101	Merrill, WI	US-51, WI-17
56	Hastings, MN	US-61, MN-55	102	Madison, WI	I-90, I-94
57	Lino Lakes, MN	I-35, I-35E, I-35W	103	Beloit, WI	I-90, WI-15
58	Barnum, MN	I-35, Co-5	104	Green Bay, WI	I-43, WI-54
59	Duluth, MN	I-35, I-535	105	Oshkosh, WI	US-41, WI-21
60	E St. Paul, MN	I-94, I-494, I-694	106	Bayside, WI	I-43, WI-100
61	Albert Lea, MN	I-35, I-90	107	Menomonee Falls, WI	US-41, WI-100
62	Dexter, MN	I-90, MN-16	108	West Allis, WI	US-45, I-94, I-894
63	Marion, MN	I-90, US-52	109	SW Milwaukee, WI	I-894, WI-15
64	La Crescent, MN	I-90, US-61	110	Milwaukee, WI	I-43, I-94
65	Minneapolis, MN	I-94, I-35W	111	S Milwaukee, WI	I-94, I-894
66	St. Paul, MN	I-35E, I-94	112	Rockford, IL	I-90, US-20
67	Ames, IA	I-35, US-30	113	Arlington Hts., IL	I-90, I-290
68	NE Des Moines, IA	I-35, I-80	114	Northbrook, IL	I-94, I-294, IL-68
69	SE Des Moines, IA	I-235, US-65	115	Highland Park, IL	I-94, US-41
70	NW Des Moines, IA	I-80, IA-141	116	Buffalo Grove, IL	I-290, IL-68
71	SW Des Moines, IA	I-35, I-80	117	Rosemont, IL	I-90, I-294
72	Tiffin, IA	I-80, I-380	118	NW Chicago, IL	I-90, I-94
73	N Davenport, IA	I-80, I-280	119	Elmhurst, IL	I-290, I-294
74	Bettendorf, IA	I-80, I-74	120	Chicago Loop, IL	I-90, I-94, I-290
75	W Davenport, IA	I-280, US-61	121	Burr Ridge, IL	I-55, I-294
76	Rock Island, IL	I-74, I-80, I-280	122	S Chicago, IL	I-90, I-94
77	Moline, IL	I-74, I-80, I-280	123	Plainfield, IL	I-55
78	Harrisonville, MO	US-71, MO-13	124	Joliet, IL	I-55, I-80
79	Joplin, MO	I-44, US-166	125	Tinley Park, IL	I-57, I-80

Node	Location	Intersection	Node	Location	Intersection
126	S Chicago, IL	I-57, I-94	180	N Ann Arbor, MI	US-23, MI-14
127	Hazel Crest, IL	I-80, I-294	181	Ann Arbor, MI	I-94, MI-14
128	South Holland, IL	I-80, I-94, I-294	182	NE Ann Arbor, MI	US-23, MI-14
129	Barstow, IL	I-80, IL-5	183	SE Ann Arbor, MI	I-94, US-23
130	Dixon, IL	IL-5, US-52	184	Farmington, MI	I-96, I-275, I-696
131	Galesburg, IL	I-74, US-34	185	Livonia, MI	I-96, I-275, MI-14
132	NW Bloomington, IL	I-55, I-74	186	Wayne, MI	I-94, I-275
133	S Bloomington, IL	I-55, I-74, US-57	187	Southfield, MI	I-696,US-10,MI-39
134	Springfield, IL	I-55, I-72, IL-54	188	W Detroit, MI	I-96, MI-39
135	W Decatur, IL	I-72, US-51	189	Dearborn, MI	I-94, MI-39
136	N Decatur, IL	I-72, US-51	190	Detroit, MI	I-75, I-94, I-96
137	Farmer City, IL	I-74, IL-54	191	Sylvania, OH	I-475, US-23
138	Champaign, IL	I-57, I-72, I-74	192	Toledo, OH	I-75, I-280
139	Effingham, IL	I-57, I-70	193	Port Huron, MI	I-69, I-94
140	S Springfield, IL	I-55, US-36	194	Fremont, IN	I-69, I-80, I-90
142	Troy, IL	I-55, I-70, I-270	195	Muncie, IN	I-69, IN-32
143	Salem, IL	I-57, US-50	196	NE Indianapolis,IN	I-69, I-465
144	Mt. Vernon, IL	I-57, I-64	197	Royalton, IN	I-65, I-465
145	Pulleys Mill, IL	I-57, I-24	198	NW Indianapolis, IN	I-465
146	S Gary, IN	I-65, I-80, I-94	199	W Indianapolis, IN	I-65, I-465
147	E Gary, IN	I-80, I-90, I-94	200	Indy Speedway, IN	I-74, I-465
148	Paducah, KY	I-24, US-45	201	Veedersburg, IN	I-74, US-41
149	Chicago, IL	I-55, I-90, I-94	202	E Indianapolis, IN	I-70, I-465
150	W Peoria, IL	I-74, I-474	203	Indianapolis, IN	I-65, I-70
151	Bartonville, IL	I-474, US-24	204	SW Indianapolis, IN	I-70, I-465
152	E Peoria, IL	I-74, I-474	205	S Indianapolis, IN	I-65, I-465
153	Sault Ste. Marie, MI	I-75	206	SE Indianapolis, IN	I-74, I-465
154	St. Ignace, MI	I-75, US-2	207	New Albany, IN	I-64, I-65
155	Grayling, MI	I-75, US-27	208	W New Albany, IN	I-64, US-150
156	Clare, MI	US-10, US-27	209	Ottawa Hills, OH	I-475, I-75
157	Bay City, MI	I-75, US-10	210	Maumee, OH	I-80, I-90, I-475
158	East Lansing, MI	I-69,I-496,US-127	211	Perrysburg, OH	I-75, I-475
159	S Lansing, MI	I-96, US-127	212	Lemoyne, OH	I-80, I-90, I-280
160	Jackson, MI	I-94, US-127	213	Amherst, OH	I-80, I-90
161	SW Lansing, MI	I-69, I-96	214	Elyria, OH	I-80, I-480
162	W Lansing, MI	I-96, I-496	215	Strongsville, OH	I-71, I-80
163	E Grand Rapids, MI	I-96, I-196	216	Brook Park, OH	I-71, I-480
164	N Grand Rapids, MI	I-96, US-131	217	Cleveland, OH	I-77, I-90, I-480
165	Grand Rapids, MI	I-196, US-131	218	Euclid, OH	I-90, OH-2
166	Reed City, MI	US-131, US-10	219	Willoughby Hills, OH	I-90, I-271
167	Muskegon, MI	I-96, US-31	220	Grand River, OH	OH-2, OH-44
168	Ludington, MI	US-31, US-10	221	Mentor, OH	I-90, OH-44
169	Holland, MI	I-196, US-31	222	Ashtabula, OH	I-90, OH-11
170	Benton Harbor, MI	I-94, I-96	223	Parma, OH	I-77, I-480
171	Kalamazoo, MI	I-94, US-131	224	Shaker Heights, OH	I-271, I-480
172	Marshall, MI	I-69, I-94	225	Northfield, OH	I-271, I-480
173	NW Flint, MI	I-75, I-475	226	Streetsboro, OH	I-80, I-480
174	NE Flint, MI	I-475, MI-54	227	Richfield, OH	I-77, I-271
175	Flint, MI	I-69, I-475	228	West Austintown, OH	I-76, I-80
176	Lapeer, MI	I-69, MI-24	229	Girard, OH	I-80, OH-11
177	W Flint, MI	I-69, I-75	230	Austintown, OH	I-80, OH-11
178	SW Flint, MI	I-75, US-23	231	Youngstown, OH	I-680, US-422
179	Brighton, MI	I-96, US-23	232	North Lima, OH	I-76, I-680

Node	Location	Intersection	Node	Location	Intersection
233	Bridgeport, OH	I-70, OH-7	283	S Louisville, KY	I-65, I-264
234	Akron, OH	I-76, I-77	284	NE Louisville, KY	I-71, I-624
235	W Akron, OH	I-76, I-77	285	E Louisville, KY	I-64, I-264
236	SW Akron, OH	I-76, I-277	286	Walton, KY	I-71, I-75
237	S Akron, OH	I-77, I-277	287	N Lexington, KY	I-64, I-75, US-25
238	Weymouth, OH	I-71, I-271	288	W Lexington, KY	US-60, KY-4
239	Seville, OH	I-71, I-76	289	Lexington, KY	US-25, US-60
240	NE Columbus, OH	I-71, I-270	290	S Lexington, KY	US-25,US-27,KY-4
241	Dublin, OH	I-270, US-33	291	E Lexington, KY	I-64, I-75, US-60
242	Lincoln Village, OH	I-70, I-270	294	Winchester, KY	I-64, BC Pkwy
243	Columbus, OH	I-70, I-71	295	Kenova, KY	I-64, US-23
244	SW Columbus, OH	I-71, I-270	296	Charleston, WV	I-64, I-77, I-79
245	Whitehall, OH	I-70, I-270	297	Ravenswood, WV	I-77, WV-2
246	Murlin Heights, OH	I-70, I-75	301	Rochelle, IL	US-51, IL-5
247	Cambridge, OH	I-70, I-77	302	Dyersburg, TN	I-155, US-51
248	Marietta, OH	I-77, OH-7	303	N Lansing, MI	I-69,US-27,US-127
249	Findlay, OH	I-75, US-23	304	NW Lansing, MI	I-69, I-96
250	N Columbus, OH	I-270, US-23	305	Charlotte, MI	I-69, US-27
251	Hamilton Meadows,OH	I-270, US-23	306	Canton, OH	I-77, US-62
252	Portsmouth, OH	US-23, US-52	307	River Falls, WI	I-94, WI-65
253	Dayton, OH	I-75, US-35	308	W Lafayette, IN	I-65, US-52
254	Glendale, OH	I-75, I-275	309	Stevens Point, WI	US-51, US-10
255	Cincinnati, OH	I-71, I-75	310	Bloomington, IN	IN-37, IN-46
256	Taylors Creek, OH	I-74, I-275	311	South Bend, IN	I-80,90, US-31
257	Miamitown, OH	I-74, I-275	312	Elkhart, IN	I-80,90, IN-19
258	Petersburg, KY	I-275, KY-338	313	Athens, OH	US-33, US-50
259	Covington, KY	I-71, I-75, I-275	314	Clinton, IA	US-67, US-30
260	Highland Heights, KY	I-275, I-471	315	Le Claire, IA	I-80, US-67
261	Withamsville, OH	I-275, OH-125	316	Atlantic, IA	I-80, US-6
262	Brecon, OH	I-71, I-275	317	Springfield, OH	I-70, US-68
263	NW Akron, OH	I-77, OH-21	318	Mason City, IA	I-35, US-18
264	Norton, OH	I-76, OH-21	334	Monticello, MN	I-94, MN-25
265	Warrenton, IN	I-64, US-41	335	Red Wing, MN	US-61, US-63
266	Fulton, KY	US-51, Pur Pkwy	336	Cedar Rapids, IA	I-380, IA-94
267	Mayfield, KY	US-45, Pur Pkwy	337	Fulton, MO	I-70, US-54
268	Gilbertsville, KY	I-24, Pur Pkwy	338	Genoa, WI	I-90, US-53
269	Eddyville, KY	I-24, W KY Pkwy	339	Manitowoc, WI	I-43, WI-42
270	Mortons Gap, KY	US-41,W KY Pkwy	340	Manitowoc, WI	I-43, WI-42
272	Henderson, KY	US-41, Aud Pkwy	348	Indian River, MI	I-75, MI-68
273	Owensboro, KY	Aud Pky, GR Pky	350	Covert, MI	I-196
274	Beaver Dam, KY	W KY Pky,GR Pky	351	Bridgman, MI	I-94
278	Elizabethtown, KY	I-65, W KY Pkwy	352	Newport, MI	I-75, I-275
279	NW Louisville, KY	I-64, I-264	354	Oak Harbor, OH	I-80,90, OH-53
280	SW Louisville, KY	I-264, US-60	355	North Perry, OH	I-90, US-20
282	Louisville, KY	I-64, I-65			

Appendix C

LINK DATA
FOR THE MILLRWC
TRANSPORTATION NETWORK

Appendix C

Link Data for the MILLRWC Transportation Network

Link	A Node	B Node	Route	Between	Miles	AcRt (E-7)	Pop Dens	PD Class	Connecting Links
1	3	334	I-94	I-29 & MN-25	193	16	327	Rural	23
2	12	61	I-90	I-229 & I-35	172	10	389	Rural	26, 45, 46
3	14	15	I-29	US-75 & I-680	75	10	141	Rural	4, 5
4	15	16	I-29, I-680	I-680 & I-680	10	5	454	Rural	3, 5, 6
5	15	24	I-680	I-29 & I-80	16	8	171	Rural	3, 4, 7, 9
6	16	17	I-29	I-680 & I-80	10	27	850	Suburban	4, 7, 8
7	17	24	I-80	I-29 & I-680	27	20	471	Rural	5, 6, 8, 9
8	17	25	I-29	I-80 & US-36	128	5	11	Rural	6, 7, 10
9	24	316	I-80	I-680 & US-6	30	12	157	Rural	5, 7, 416
10	25	26	I-29	US-36 & I-635	40	9	550	Suburban	8, 11, 12
11	26	27	I-29	I-635 & I-35	4	3	1150	Suburban	10, 12, 13, 14
12	26	30	I-635, I-435	I-29 & US-71	29	7	1050	Suburban	10, 11, 17, 20
13	27	28	I-35	I-29 & I-435	4	12	1050	Suburban	11, 14, 15, 16
14	27	31	I-29, I-35	I-29, I-35 & I-70	4	16	2300	Urban	11, 13, 18
15	28	29	I-435	I-35 & I-70	7	7	750	Suburban	13, 16, 17, 18, 19
16	28	71	I-35	I-435 & I-80	168	3	109	Rural	13, 15, 56, 57, 416
17	29	30	I-435	I-70 & US-71	7	11	1900	Urban	12, 15, 18, 19, 20
18	29	31	I-70	I-435 & I-29,I-35	5	54	2300	Urban	14, 15, 17, 19
19	29	93	I-70	I-435 & US-63	124	5	266	Rural	15, 17, 18, 89
20	30	78	US-71	I-435 & MO-7	23	8	394	Rural	12, 17, 69
21	48	49	I-494	I-94 & US-169	16	20	1250	Suburban	22, 23, 24
22	48	53	I-94, I-694	I-494 & I-35W	14	15	1350	Suburban	21, 23, 32, 33, 34
23	48	334	I-94	MN-25 & I-494	23	10	192	Rural	1, 21, 22
24	49	50	I-494	US-169 & I-35W	6	9	1550	Suburban	21, 25, 26, 27
25	50	51	I-494	I-35W & MN-3	9	5	750	Suburban	24, 26, 27, 28, 29
26	50	61	I-35	I-494 & I-90	82	8	305	Rural	2, 24, 25, 27, 45, 46
27	50	65	I-35W	I-494 & I-94	6	21	2100	Urban	24, 25, 26, 34, 39, 51
28	51	52	I-494	MN-3 & US-10	3	5	650	Suburban	25, 29, 30, 31

Link	A Node	B Node	Route	Between	Miles	AcRt (E-7)	Pop Dens	PD Class	Connecting Links
29	51	66	MN-3	MN-110 & I-94	5	40	3500	Urban	25, 28, 37, 43, 51
30	52	56	US-10	I-494 & US-61	12	7	550	Suburban	28, 31, 40
31	52	60	I-494	US-10 & I-94	5	9	650	Suburban	28, 30, 38, 43, 44
32	53	54	I-694	I-35W & I-35E	6	12	1150	Suburban	22, 33, 34, 35, 36, 37
33	53	57	I-35W	I-694 & I-35E	15	35	850	Suburban	22, 32, 34, 36, 41
34	53	65	I-35W	I-94 & I-694	11	16	3500	Urban	22, 27, 32, 33, 39, 51
35	54	55	I-694	I-35E & MN-36	5	9	1550	Suburban	32, 36, 37, 38, 39
36	54	57	I-35E	I-694 & I-35W	10	20	950	Suburban	32, 33, 35, 37, 41
37	54	66	I-35E	I-694 & I-94	6	29	1900	Urban	29, 32, 35, 36, 43, 51
38	55	60	I-694	MN-36 & I-94	6	12	650	Suburban	31, 35, 39, 43, 44
39	55	65	MN-36,I-35W	I-694 & I-94	15	54	2700	Urban	27, 34, 35, 38, 51
40	56	335	US-61	US-10 & US-63	24	10	380	Rural	30
41	57	58	I-35	I-35E,W & Co-5	95	6	351	Rural	33, 36, 42
42	58	59	I-35	Co-5 & I-535	32	10	376	Rural	41
43	60	66	I-94	I-694 & I-35E	6	16	1700	Urban	29, 31, 37, 38, 44, 51
44	60	307	I-94	I-694 & WI-65	21	5	79	Suburban	31, 38, 43, 406
45	61	62	I-90	I-35 & MN-16	30	4	266	Rural	2, 26, 46, 47
46	61	318	I-35	I-90 & US-18	40	12	287	Rural	2, 26, 45, 418
47	62	63	I-90	MN-16 & US-52	24	3	375	Rural	45, 48
48	63	64	I-90	US-52 & US-61	58	6	245	Rural	47, 49, 50
49	64	335	US-61	I-90 & US-63	78	16	49	Rural	40, 48, 50
50	64	338	I-90	US-61 & WI-16	5	6	218	Rural	48, 49, 97
51	65	66	I-94	I-35E & I-35W	9	21	3100	Urban	27, 29, 34, 37, 39, 43
52	67	68	I-35	US-30 & I-80	25	5	279	Rural	53, 54, 55, 418
53	68	69	I-235	I-80 & US-65	4	7	850	Suburban	52, 54, 55, 56
54	68	70	I-35,80	I-235 & IA-141	9	20	750	Suburban	52, 53, 55, 57
55	68	72	I-80	I-35 & I-380	99	10	381	Rural	52, 53, 54, 58, 59
56	69	71	I-235	US-65 & I-35	9	5	750	Suburban	16, 53, 57, 416
57	70	71	I-35,80	IA-141 & I-235	5	46	750	Suburban	16, 54, 56, 416
58	72	73	I-80	I-380 & I-280	53	5	396	Rural	55, 59, 60, 61
59	72	336	I-380	I-80 & IA-94	20	9	650	Suburban	55, 58
60	73	74	I-80	I-280 & I-74	9	4	383	Rural	58, 61, 62, 63
61	73	75	I-280	I-80 & US-61	6	4	474	Rural	58, 60, 64
62	74	76	I-74	I-80 & I-280	11	12	1250	Suburban	60, 63, 64, 65
63	74	315	I-80	I-74 & US-67	8	35	550	Suburban	60, 62, 414, 415

Link	A Node	B Node	Route	Between	Miles	AcRt (E-7)	Pop Dens	PD Class	Connecting Links
64	75	76	I-280	US-61 & US-150	10	7	1150	Suburban	61, 62, 65
65	76	77	I-280	US-150 & I-80,I-74	11	9	850	Suburban	62, 64, 66, 67, 68
66	77	124	I-80	I-74 & I-55	116	8	390	Rural	65, 67, 68, 138, 139, 140
67	77	129	I-80	I-74 & IL-5	6	10	426	Rural	63, 65, 66, 68, 147, 414
68	77	131	I-74	I-80 & US-150	34	10	248	Rural	65, 66, 67, 149
69	78	80	US-71	MO-7 & I-44	105	8	128	Rural	20, 70, 71
70	79	80	I-44	US-166 & US-71	17	3	650	Suburban	69, 71
71	80	81	I-44	US-71 & US-65	61	20	408	Rural	69, 70, 72
72	81	82	I-44	US-65 & I-270	189	5	64	Rural	71, 73, 74, 75
73	82	83	I-270	I-44 & I-55	6	7	750	Suburban	72, 74, 75, 76, 77
74	82	91	I-270	I-44 & I-70	14	3	1050	Suburban	72, 73, 75, 86, 87, 403
75	82	92	I-44	I-270 & I-55,I-70	14	8	1900	Urban	72, 73, 74, 77, 86, 88
76	83	84	I-55	I-270 & US-67	22	3	155	Rural	73, 77, 78
77	83	92	I-55	I-270 & I-70	13	21	3500	Urban	73, 75, 76, 86, 88
78	84	85	I-55	US-67 & MO-64	81	4	327	Rural	76, 79
79	85	86	I-55	MO-74 & I-57	27	6	186	Rural	78, 80, 81
80	86	87	I-55	I-57 & I-155	45	5	351	Rural	79, 81, 82, 83
81	86	90	I-57	I-55 & US-60	13	6	144	Rural	79, 80, 85
82	87	88	I-55	I-155 & US-61	17	10	112	Rural	80, 83
83	87	89	I-155	I-55 & Co-J	6	12	400	Rural	80, 82, 84
84	89	302	I-155	I-55 & US-51	19	12	99	Rural	83, 366
85	90	145	I-57	US-60 & I-24	53	6	109	Rural	81, 166, 168
86	91	92	I-70	I-270 & I-55	20	8	3300	Urban	74, 75, 77, 87, 88, 403
87	91	337	I-70	I-270 & US-54	84	8	134	Rural	74, 86, 89, 403
88	92	98	I-55,70	I-70 & I-64	4	16	2100	Urban	75, 77, 86, 94, 95
89	93	337	I-70	US-63 & US-54	19	8	206	Rural	19, 87
90	94	97	I-94	WI-29 & US-53	19	12	448	Rural	92, 93, 406
91	95	96	US-53	WI-48 & WI-29	48	10	163	Rural	92
92	96	97	US-53	WI-29 & I-94	11	8	283	Rural	90, 91, 93
93	97	99	I-94	US-53 & I-90	78	10	116	Rural	90, 92, 96, 97
94	98	142	I-55,70	I-64 & I-270	15	9	1550	Suburban	88, 95, 161, 164, 403
95	98	144	I-64	I-55,70 & I-57	72	3	550	Suburban	88, 94, 165, 166, 167
96	99	100	I-90,94	I-94 & US-51	64	5	346	Rural	93, 97, 98, 99
97	99	338	I-90	US-53 & I-94	41	8	156	Rural	50, 93, 96
98	100	309	US-51	I-90 & US-10	80	4	16	Rural	96, 99, 408

Link	A Node	B Node	Route	Between	Miles	AcRt (E-7)	Pop Dens	PD Class	Connecting Links
99	100	102	I-90,94	US-51 & I-94	30	5	496	Rural	96, 98, 100, 101
100	102	103	I-90	I-94 & WI-15	47	27	750	Suburban	99, 101, 102, 103
101	102	108	I-94	I-90 & I-894	64	5	499	Rural	99, 100, 110, 111, 112
102	103	109	WI-15	I-90 & I-894	54	8	163	Rural	100, 103, 111, 113
103	103	112	I-90	WI-15 & US-20	18	35	650	Suburban	100, 102, 116, 117
104	104	105	US-41	I-43 & WI-21	52	7	650	Suburban	105, 106
105	104	339	I-43	US-41 & WI-42	39	6	422	Rural	104, 109
106	105	107	US-41	WI-21 & US-45	64	20	415	Rural	104, 107, 110
107	106	107	WI-100	I-43 & US-45	8	7	650	Suburban	106, 108, 109, 110
108	106	110	I-43	WI-100 & I-94	10	6	2300	Urban	107, 109, 112, 114
109	106	339	I-43	WI-100 & WI-42	67	6	457	Rural	105, 107, 108
110	107	108	I-894	WI-100 & I-94	7	5	1250	Suburban	10, 106, 107, 111, 112
111	108	109	I-894	I-94 & WI-15	4	9	1050	Suburban	101, 102, 110, 112, 112
112	108	110	I-94	I-894 & I-43	2	21	1700	Urban	101, 108, 110, 111, 114
113	109	111	I-894	WI-15 & I-94	2	12	750	Suburban	102, 111, 114, 115
114	110	111	I-94	I-43 & I-894	6	29	1900	Urban	108, 112, 113, 115
115	111	114	I-94	I-894 & I-294	74	9	950	Suburban	113, 114, 121, 122, 123
116	112	113	I-90	US-20 & I-290	48	12	432	Rural	103, 117, 118, 119, 120
117	112	301	US-51	I-90 & IL-5	30	12	277	Rural	103, 116, 130, 148
118	113	116	I-290	I-90 & IL-68	6	15	950	Suburban	116, 119, 120, 122
119	113	117	I-90	I-290 & I-294	9	12	1250	Suburban	116, 118, 120, 123, 125, 126
120	113	119	I-290	I-90 & I-294	17	7	750	Suburban	116 ,118, 119, 126, 128, 129, 130
121	114	115	I-94	I-294 & US-41	6	15	550	Suburban	115, 122, 123, 124
122	114	116	IL-68	I-290 & I-94	6	4	850	Suburban	115, 118, 121 ,123
123	114	117	I-294	I-94 & I-90	12	12	1550	Suburban	115, 119, 121, 122, 125, 126
124	115	118	I-94	US-41 & I-90	15	11	1700	Urban	121, 125, 127
125	117	118	I-90	I-294 & I-94	7	8	2300	Urban	119, 123, 124, 126, 127
126	117	119	I-294	I-90 & I-290 & IL-5	8	15	1550	Suburban	119, 120, 123, 125, 128, 129, 130
127	118	120	I-90,94	I-94 & I-290	8	21	3100	Urban	124, 124, 128, 131
128	119	120	I-290	IL-5& I-294 & I-90,94	15	4	2500	Urban	120, 126, 127, 129, 130, 131
129	119	121	I-294	IL-5 & I-290 & I-55	8	27	1050	Suburban	120, 126, 128, 130, 132, 134
130	119	301	IL-5	I-290& I-294 & US-51	63	6	464	Rural	117, 120, 126, 128, 129, 148
131	120	149	I-90,94	I-290 & I-55	2	21	2300	Urban	127, 128, 134, 137
132	121	123	I-55	I-294 & Plainfield	16	8	290	Rural	129, 133, 134, 138
133	121	127	I-294	I-55 & I-94	18	27	1350	Suburban	129, 132, 134, 142, 145

Link	A Node	B Node	Route	Between	Miles	AcRt (E-7)	Pop Dens	PD Class	Connecting Links
134	121	149	I-55	I-294 & I-90,94	22	16	2500	Urban	129, 131, 132, 133, 137
135	122	126	I-94	I-90 & I-57	4	16	3300	Urban	136, 137, 141, 144
136	122	147	I-90	I-94 & I-80	27	21	3100	Urban	135, 137, 169, 171, 172
137	122	149	I-90,94	I-90 & I-55	6	40	3500	Urban	131, 134, 135 ,136
138	123	124	I-55	Plainfield & I-80	14	6	409	Rural	66, 132, 139, 140
139	124	125	I-80	I-55 & I-57	31	4	750	Suburban	66, 138, 140, 141, 142, 143
140	124	132	I-55	I-80 & I-74	87	6	206	Rural	66, 138, 139, 150, 151
141	125	126	I-57	I-80 & I-94	10	7	1250	Suburban	135, 139, 142, 143, 144
142	125	127	I-80	I-57 & I-294	3	20	1550	Suburban	133, 139, 141, 143, 145
143	125	138	I-57	I-80 & I-74	106	10	238	Rural	139, 141, 142, 157, 158, 159, 160
144	126	128	I-94	I-57 & I-80	12	12	1450	Suburban	135, 141, 145, 146
145	127	128	I-80	I-57 & I-94	5	20	1350	Suburban	133, 142, 144, 146
146	128	146	I-80,94	I-94 & I-65	15	16	1900	Urban	144, 145, 169, 170
147	129	130	IL-5	I-80 & US-52	52	6	133	Rural	63, 67, 148, 414
148	130	301	IL-5	US-52 & US-51	26	12	126	Rural	117, 130, 147
149	131	150	I-74	US-150 & I-474	42	12	109	Rural	68, 175, 176
150	132	133	I-74	I-55 & I-55	8	5	1250	Suburban	140, 151, 152, 153
151	132	152	I-74	I-474 & I-55	28	8	446	Rural	140, 150, 176, 177
152	133	134	I-55	I-74 & I-72	59	5	457	Rural	150, 153, 154, 155
153	133	137	I-74	I-55 & IL-54	24	6	62	Rural	150, 152, 158
154	134	135	I-72	I-55 & US-51	30	8	245	Rural	152, 155, 156
155	134	140	I-72	I-55 & US-36	7	20	1050	Suburban	152, 154, 164
156	135	136	I-72	US-36 & US-51	10	35	650	Suburban	154, 157
157	136	138	I-72	US-51 & I-74	40	5	355	Rural	143, 156, 158, 159, 160
158	137	138	I-74	IL-54 & I-72	20	8	225	Rural	143, 153, 157, 159, 160
159	138	139	I-57	I-74 & I-70	74	10	195	Rural	143, 157, 158, 160, 161, 162, 163
160	138	201	I-74	I-57 & US-41	55	8	244	Rural	143, 157 ,158, 159, 261
161	139	142	I-70	I-57 & I-55	84	6	87	Rural	94, 159, 162, 163, 164, 403
162	139	143	I-57	I-70 & US-50	47	8	128	Rural	159, 161, 163, 165
163	139	204	I-70	I-57 & I-465	132	12	274	Rural	159, 161, 162, 262, 266, 268
164	140	142	I-55	I-72 & I-70	72	10	157	Rural	94, 155, 161, 403
165	143	144	I-57	US-50 & I-64	22	6	134	Rural	95, 162, 166, 167
166	144	145	I-57	I-64 & I-24	50	12	271	Rural	85, 95, 165, 167, 168
167	144	265	I-64	I-57 & US-41	78	4	114	Rural	95, 165, 166, 274, 364
168	145	148	I-24	I-57 & US-45	44	10	383	Rural	85, 166, 173, 174

Link	A Node	B Node	Route	Between	Miles	AcRt (E-7)	Pop Dens	PD Class	Connecting Links
169	146	147	I-80,94	I-65 & I-90	3	74	2100	Urban	136, 146, 170, 171, 172
170	146	308	I-65	I-80,94 & US-52	85	2	104	Rural	146, 169, 407
171	147	311	I-80,90	I-94 & US-31	56	12	337	Rural	136, 169, 172, 410
172	147	351	I-94	I-80,90 & Bridgman	44	4	221	Rural	136, 169, 171, 211
173	148	267	US-41	I-24 & Purchase Pky	20	8	197	Rural	168, 174, 365, 367
174	148	268	I-24	US-41&Purchase Pky	18	6	435	Rural	168, 173, 367, 368
175	150	151	I-474	I-74 & US-24	7	15	850	Suburban	149, 176, 177
176	150	152	I-74	I-474 & I-474	10	54	2500	Urban	149, 151, 175, 177
177	151	152	I-474	US-24 & I-74	8	4	650	Suburban	151, 175, 176
178	153	154	I-75	Canada & US-2	51	9	59	Rural	179
179	154	348	I-75	US-2 & MI-66	34	5	11	Rural	178, 182
180	155	156	US-27	I-75 & US-10	53	13	67	Rural	181, 182, 183, 184, 401
181	155	157	I-75	US-27 & US-10	88	11	247	Rural	180, 182, 183, 185
182	155	348	I-75	US-27 & MI-66	61	6	73	Rural	179, 180, 181
183	156	157	US-10	US-27 & I-75	47	3	185	Rural	180, 181, 184, 185, 401
184	156	303	US-27	US-10 & US-127	72	8	419	Rural	180, 183, 189, 399, 401
185	157	173	I-75	US-10 & I-475	36	12	948	Suburban	181, 183, 214, 215
186	158	159	I-496, US-127	I-69 & I-96	4	13	1059	Suburban	187, 188, 189, 190, 191, 192
187	158	162	I-496	US-127 & I-96	7	9	1712	Urban	186, 188, 189, 195, 197
188	158	177	I-69	I-496,US-127 & I-75	45	13	704	Suburban	186, 187, 189, 215, 218, 221
189	158	303	US-127	I-69 & US-27	6	18	1735	Urban	184, 186, 187, 188, 399
190	159	160	US-127	I-96 & I-94	29	11	255	Rural	186, 191, 192 ,193, 194
191	159	161	I-96	US-127 & I-69	8	15	538	Suburban	186, 190, 192 ,195 ,196
192	159	179	I-96	US-127 & US-23	40	8	393	Rural	186, 190, 191, 222, 224, 225
193	160	172	I-94	US-127 & I-69	30	10	402	Rural	190, 194, 212, 213, 404
194	160	181	I-94	US-127 & MI-14	33	10	437	Rural	190, 193, 226, 228
195	161	162	I-96	I-69 & I-496	5	7	865	Suburban	187, 191, 196, 197
196	161	305	I-69	I-96 & US-27	12	18	253	Suburban	191, 195, 404
197	162	304	I-96	I-496 & US-27	3	12	442	Rural	187, 195, 200, 399
198	163	164	I-96	I-196 & US-131	6	9	1583	Suburban	199, 200, 201, 202, 203
199	163	165	I-196	I-96 & US-131	4	23	2109	Urban	198, 200, 201, 204, 205
200	163	304	I-96	I-196 & US-27	60	7	326	Rural	197, 198, 199, 399
201	164	165	US-131	I-96 & I-196	2	53	1708	Urban	198, 199, 202, 203, 204, 205
202	164	166	US-131	I-96 & US-10	68	10	154	Rural	198, 201, 203, 401, 402
203	164	167	I-96	US-131 & US-31	30	8	442	Rural	198, 201, 202, 206, 207

Link	A Node	B Node	Route	Between	Miles	AcRt (E-7)	Pop Dens	PD Class	Connecting Links
204	165	169	I-196	US-131 & US-31	32	9	765	Suburban	199, 201, 205, 207, 208
205	165	171	US-131	I-196 & I-94	52	23	623	Suburban	199, 201, 204, 209, 212
206	167	168	US-31	I-96 & US-10	67	17	202	Rural	203, 207, 402
207	167	169	US-31	I-96 & I-196	35	20	394	Rural	203, 204, 206, 208
208	169	350	I-196	US-31 & Covert	31	6	224	Rural	204, 207, 210
209	170	171	I-94	I-196 & US-131	39	8	247	Rural	205, 210, 211, 212
210	170	350	I-196	I-94 & Covert	13	5	72	Rural	208, 209, 211
211	170	351	I-94	I-196 & Bridgman	19	16	873	Suburban	172, 209, 210
212	171	172	I-94	US-131 & I-69	35	12	590	Suburban	193, 205, 209, 213, 404
213	172	194	I-69	I-94 & I-80,90	40	8	139	Rural	193, 212, 251, 252, 404, 411
214	173	174	I-475	I-75 & MI-54	3	1	1203	Suburban	185, 215, 216
215	173	177	I-75	I-475 & I-69	9	8	1890	Urban	185, 188, 214, 218, 221
216	174	175	I-475	MI-54 & I-69	8	16	2348	Urban	214, 217, 218, 219
217	175	176	I-69	I-475 & MI-24	20	15	717	Suburban	216, 218, 219, 220
218	175	177	I-69	I-475 & I-75	4	6	2124	Urban	188, 215, 216, 217, 219, 221
219	175	178	I-475	I-69 & I-75	8	10	797	Suburban	216, 217, 218, 221, 222, 223
220	176	193	I-69	MI-24 & I-94	46	1	171	Rural	217, 244
221	177	178	I-75	I-69 & US-23,I-475	2	55	1190	Suburban	188, 215 ,218, 219, 222, 223
222	178	179	US-23	I-75 & I-96	33	7	220	Rural	192, 219, 221, 223, 224, 225
223	178	190	I-75	US-23 & I-94, I-96	65	25	1118	Suburban	219, 221, 222, 240, 242, 243, 244, 245
224	179	180	US-23	I-96 & MI-14	14	12	187	Rural	192, 222, 225, 226, 227
225	179	184	I-96	US-23 & I-275,I-696	17	33	148	Rural	192, 222, 224, 233, 234
226	180	181	MI-14	US-23 & I-94	5	42	1940	Urban	194, 224, 227, 228
227	180	182	US-23, MI-14	US-23 & MI-14	3	19	514	Suburban	224, 226, 229, 230
228	181	183	I-94	MI-14 & US-23	9	14	1824	Urban	194, 226, 229, 231, 232
229	182	183	US-23	MI-14 & I-94	7	15	1889	Urban	227, 228, 230, 231, 232
230	182	185	MI-14	US-23 & I-275, I-96	15	4	535	Rural	227, 229, 233, 235, 236
231	183	186	I-94	US-23 & I-275	18	12	1359	Suburban	228, 229, 232, 235, 237, 238
232	183	191	US-23	I-94 & I-475	37	12	236	Rural	228, 229, 231, 246, 247
233	184	185	I-96, I-275	I-696 & I-96,I-275	7	8	659	Suburban	225, 230, 234, 235, 236
234	184	187	I-696	I-96,I-275 & MI-39	12	5	1485	Suburban	225, 233, 239, 240
235	185	186	I-275	I-96 & I-94	12	22	1088	Suburban	230, 231, 233, 236, 237, 238
236	185	188	I-96	I-275 & MI-39	8	121	2305	Urban	230, 233, 235, 239, 241, 242
237	186	189	I-94	I-275 & MI-39	10	24	1636	Urban	231, 235, 238, 241, 243
238	186	352	I-275	I-94 & I-75	17	12	243	Rural	231, 235, 237, 245, 250

Link	A Node	B Node	Route	Between	Miles	AcRt (E-7)	Pop Dens	PD Class	Connecting Links
239	187	188	MI-39	US-10,I-696 & I-96	5	21	3556	Urban	234, 236, 240, 241, 242
240	187	190	US-10	MI-39&I-75,I-94,I-96	10	17	3356	Urban	223, 234, 239, 242, 243, 244, 245
241	188	189	MI-39	I-96 & I-94	9	14	2474	Urban	236, 237, 239, 242, 243
242	188	190	I-96	MI-39 & I-75, I-94	9	60	2984	Urban	223, 236, 239, 240, 241, 243, 244, 245
243	189	190	I-94	MI-39 & I-75, I-96	11	68	2747	Urban	223, 237, 240 ,241, 242, 244, 245
244	190	193	I-94	I-75,I-96,US-10&I-69	57	11	1373	Suburban	220, 223, 240, 242, 243, 245
245	190	352	I-75	I-94, I-96 & I-275	30	51	1538	Suburban	223, 238, 240, 242, 243, 244, 250
246	191	209	I-475	US-23 & I-75	7	7	1350	Suburban	232, 247, 248, 276
247	191	210	I-475	US-23 & I-80,90	7	4	1150	Suburban	232, 246, 252, 277, 278
248	192	209	I-75	I-280 & I-475	4	54	2300	Urban	246, 249, 250, 276
249	192	212	I-280	I-75 & I-80,90	13	54	1900	Urban	248, 250, 278, 280
250	192	352	I-75	I-475 & I-275	24	9	424	Rural	238, 245, 248, 249
251	194	195	I-69	I-80,90 & IN-32	123	10	277	Rural	213, 252, 253, 411
252	194	210	I-80,90	I-69 & I-475	70	5	71	Rural	213, 247, 251, 277, 278, 411
253	195	196	I-69	IN-32 & I-465	33	12	163	Rural	251, 254, 255
254	196	198	I-465	I-69 & I-465	13	27	750	Suburban	253, 255, 256, 258
255	196	202	I-465	I-69 & I-70	7	9	1050	Suburban	253, 254, 263, 264, 265
256	197	198	I-465	I-65 & I-465	3	10	436	Rural	254, 257, 258, 407
257	197	199	I-65	I-465 & I-465	6	12	351	Rural	256, 258, 259, 260, 407
258	198	199	I-465	I-465 & I-65	5	10	397	Rural	254, 256, 257, 259, 260
259	199	200	I-465	I-65 & I-74	4	15	650	Suburban	257, 258, 260, 261, 262
260	199	203	I-65	I-465 & I-70	10	29	2100	Urban	257, 258, 259, 263, 266, 267
261	200	201	I-74	I-465 & US-41	58	8	214	Rural	160, 259, 262
262	200	204	I-465	I-74 & I-70	7	35	650	Suburban	163, 259, 261, 266, 268
263	202	203	I-70	I-465 & I-65	9	11	2700	Urban	255, 260, 264, 265, 266, 267
264	202	206	I-465	I-70 & I-74	5	9	1150	Suburban	255, 263, 265, 269, 271
265	202	246	I-70	I-465 & I-75	100	10	336	Rural	255, 263, 264, 341, 342, 417
266	203	204	I-70	I-65 & I-465	11	8	1900	Urban	163, 260, 262, 263, 267, 268
267	203	205	I-65	I-70 & I-465	7	16	2100	Urban	260, 263, 266, 268, 269, 270, 409
268	204	205	I-465	I-70 & I-65	9	15	1550	Suburban	163, 262, 266, 267, 269, 270, 409
269	205	206	I-465	I-65 & I-74	4	12	750	Suburban	264, 267, 268, 270, 271, 409
270	205	207	I-65	I-465 & I-64	102	8	372	Rural	267, 268, 269, 272, 273, 409
271	206	257	I-74	I-465 & I-275	80	12	319	Rural	264, 269, 356, 357
272	207	208	I-264	I-65 & I-64	7	35	550	Suburban	270, 273, 274, 275
273	207	282	I-65	I-264 & I-64	6	11	2100	Urban	270, 272, 377, 379, 380, 381

Link	A Node	B Node	Route	Between	Miles	AcRt (E-7)	Pop Dens	PD Class	Connecting Links
274	208	265	I-64	I-264 & US-41	96	4	196	Rural	167, 272, 275, 364
275	208	279	I-64	I-264 & I-264	5	9	1350	Suburban	272, 274, 376, 377
276	209	211	I-75	I-475 & I-475	15	8	1900	Urban	246, 248, 277, 279
277	210	211	I-475	I-80,90 & I-75	9	12	950	Suburban	247, 252, 276, 278, 279
278	210	212	I-80,90	I-475 & I-280	11	12	1350	Suburban	247, 249, 252, 277, 280
279	211	249	I-75	I-475 & OH-15	36	10	387	Rural	276, 277, 341, 345
280	212	354	I-80,90	I-280 & OH-53	21	5	443	Rural	249, 278, 283
281	213	214	I-80,90	I-90 & I-480	9	10	227	Rural	282, 283, 284, 285
282	213	217	I-90	I-80,90 & I-71 & I-77	35	9	1250	Suburban	281, 283, 289, 290, 291
283	213	354	I-80,90	I-90 & OH-53	52	5	197	Rural	280, 281, 282
284	214	215	I-80	I-480 & I-71	10	5	750	Suburban	281, 285, 286, 287, 288
285	214	216	I-480	I-80 & I-71	13	7	1450	Suburban	281, 284, 286, 289
286	215	216	I-71	I-80 & I-480	8	27	1450	Suburban	284, 285, 287, 288, 289
287	215	226	I-80	I-71 & I-480	25	46	650	Suburban	284, 286, 288, 303, 305
288	215	238	I-71	I-80 & I-271	12	5	225	Rural	284, 286, 287, 306, 323
289	216	217	I-71	I-480 & I-90 & I-77	11	8	2900	Urban	282, 285, 286, 290, 291
290	217	218	I-90	I-77 & I-71 & OH-2	13	8	3300	Urban	282, 289, 291, 292, 293
291	217	223	I-77	I-90 & I-71 & I-480	8	6	3500	Urban	282, 289, 290, 300, 301
292	218	219	I-90	OH-2 & I-271	2	12	1250	Suburban	290, 293, 294, 295
293	218	220	OH-2	I-90 & OH-44	13	20	1150	Suburban	290, 292, 296, 297
294	219	221	I-90	I-271 & OH-44	12	5	650	Suburban	292, 295, 296, 298
295	219	224	I-271	I-90 & I-480	13	27	1350	Suburban	292, 294, 300, 302
296	220	221	OH-44	OH-2 & I-90	4	7	950	Suburban	293, 293, 294, 297, 298
297	220	355	OH-2	OH-44 & US-20	4	5	182	Rural	293, 296
298	221	222	I-90	OH-44 & OH-11	29	16	212	Rural	294, 296, 299
299	222	229	OH-11	I-90 & I-80	49	10	174	Rural	298, 311
300	223	224	I-480	I-77 & I-271	9	7	1050	Suburban	291, 295, 301, 302
301	223	227	I-77	I-480 & I-271	10	20	850	Suburban	291, 300, 304, 306, 307
302	224	225	I-271	I-480 & I-480	4	3	1050	Suburban	295, 300, 303, 304
303	225	226	I-480	I-271 & I-80	11	10	491	Rural	287, 302, 304, 305
304	225	227	I-271	I-480 & I-77	12	16	457	Rural	301, 302, 303, 306, 307
305	226	228	I-80	I-480 & I-76	26	12	129	Rural	287, 303, 308, 309, 310
306	227	238	I-271	I-77 & I-71	11	10	239	Rural	288, 301, 304, 307, 323
307	227	263	I-77	I-271 & OH-21	8	5	259	Rural	301, 304, 306, 319, 363
308	228	230	I-76	I-80 & OH-11	6	10	407	Rural	305, 309, 310, 311, 312, 313

Link	A Node	B Node	Route	Between	Miles	AcRt (E-7)	Pop Dens	PD Class	Connecting Links
309	228	232	I-80	I-76 & I-680	14	20	850	Suburban	305, 308, 310, 314
310	228	234	I-76	I-80 & OH-8	35	7	550	Suburban	305, 308, 309, 316, 317
311	229	230	I-80	I-76 & OH-11	3	7	950	Suburban	299, 308, 312, 313
312	230	231	I-680	I-80 & US-422	8	11	2100	Urban	308, 311, 313, 314
313	230	233	OH-11,7	I-80 & I-70	89	25	379	Rural	308, 311, 312, 315
314	231	232	I-680	US-422 & I-76	11	74	1700	Urban	309, 312
315	233	247	I-70	OH-7 & I-77	46	5	230	Rural	313, 339, 343, 405
316	234	235	I-76,77	I-76 & I-77	4	29	2900	Urban	310, 317, 318, 319
317	234	237	I-77	I-76 & I-277	4	40	3300	Urban	310, 316, 320, 322
318	235	236	I-277	I-77 & I-76	3	40	2500	Urban	316, 319, 320, 321
319	235	263	I-77	I-76 & OH-21	10	11	3100	Urban	307, 316, 318, 363
320	236	237	I-277	I-76 & I-77	4	15	1550	Suburban	317, 318, 321, 322
321	236	264	I-76	I-277 & OH-21	5	15	1250	Suburban	318, 320, 325, 363
322	237	306	I-77	I-277 & US-62	15	12	230	Suburban	317, 320, 405
323	238	239	I-71	I-271 & I-76	11	5	311	Rural	288, 306, 324, 325
324	239	240	I-71	I-76 & I-270	90	20	215	Rural	323, 325, 326, 327, 328
325	239	264	I-76	I-71 & OH-21	10	8	337	Rural	321, 323, 324, 363
326	240	243	I-71	I-270 & I-70 & OH-315	15	11	2900	Urban	324, 327, 328, 331, 334, 335, 336
327	240	245	I-270	I-71 & I-70	18	20	1050	Suburban	324, 326, 328, 335, 339, 340, 412
328	240	250	I-270	I-71 & OH-315	3	15	1150	Suburban	324, 326, 327, 330, 336, 345
329	241	242	I-270	US-33 & I-70	9	15	850	Suburban	330, 331, 332, 333
330	241	250	I-270	US-33 & OH-315	5	15	750	Suburban	328, 329, 336, 345
331	242	243	I-70	I-270&I-71&OH-315	5	29	2500	Urban	326, 329, 332, 333, 334, 335, 336
332	242	244	I-270	I-70 & I-71	9	7	550	Suburban	329, 331, 333, 334, 337, 338
333	242	317	I-70	I-270 & US-68	20	4	317	Rural	329, 331, 332, 417
334	243	244	I-71	I-70&OH-315&I-270	6	16	2100	Urban	326, 331, 332, 335, 336, 337, 338
335	243	245	I-70	I-71&OH-315&I-270	10	21	1900	Urban	326, 327, 331, 334, 336, 339, 340, 412
336	243	250	OH-315	I-70 & I-71 & I-270	13	4	3500	Urban	326, 328, 330, 331, 334, 335, 345
337	244	251	I-270	I-71 & US-23	2	20	1550	Suburban	332, 334, 338, 340, 346
338	244	262	I-71	I-270 & I-275	85	20	149	Rural	332, 334, 337, 351, 355, 362
339	245	247	I-70	I-270 & I-77	72	10	371	Rural	315, 327, 335, 340, 343, 405, 412
340	245	251	I-270	I-70 & US-23	12	3	1350	Suburban	327, 335, 337, 339, 346, 412
341	246	249	I-75	I-70 & OH-15	95	8	192	Rural	265, 279, 342, 345, 417
342	246	253	I-75	I-75 & US-35	9	16	3100	Urban	265, 341, 348, 417
343	247	248	I-77	I-70 & OH-7	43	25	338	Rural	315, 339, 344, 405, 413

Link	A Node	B Node	Route	Between	Miles	AcRt (E-7)	Pop Dens	PD Class	Connecting Links
344	248	297	I-77	OH-7 & WV-2	41	6	216	Rural	343, 398, 413
345	249	250	OH-15,US-23	I-75 & I-270	83	4	480	Rural	279, 328, 330, 336, 341
346	251	252	US-23	I-270 & US-52	91	6	191	Rural	337, 340, 347
347	252	295	US-23	US-52 & I-64	41	8	329	Rural	346, 396, 397
348	253	254	I-75	US-35 & I-275	38	27	425	Suburban	342, 349, 350, 351
349	254	255	I-75	I-275 & I-71	17	21	2500	Urban	348, 350, 351, 352, 353, 354, 355
350	254	256	I-275	I-75 & I-74	17	15	1550	Suburban	348, 349, 351, 352, 356
351	254	262	I-275	I-75 & I-71	6	12	1050	Suburban	338, 348, 349, 350, 355, 362
352	255	256	I-74,75	I-275 & I-75 & I-71	15	40	2100	Urban	349, 350, 353, 354, 355, 356
353	255	259	I-71,75	I-71 & I-275	8	8	1700	Urban	349, 352, 354, 355, 358, 359, 360
354	255	260	I-471	I-75 & I-71 & I-275	8	54	1900	Urban	349, 352, 353, 355, 359, 361
355	255	262	I-71	I-75 & I-275	16	6	3100	Urban	338, 349, 351, 352, 353, 354, 362
356	256	257	I-74,275	I-74 & I-275	4	16	445	Rural	271, 350, 352, 357
357	257	258	I-275	I-74 & KY-338	15	2	352	Rural	271, 356, 358
358	258	259	I-275	KY-338 & I-71,75	12	16	305	Rural	353, 357, 359, 360
359	259	260	I-275	I-71, 75 & I-471	9	12	650	Suburban	353, 354, 358, 360, 361
360	259	286	I-71,75	I-275 & I-71	13	16	210	Rural	353, 358, 359, 384, 386
361	260	261	I-275	I-471 & OH-125	9	7	750	Suburban	354, 359, 362
362	261	262	I-275	OH-125 & I-71	18	9	750	Suburban	338, 351, 355, 361
363	263	264	OH-21	I-77 & I-76	6	20	650	Suburban	307, 319, 321, 325
364	265	272	US-41	I-64 & Audubon Pky	28	27	950	Suburban	167, 274, 370, 371
365	266	267	Purchase Pky	US-45W,51 & US-45	25	16	285	Rural	173, 366, 367
366	266	302	US-51	I-155 & Purchase Pky	40	10	112	Rural	84, 365
367	267	268	Purchase Pky	US-45 & I-24	27	6	110	Rural	173, 174, 365, 368
368	268	269	I-24	Pur Pky & W KY Pky	15	5	250	Rural	174, 367, 369
369	269	270	W KY Pky	I-24 & US-41	39	16	252	Rural	368, 370, 400
370	270	272	US-41	W KY Pky & Au Pky	44	5	208	Rural	364, 369, 371, 400
371	272	273	Audubon Pky	US-41 & Gr Riv Pky	30	5	226	Rural	364, 370, 372
372	273	274	Gr. Riv. Pky	Au Pky & W KY Pky	30	8	276	Rural	371, 373, 400
373	274	278	W KY Pky	GreenRiverPky&I-65	64	8	197	Rural	372, 374, 375, 400
374	278	283	I-65	W KY Pky & I-264	39	12	343	Rural	373, 375, 378, 379, 382
375	278	288	Blue Gr. Pky	I-65 & US-60	82	12	101	Rural	373, 374, 387, 390, 391
376	279	280	I-264	I-64 & US-31W	8	15	1050	Suburban	275, 377, 378
377	279	282	I-64	I-264 & I-65	6	74	1900	Urban	273, 275, 376, 379, 380, 381
378	280	283	I-264	US-31W & I-65	5	12	750	Suburban	374, 376, 379, 382

Link	A Node	B Node	Route	Between	Miles	AcRt (E-7)	Pop Dens	PD Class	Connecting Links
379	282	283	I-65	I-64 & I-264	4	8	2100	Urban	273, 374, 377, 378, 380, 381, 382
380	282	284	I-71	I-65 & I-71,264	6	21	1900	Urban	273, 377, 379, 381, 383, 384
381	282	285	I-64	I-65 & I-264	10	16	2900	Urban	273, 377, 379, 380, 382, 383, 385
382	283	285	I-264	I-65 & I-64	7	35	1050	Suburban	374, 378, 379, 381, 383, 385
383	284	285	I-264	I-64 & I-71	3	9	1250	Suburban	380, 381, 382, 384, 385
384	284	286	I-71	I-264 & I-75	73	8	105	Rural	360, 380, 383, 386
385	285	287	I-64	I-264 & I-75	63	16	372	Rural	381, 382, 383, 386, 387, 388, 389
386	286	287	I-75	I-71 & I-64	55	5	379	Rural	360, 384, 385, 387, 388, 389
387	287	288	US-25,60	I-75 & BlueGrass Pky	8	9	1450	Suburban	375, 385, 386, 388, 389, 390, 391
388	287	289	US-25	I-75 & Bus US-60	5	40	1900	Urban	385, 386, 387, 389, 390, 392, 393
389	287	291	I-75	I-64 & I-64	7	15	650	Suburban	385, 386, 387, 388, 393, 394, 395
390	288	289	Bus US-60	US-60 & US-25	3	40	2300	Urban	375, 387, 388, 391, 392, 393
391	288	290	US-60	Bus US-60 & US-27	6	7	950	Suburban	375, 387, 390, 392, 394
392	289	290	US-27	Bus US-60 & US-60	4	54	3100	Urban	388, 390, 391, 393, 394
393	289	291	Bus US-60	US-25 & I-75 & I-64	5	8	2900	Urban	388, 389, 390, 392, 394, 395
394	290	291	US-60	US-27 & I-75 & I-64	6	20	850	Suburban	389, 391, 392, 393, 395
395	291	294	I-64	I-75 & B Combs Pky	17	12	425	Rural	389, 393, 394, 396
396	294	295	I-64	B Combs Pky & US-23	87	2	186	Rural	347, 395, 397
397	295	296	I-64	St. Line & I-77	57	6	56	Rural	347, 396, 398
398	296	297	I-77	I-64 & WV-2	40	6	99	Rural	344, 397
399	303	304	US-27	US-127 & I-96	8	1	159	Rural	184, 189, 197, 200
400	270	274	W KY Pky	US-41 & Gr Riv Pky	39	12	144	Rural	369, 370, 372, 373
401	156	166	US-10	US-27 & US-131	40	30	99	Rural	180, 183, 184, 202, 402
402	166	168	US-10	US-131 & US-31	48	24	39	Rural	202, 206, 401
403	91	142	I-270	I-70 & I-55	29	15	1250	Suburban	74, 86, 87, 94, 161, 164
404	172	305	I-69	US-27 & I-94	24	10	343	Rural	193, 196, 212, 213
405	247	306	I-77	US-62 & I-70	63	4	105	Rural	315, 322, 339, 343
406	94	307	I-94	WI-65 & WI-29	40	4	39	Rural	44, 90
407	197	308	I-65	US-52 & I-465	46	10	208	Rural	170, 256, 257
408	101	309	US-51	WI-64 & US-10	52	2	425	Rural	98
409	205	310	IN-37	I-465 & IN-46	45	6	317	Rural	267, 268, 269, 270
410	311	312	I-80,90	US-31 & IN-19	15	15	1050	Suburban	171, 411
411	194	312	I-80,90	I-69 & IN-19	52	10	149	Rural	213, 251, 252, 410
412	245	313	US-33	I-270 & US-50	69	4	371	Rural	327, 335, 339, 340, 413
413	248	313	US-50,OH-7	I-77 & US-33	48	3	141	Rural	343, 344, 412

Link	A Node	B Node	Route	Between	Miles	AcRt (E-7)	Pop Dens	PD Class	Connecting Links
414	129	315	I-80	IL-5 & US-67	3	15	1250	Suburban	63, 67, 147, 415
415	314	315	US-67	US-30 & I-80	24	16	454	Rural	63, 414
416	71	316	I-80	I-35 & US-6	65	12	186	Rural	9, 16, 56, 57
417	246	317	I-70	I-75 & US-68	40	4	1450	Suburban	265, 333, 341, 342
418	67	318	I-35	US-30 & US-18	82	12	99	Rural	46, 52

Appendix D

MASS ATTENUATION AND DOSE BUILDUP FACTORS

Appendix D

Mass Attenuation and Dose Buildup Factors

The attenuation of gamma photons in a medium is a function of the mass attenuation coefficient μ for that medium and the distance r travelled through the medium. The attenuation function exponentially decreases over distance:

$$\text{Attenuation} = e^{-\mu r} \qquad \text{(D1)}$$

μ in turn is dependent on the energy of the photon. In air the mass attenuation coefficients are:

E = 0.5 MeV: $\mu = 1.15\ \text{E-2}\ m^{-1}$
E = 1.0 MeV: $\mu = 8.20\ \text{E-3}\ m^{-1}$

Dose buildup factors $B(\mu r)$ are empirical corrections which account for measured dose rates being greater than predicted by theories that incorporate only the inverse-square law and mass attenuation. The dose rate (and integrated dose) at a point r from the source is larger than predicted due to scattering of the photons from the surrounding medium to the reception point. Analytical models have been fit to the empirical data, Lamarsh [46] favors the Berger form:

$$B(\mu r) = 1 + C\mu r e^{-\beta \mu r} \qquad \text{(D2)}$$

Substituting the values given in [46] for the parameters gives the following buildup functions:

E = 0.5 MeV: $B(\mu r) = 1 + 1.5411\mu r e^{-0.099\mu r}$ (D3)
E = 1.0 MeV: $B(\mu r) = 1 + 1.1305\mu r e^{-0.057\mu r}$ (D4)

Using the values given above, the product of the attenuation and buildup factors, $e^{-\mu r} \bullet B(\mu r)$, is found in the following tables for photon energies of 0.5 MeV and 1.0 MeV. Distances range from 1 to 800 meters. Also calculated for each 100 meter band is an average value for the product over the band. This value is the geometric mean of the endpoint values. If attenuation and buildup are insignificant, the product would equal 1 at all distances and the mean over any range of distances would also equal 1. The sum of the mean values for each 100 meter band from 0 to 800 meters is thus 8. Taking the ratio of the cumulative mean product with attenuation to the cumulative mean product without attenuation (= 8) gives K_E, the attenuation and buildup factor used in Chapter 4.

Table D-1. $e^{-\mu r}$ $B(\mu r)$ at 0.5 MeV

Distance (m)	$e^{-\mu r}$	$B(\mu r)$	$e^{-\mu r}$ $B(\mu r)$	Mean $e^{-\mu r}$ $B(\mu r)$	Cum. Value w/Atten.	Cum. Value w/o Atten.
1	0.99	1.01	1.00			
5	0.94	1.06	1.01			
10	0.89	1.13	1.01			
50	0.56	1.63	0.92			
100	0.32	2.22	0.70	0.84	0.84	1.00
200	0.10	3.28	0.33	0.48	1.32	2.00
300	0.03	4.20	0.13	0.21	1.53	3.00
400	0.01	5.00	0.05	0.08	1.61	4.00
500	3.18E-03	5.68	0.02	0.03	1.64	5.00

Table D-1. (continued)

Distance (m)	$e^{-\mu r}$	$B(\mu r)$	$e^{-\mu r} B(\mu r)$	Mean $e^{-\mu r} B(\mu r)$	Cum. Value w/Atten.	Cum. Value w/o Atten.
600	1.01E-03	6.26	0.01	0.01	1.65	6.00
700	3.19E-04	6.75	2.15E-03	3.69E-03	1.66	7.00
800	1.01E-04	7.16	7.23E-04	1.25E-03	1.66	8.00

Table D-2. $e^{-\mu r} B(\mu r)$ at 1.0 MeV

Distance (m)	$e^{-\mu r}$	$B(\mu r)$	$e^{-\mu r} B(\mu r)$	Mean $e^{-\mu r} B(\mu r)$	Cum. Value w/Atten.	Cum. Value w/o Atten.
1	0.99	1.01	1.00			
5	0.96	1.05	1.00			
10	0.92	1.09	1.01			
50	0.66	1.45	0.96			
100	0.44	1.88	0.83	0.91	0.91	1.00
200	0.19	2.69	0.52	0.66	1.57	2.00
300	0.09	3.42	0.29	0.39	1.96	3.00
400	0.04	4.08	0.15	0.21	2.17	4.00
500	0.02	4.67	0.08	0.11	2.28	5.00
600	0.01	5.20	0.04	0.05	2.33	6.00
700	3.21E-03	5.68	1.83E-02	2.63E-02	2.36	7.00
800	1.42E-03	6.10	8.64E-03	1.26E-02	2.37	8.00

From the data above:

$$K_{0.5} = \frac{1.66}{8} = 0.207$$

$$K_{1.0} = \frac{2.37}{8} = 0.297$$

To simplify matters, assume that $K_{0.5}$ applies to all energies less than 0.75 MeV and $K_{1.0}$ applies to all energies greater than 0.75 MeV, in other words:

$$K_{0.5} = K_{E<0.75}$$
$$K_{1.0} = K_{E\geq 0.75}$$

Appendix E

CALCULATION OF ATMOSPHERIC DISPERSION AND DEPOSITION

Appendix E

Calculation of Atmospheric Dispersion and Deposition

The airborne concentration χ can be calculated downwind from an emission source. The concentration will depend on the strength of the source, the distance downwind, the wind speed and the turbulence or mixing characteristics of the atmosphere. **Meteorology and Atomic Energy 1968** [66] is a collection of methods for calculating the downwind concentration.

To remove the effects of source strength from the process, the calculations are based on the concentration normalized to the source amount Q (if the data is time averaged) or the rate of release Q′ (if instantaneous data is being used). The resulting quantity, χ/Q, (pronounced ki over Q) has the units of seconds per cubic meter or Curie-seconds per cubic meter per Cuire released. To account for differing wind speeds, the χ/Q values are often reported for a wind speed of 1 m/sec. The wind speed is represented by the variable u and the reported values are designated $\chi u/Q$ (ki u over Q). These values are corrected for the appropriate wind speed when used in calculations.

The general release model is a plume originating at the release point and travelling downwind. The axis of the wind direction is designated x. The horizontal radius of the plume is designated y and the vertical radius is designated z. The concentration within the plume at any downwind location x is described by a Gaussian distribution about the centerline in both the y and z directions. Reference 66 provides results of $\chi u/Q$ calculations in graphical form for continuous distances downwind up to 100,000 meters in some cases.

Turbulence in the atmosphere can be caused by mechanical processes such as the flow of air over the topography or by thermal gradients. Atmospheric turbulence is classified by a number of methods, the most frequently used measure is the Pasquill stability categories. These categories range from A which denotes unstable conditions (usually low-speed, meandering winds) to G which signifies extremely stable conditions (usually low-speed, constant direction winds). A plume produced under class A conditions would be broad and widely dispersed, a plume formed in class G conditions would be narrow and concentrated.

Deposition of material from the plume onto the ground is also dependent on the concentration of material in the plume. **Meteorology and Atomic Energy 1968** [67] shows that the rate of depositon is proportional to the concentration χ. The proportionality constant is called the deposition velocity. The experimental values of depositon velocity for fission products reported in [67] range from 0.057 m/sec for Nb-95 over water to 0.0004 m/sec for Cs-137 over soil. Accordingly, a deposition velocity of 0.005 m/sec will be used for all deposition calculations. The graphical method presented in [67] will be used, corrected to a deposition velocity = 0.005 m/sec.

RADTRAN [51] has adapted the methods used in **Meteorology and Atomic Energy 1968** [66] for calculation of χ/Q. Rather than determine the concentration downwind and off axis from the plume centerline, RADTRAN assumes that the plume can be modeled as a set of nested ellipses originating at the release point (figure E-1). The ellipses connect points of constant χ or χ/Q (or quantities proportional to χ). The ellipses are referred to as iso-dose lines. RADTRAN gives the values for the area enclosed by each ellipse and time-integrated χ/Q at the boundary of each ellipse.

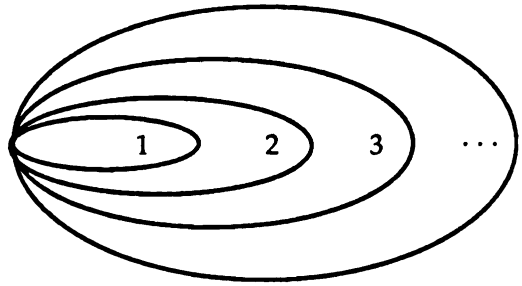

Figure E-1. Nested Ellipses

Also given in Reference 51 are values of wind speed typical of the Pasquill categories A through F. (Category G is not used in [51].) With these numbers, χ/Q can be calculated for each stability class at each iso-dose line. At this point, the method which follows departs from that used in RADTRAN III.

Examining the exposure equations derived in Chapter 4 reveals that the parameters critical to the calculations are the amount of material deposited on the ground and the airborne concentration which has taken such deposition into consideration. This concentration is the Depleted χ/Q and can be calculated from the values of χ/Q at each iso-dose line using the method presented in **Meteorology and Atomic Energy 1968** [66] and the boundary condition that the amount of material entering Area(n) is equal to the amount of material leaving Area(n-1). The amount deposited within Area(n) is the difference between that entering and that leaving the area.

The first step in calculating Depleted χ/Q for a particular Pasquill stability class is to convert the area used by RADTRAN into a downwind distance on which the graphs in Reference 67 are based. This was done by referring to the $\chi u/Q$ versus distance graphs in **Meteorology and Atomic Energy 1968** [66]. The downwind distance can be read from these graphs by multiplying the χ/Q value at the area boundary by the wind speed u for the Pasquill category. The depletion fraction Q_x/Q_0 at the downwind distance is estimated from the appropriate graph on page 205 of **Meteorology and Atomic Energy 1968** [67] and corrected for the assumed deposition velocity of 0.005 m/sec using the formula given on page 206 of [67]. Multiplying χ/Q by the depletion fraction produces the Depleted χ/Q value at the iso-dose line.

The following tables present the χ/Q, the depletion fraction and Depleted χ/Q values for each Pasquill category. The units of the parameters are:

Area in square meters,
χ/Q and Depleted χ/Q in seconds per cubic meter,
Length and width in meters.

Table E-1. Plume Depletion Calculation

Pasquill Category A wind speed = 1 m/s P(A) = 0.10

Area	**χ/Q**	**Plume Length**	**Plume Width**	**Q_x/Q_0**	**Depleted χ/Q**
4.59E+02	6.00E-03	4.00E+01	3.65E+00	9.10E-01	5.46E-03
1.53E+03	1.70E-03	7.50E+01	6.49E+00	8.90E-01	1.51E-03
3.94E+03	8.40E-04	1.10E+02	1.14E+01	8.90E-01	7.48E-04
1.25E+04	1.70E-04	2.20E+02	1.81E+01	8.80E-01	1.50E-04
3.04E+04	7.80E-05	3.00E+02	3.23E+01	8.80E-01	6.86E-05
6.85E+04	2.80E-05	4.50E+02	4.85E+01	8.60E-01	2.41E-05
1.76E+05	8.00E-06	8.00E+02	7.00E+01	8.60E-01	6.88E-06
4.46E+05	2.20E-06	1.30E+03	1.09E+02	8.50E-01	1.87E-06
8.59E+05	9.00E-07	1.70E+03	1.61E+02	8.40E-01	7.56E-07
2.55E+06	1.40E-07	2.20E+03	3.69E+02	8.40E-01	1.18E-07
4.45E+06	7.00E-08	3.20E+03	4.43E+02	8.40E-01	5.88E-08

Table E-1. (continued)

Pasquill Category B wind speed = 2 m/s P(B) = 0.05

Area	χ/Q	Plume Length	Plume Width	Q_x/Q_0	Depleted χ/Q
4.59E+02	4.00E-03	5.00E+01	2.92E+00	9.50E-01	3.80E-03
1.53E+03	1.30E-03	9.00E+01	5.41E+00	9.40E-01	1.22E-03
3.94E+03	5.50E-04	1.40E+02	8.96E+00	9.40E-01	5.17E-04
1.25E+04	1.30E-04	2.50E+02	1.59E+01	9.30E-01	1.21E-04
3.04E+04	6.00E-05	3.80E+02	2.55E+01	9.20E-01	5.52E-05
6.85E+04	2.70E-05	5.50E+02	3.96E+01	9.10E-01	2.46E-05
1.76E+05	1.00E-05	9.00E+02	6.23E+01	9.10E-01	9.10E-06
4.46E+05	3.50E-06	1.50E+03	9.46E+01	9.00E-01	3.15E-06
8.59E+05	1.60E-06	2.05E+03	1.33E+02	8.90E-01	1.42E-06
2.55E+06	4.10E-07	3.10E+03	2.62E+02	8.80E-01	3.61E-07
4.45E+06	2.20E-07	4.00E+03	3.54E+02	8.80E-01	1.94E-07

Pasquill Category C wind speed= 3 m/s P(C) = 0.10

Area	χ/Q	Plume Length	Plume Width	Q_x/Q_0	Depleted χ/Q
4.59E+02	4.00E-03	6.00E+01	2.44E+00	9.60E-01	3.84E-03
1.53E+03	1.10E-03	1.10E+02	4.43E+00	9.40E-01	1.03E-03
3.94E+03	5.70E-04	1.80E+02	6.97E+00	9.40E-01	5.36E-04
1.25E+04	1.30E-04	3.10E+02	1.28E+01	9.20E-01	1.20E-04
3.04E+04	6.70E-05	4.70E+02	2.06E+01	9.20E-01	6.16E-05
6.85E+04	3.00E-05	7.00E+02	3.12E+01	9.20E-01	2.76E-05
1.76E+05	1.00E-05	1.20E+03	4.67E+01	9.10E-01	9.10E-06
4.46E+05	5.00E-06	2.00E+03	7.10E+01	9.00E-01	4.50E-06
8.59E+05	2.80E-06	3.00E+03	9.11E+01	8.90E-01	2.49E-06
2.55E+06	1.00E-06	5.00E+03	1.62E+02	8.80E-01	8.80E-07
4.45E+06	6.00E-07	6.20E+03	2.28E+02	8.80E-01	5.28E-07

Pasquill Category D wind speed = 4 m/s P(D) = 0.40

Area	χ/Q	Plume Length	Plume Width	Q_x/Q_0	Depleted χ/Q
4.59E+02	4.30E-03	7.00E+01	2.09E+00	9.60E-01	4.13E-03
1.53E+03	1.30E-03	1.30E+02	3.75E+00	9.40E-01	1.22E-03
3.94E+03	6.50E-04	2.10E+02	5.97E+00	9.30E-01	6.05E-04
1.25E+04	1.80E-04	4.00E+02	9.95E+00	9.20E-01	1.66E-04
3.04E+04	9.50E-05	5.50E+02	1.76E+01	9.10E-01	8.65E-05
6.85E+04	4.30E-05	9.00E+02	2.42E+01	8.90E-01	3.83E-05
1.76E+05	1.80E-05	1.60E+03	3.50E+01	8.80E-01	1.58E-05
4.46E+05	8.50E-06	2.50E+03	5.68E+01	8.60E-01	7.31E-06
8.59E+05	5.00E-06	4.00E+03	6.84E+01	8.40E-01	4.20E-06
2.55E+06	1.90E-06	7.00E+03	1.16E+02	8.10E-01	1.54E-06
4.45E+06	1.30E-06	9.00E+03	1.57E+02	8.00E-01	1.04E-06

Table E-1. (continued)

Pasquill Category E wind speed = 2.5 m/s P(E) = 0.25

Area	χ/Q	Plume Length	Plume Width	Q_x/Q_0	Depleted χ/Q
4.59E+02	9.60E-03	9.00E+01	1.62E+00	9.00E-01	8.64E-03
1.53E+03	3.20E-03	1.60E+02	3.04E+00	8.70E-01	2.78E-03
3.94E+03	1.60E-03	2.20E+02	5.70E+00	8.60E-01	1.38E-03
1.25E+04	4.00E-04	4.80E+02	8.29E+00	8.30E-01	3.32E-04
3.04E+04	2.10E-04	7.00E+02	1.38E+01	8.00E-01	1.68E-04
6.85E+04	1.40E-04	1.10E+03	1.98E+01	7.70E-01	1.08E-04
1.76E+05	4.40E-05	1.90E+03	2.95E+01	7.50E-01	3.30E-05
4.46E+05	2.10E-05	3.00E+03	4.73E+01	7.20E-01	1.51E-05
8.59E+05	1.20E-05	5.00E+03	5.47E+01	6.70E-01	8.04E-06
2.55E+06	4.80E-06	8.00E+03	1.01E+02	6.20E-01	2.98E-06
4.45E+06	3.60E-06	1.10E+04	1.29E+02	5.70E-01	2.05E-06

Pasquill Category F wind speed = 1 m/s P(F) = 0.10

Area	χ/Q	Plume Length	Plume Width	Q_x/Q_0	Depleted χ/Q
4.59E+02	6.20E-02	9.50E+01	1.54E+00	7.10E-01	4.40E-02
1.53E+03	1.80E-02	1.80E+02	2.71E+00	6.30E-01	1.13E-02
3.94E+03	8.40E-03	2.40E+02	5.23E+00	5.70E-01	4.79E-03
1.25E+04	2.00E-03	5.50E+02	7.23E+00	4.60E-01	9.20E-04
3.04E+04	9.20E-04	8.00E+02	1.21E+01	4.20E-01	3.86E-04
6.85E+04	4.40E-04	1.30E+03	1.68E+01	3.50E-01	1.54E-04
1.76E+05	2.00E-04	2.20E+03	2.55E+01	2.80E-01	5.60E-05
4.46E+05	1.00E-04	3.70E+03	3.84E+01	2.20E-01	2.20E-05
8.59E+05	6.20E-05	5.50E+03	4.97E+01	1.80E-01	1.12E-05
2.55E+06	2.60E-05	1.00E+04	8.12E+01	1.30E-01	3.38E-06
4.45E+06	1.90E-05	1.60E+04	8.85E+01	8.00E-02	1.52E-06

The probability of occurrence for each Pasquill category is typical of the Great Lakes region. χ/Q and Depleted χ/Q can be weighted using these probabilities to produce expected values at each area boundary or iso-dose line. The weighted values can now be applied to the estimation of exposure and unit risk factors required by this research. Since the URF's are calculated assuming a release of 1 Curie, the weighted values for χ/Q and Depleted χ/Q actually represent weighted χ and Depleted χ in this case. The exposure equations derived in Chapter 4 calculate the dose to populations within an area, so an average value for Depleted χ has been calculated equal to the geometric mean of the concentrations at the inner and outer boundaries. This average is designated Depleted $\bar{\chi}$. The amount deposited within each area is calculated through conservation of mass considerations. The amount of material leaving an area must be equal to the amount entering the area minus the amount deposited. The ratio of the the undepleted quantity Q_0 to χ/Q is equal to the ratio of the depleted quantity $Q_0 - Q_{dep}$ to the Depleted χ/Q:

$$\frac{Q_0}{\chi/Q} = \frac{Q_0 - Q_{dep}}{\text{Depleted } \chi/Q} \qquad \text{(E1)}$$

Since Q_0 = 1 Curie, it follows that the amount deposited in the first area is:

$$Q_{dep} = 1 - \frac{\text{Depleted } \chi/Q}{\chi/Q} \qquad \text{(E2)}$$

This formula is recursive since the amount entering the second area is 1 - Q_{dep} which replaces the value of 1 in equation (E2). The following table presents the weighted parameters discussed above for the eleven elliptical areas. Depleted χ has units of Ci per cubic meter.

Table E-2. χ and Deposition Values

Area	Weighted χ/Q	Weighted Depleted χ/Q	Depleted χ	Ci Deposited	Cumulative Ci Deposited
4.59E+02	1.15E-02	9.33E-03	9.66E-02	1.90E-01	1.90E-01
1.53E+03	3.47E-03	2.63E-03	4.96E-03	4.98E-02	2.40E-01
3.94E+03	1.67E-03	1.22E-03	1.79E-03	2.99E-02	2.70E-01
1.25E+04	4.09E-04	2.74E-04	5.78E-04	5.92E-02	3.29E-01
3.04E+04	2.00E-04	1.31E-04	1.90E-04	1.62E-02	3.45E-01
6.85E+04	1.03E-04	6.41E-05	9.16E-05	3.53E-02	3.80E-01
1.76E+05	4.05E-05	2.22E-05	3.77E-05	7.07E-02	4.51E-01
4.46E+05	1.95E-05	9.70E-06	1.47E-05	5.29E-02	5.04E-01
8.59E+05	1.17E-05	5.20E-06	7.10E-06	4.97E-02	5.53E-01
2.55E+06	4.69E-06	1.82E-06	3.07E-06	5.98E-02	6.13E-01
4.45E+06	3.40E-06	1.15E-06	1.44E-06	4.85E-02	6.62E-01

Appendix F

RISK FACTOR COMPONENTS

Appendix F

Risk Factor Components

Table F-1 contains data which are specific to the three population density classifications:

Table F-1. Population Zone Parameters

	V (km/hr)	TC(veh/hr)	PD(p/km^2)
Rural	88	470	50
Suburban	88	1200	1000
Urban	64	2800	3500

Data specific to the isotopes shipped in quantity in the MILLRWC are contained in Table F-2. Energy is given in MeV, half-life in days and the photon fluence to dose rate conversion factor ϕ is in units of photons/cm^2-sec per R/hr (which is approximately equal to rem/hr for gamma radiation) [26,47,81]. Rem per Curie inhaled values were calculated from maximum permissible concentration (MPC) values in Table 1 of **Permissible Dose for Internal Radiation** [36]. Those MPC values are expressed in terms of Ci/cubic meter in air or water which if ingested result during the course of a 40-hour work week in an exposure of 0.1 rem. (MPC values for 168 hours per week of environmental exposure are also given but the occupational exposure values were used because they result in a greater dose per Curie inhaled.) Since airborne contaminants are being modeled, the airborne factors for the total body, (MPC)a, are used in the calculation. Breathing in an atmosphere containing 1 (MPC)a for 40 hours results in a whole body dose of 0.1 rem, therefore a 10 (MPC)a atmosphere for 40 hours yields and exposure of 1 rem. To calculate the rem per Curie inhaled from this information, all that is needed is the breating rate. The standard breathing rate of the reference man at light activity is 3.3 E-4 cubic meters per second as given by Reference 39. The calculation becomes:

$$\frac{\text{Rem}}{\text{Ci inhaled}} = \frac{1}{10 \bullet \left((\text{MPC})\text{a} \, \frac{\text{Ci-wk}}{\text{m}^3\text{-0.1rem}} \right) \bullet 3.3\text{E-4} \, \frac{\text{m}^3}{\text{sec}} \bullet 3600 \, \frac{\text{sec}}{\text{hr}} \bullet 40 \, \frac{\text{hr}}{\text{wk}}} \tag{F1}$$

Table F-2. Isotope Data

Isotope	Energy	Half-life	ϕ	Rem/Ci inhaled
Am241	0.022	1.67E+05	1.80E+06	1.00E+08
Cl36	0.015	1.13E+08	8.00E+05	5.20E+03
Co58	0.977	7.08E+01	5.60E+05	2.10E+03
Co60	2.505	1.92E+03	2.70E+05	5.20E+03
Cr51	0.029	2.78E+01	3.50E+06	2.10E+02
Cs134	1.591	7.53E+02	3.70E+05	5.20E+04
Cs137	0.563	1.10E+04	9.00E+05	3.50E+04
Ir192	0.779	7.42E+01	7.80E+06	5.20E+03
Nb94	1.573	7.30E+06	3.70E+05	4.20E+03
Ni59	1.060	2.92E+07	5.20E+05	2.10E+03
P32	0.000	1.43E+01	0.00E+00	5.20E+03
Pu241	0.022	4.82E+03	1.80E+06	2.60E+06
Ra226	1.544	5.85E+05	3.80E+05	4.20E+07

Table F-2. (continued)

Isotope	Energy	Half-life	ϕ	Rem/Ci inhaled
S35	0.000	8.79E+01	0.00E+00	2.10E+03
Sr90	0.000	1.06E+04	0.00E+00	2.30E+06
Th232	0.001	5.11E+12	0.00E+00	2.10E+08
U238	0.014	1.65E+12	6.80E+05	1.00E+06
Misc	0.511	7.30E+02	7.60E+06	2.10E+03

Table F-3. Package Shielding Factor

Isotope & Package	Energy	C_{jk}
Am241 Cask	0.022	0.001
Am241 LSA	0.022	1
Cl36 LSA	0.015	1
Co58 Cask	0.977	0.01
Co60 Cask	2.505	0.01
Co60 Drum	2.505	0.5
Co60 LSA	2.505	1
Cr51 LSA	0.029	1
Cs134 Cask	1.591	0.01
Cs137 Cask	0.563	0.005
Cs137 Drum	0.563	0.1
Cs137 LSA	0.563	1
Ir192 Cask	0.779	0.01
Nb94 Cask	1.573	0.01
Nb94 Drum	1.573	0.5
Nb94 LSA	1.573	1
Ni59 Cask	1.06	0.01
Ni59 Drum	1.06	0.5
Ni59 LSA	1.06	1
Pu241 Drum	0.022	0.05
Pu241 LSA	0.022	1
Ra226 Cask	1.544	0.01
Ra226 LSA	1.544	1
U238 LSA	0.014	1
Misc Drum	0.511	0.1
Misc LSA	0.511	1

Table F-4. Accident-Free Dose Components

RURAL

Isotope & Package	D_{path}	D_{crew}	D_{opp}	D_{same}	AFD_{Total}
Am241 Cask	6.14E-10	2.27E-05	7.52E-11	1.67E-13	2.27E-05
Am241 LSA	6.14E-07	2.27E-05	7.52E-08	1.67E-10	2.34E-05
Cl36 LSA	1.38E-06	2.27E-05	1.69E-07	3.75E-10	2.43E-05
Co58 Cask	2.83E-08	2.27E-05	2.42E-09	7.68E-12	2.28E-05
Co60 Cask	5.88E-08	2.27E-05	5.01E-09	1.59E-11	2.28E-05
Co60 Drum	2.94E-06	2.27E-05	2.51E-07	7.97E-10	2.59E-05

Table F-4. (continued)

RURAL

Isotope & Package	D_{path}	D_{crew}	D_{opp}	D_{same}	AFD_{Total}
Co60 LSA	5.88E-06	2.27E-05	5.01E-07	1.59E-09	2.91E-05
Cr51 LSA	3.16E-07	2.27E-05	3.87E-08	8.57E-11	2.31E-05
Cs134 Cask	4.29E-08	2.27E-05	3.66E-09	1.16E-11	2.28E-05
Cs137 Cask	6.14E-09	2.27E-05	7.52E-10	1.67E-12	2.27E-05
Cs137 Drum	1.23E-07	2.27E-05	1.50E-08	3.33E-11	2.29E-05
Cs137 LSA	1.23E-06	2.27E-05	1.50E-07	3.33E-10	2.41E-05
Ir192 Cask	2.03E-09	2.27E-05	1.74E-10	5.51E-13	2.27E-05
Nb94 Cask	4.29E-08	2.27E-05	3.66E-09	1.16E-11	2.28E-05
Nb94 Drum	2.14E-06	2.27E-05	1.83E-07	5.81E-10	2.51E-05
Nb94 LSA	4.29E-06	2.27E-05	3.66E-07	1.16E-09	2.74E-05
Ni59 Cask	3.05E-08	2.27E-05	2.60E-09	8.27E-12	2.28E-05
Ni59 Drum	1.53E-06	2.27E-05	1.30E-07	4.14E-10	2.44E-05
Ni59 LSA	3.05E-06	2.27E-05	2.60E-07	8.27E-10	2.60E-05
Pu241 Drum	3.07E-08	2.27E-05	3.76E-09	8.33E-12	2.28E-05
Pu241 LSA	6.14E-07	2.27E-05	7.52E-08	1.67E-10	2.34E-05
Ra226 Cask	4.17E-08	2.27E-05	3.56E-09	1.13E-11	2.28E-05
Ra226 LSA	4.17E-06	2.27E-05	3.56E-07	1.13E-09	2.73E-05
U238 LSA	1.63E-06	2.27E-05	1.99E-07	4.41E-10	2.46E-05
Misc Drum	1.45E-08	2.27E-05	1.78E-09	3.94E-12	2.27E-05
Misc LSA	1.45E-07	2.27E-05	1.78E-08	3.94E-11	2.29E-05

SUBURBAN

Isotope & Package	D_{path}	D_{crew}	D_{opp}	D_{same}	AFD_{Total}
Am241 Cask	1.23E-08	2.27E-05	1.92E-10	4.25E-13	2.27E-05
Am241 LSA	1.23E-05	2.27E-05	1.92E-07	4.25E-10	3.52E-05
Cl36 LSA	2.76E-05	2.27E-05	4.32E-07	9.57E-10	5.08E-05
Co58 Cask	5.67E-07	2.27E-05	6.17E-09	1.96E-11	2.33E-05
Co60 Cask	1.18E-06	2.27E-05	1.28E-08	4.07E-11	2.39E-05
Co60 Drum	5.88E-05	2.27E-05	6.40E-07	2.03E-09	8.21E-05
Co60 LSA	1.18E-04	2.27E-05	1.28E-06	4.07E-09	1.42E-04
Cr51 LSA	6.32E-06	2.27E-05	9.87E-08	2.19E-10	2.91E-05
Cs134 Cask	8.57E-07	2.27E-05	9.34E-09	2.97E-11	2.36E-05
Cs137 Cask	1.23E-07	2.27E-05	1.92E-09	4.25E-12	2.29E-05
Cs137 Drum	2.46E-06	2.27E-05	3.84E-08	8.51E-11	2.52E-05
Cs137 LSA	2.46E-05	2.27E-05	3.84E-07	8.51E-10	4.77E-05
Ir192 Cask	4.07E-08	2.27E-05	4.43E-10	1.41E-12	2.28E-05
Nb94 Cask	8.57E-07	2.27E-05	9.34E-09	2.97E-11	2.36E-05
Nb94 Drum	4.29E-05	2.27E-05	4.67E-07	1.48E-09	6.61E-05
Nb94 LSA	8.57E-05	2.27E-05	9.34E-07	2.97E-09	1.09E-04
Ni59 Cask	6.10E-07	2.27E-05	6.65E-09	2.11E-11	2.33E-05
Ni59 Drum	3.05E-05	2.27E-05	3.32E-07	1.06E-09	5.36E-05
Ni59 LSA	6.10E-05	2.27E-05	6.65E-07	2.11E-09	8.44E-05
Pu241 Drum	6.14E-07	2.27E-05	9.60E-09	2.13E-11	2.34E-05
Pu241 LSA	1.23E-05	2.27E-05	1.92E-07	4.25E-10	3.52E-05

Table F-4. (continued)

SUBURBAN

Isotope & Package	D_{path}	D_{crew}	D_{opp}	D_{same}	AFD_{Total}
Ra226 Cask	8.35E-07	2.27E-05	9.09E-09	2.89E-11	2.36E-05
Ra226 LSA	8.35E-05	2.27E-05	9.09E-07	2.89E-09	1.07E-04
U238 LSA	3.25E-05	2.27E-05	5.08E-07	1.13E-09	5.58E-05
Misc Drum	2.91E-07	2.27E-05	4.55E-09	1.01E-11	2.30E-05
Misc LSA	2.91E-06	2.27E-05	4.55E-08	1.01E-10	2.57E-05

URBAN

Isotope & Package	D_{path}	D_{crew}	D_{opp}	D_{same}	AFD_{Total}
Am241 Cask	5.91E-08	3.13E-05	8.47E-10	2.58E-12	3.13E-05
Am241 LSA	5.91E-05	3.13E-05	8.47E-07	2.58E-09	9.12E-05
Cl36 LSA	1.33E-04	3.13E-05	1.91E-06	5.80E-09	1.66E-04
Co58 Cask	2.73E-06	3.13E-05	2.72E-08	1.19E-10	3.40E-05
Co60 Cask	5.65E-06	3.13E-05	5.65E-08	2.47E-10	3.70E-05
Co60 Drum	2.83E-04	3.13E-05	2.82E-06	1.23E-08	3.17E-04
Co60 LSA	5.65E-04	3.13E-05	5.65E-06	2.47E-08	6.02E-04
Cr51 LSA	3.04E-05	3.13E-05	4.36E-07	1.33E-09	6.21E-05
Cs134 Cask	4.13E-06	3.13E-05	4.12E-08	1.80E-10	3.54E-05
Cs137 Cask	5.91E-07	3.13E-05	8.47E-09	2.58E-11	3.18E-05
Cs137 Drum	1.18E-05	3.13E-05	1.69E-07	5.16E-10	4.32E-05
Cs137 LSA	1.18E-04	3.13E-05	1.69E-06	5.16E-09	1.51E-04
Ir192 Cask	1.96E-07	3.13E-05	1.95E-09	8.54E-12	3.14E-05
Nb94 Cask	4.13E-06	3.13E-05	4.12E-08	1.80E-10	3.54E-05
Nb94 Drum	2.06E-04	3.13E-05	2.06E-06	9.00E-09	2.40E-04
Nb94 LSA	4.13E-04	3.13E-05	4.12E-06	1.80E-08	4.48E-04
Ni59 Cask	2.94E-06	3.13E-05	2.93E-08	1.28E-10	3.42E-05
Ni59 Drum	1.47E-04	3.13E-05	1.47E-06	6.41E-09	1.80E-04
Ni59 LSA	2.94E-04	3.13E-05	2.93E-06	1.28E-08	3.28E-04
Pu241 Drum	2.96E-06	3.13E-05	4.23E-08	1.29E-10	3.42E-05
Pu241 LSA	5.91E-05	3.13E-05	8.47E-07	2.58E-09	9.12E-05
Ra226 Cask	4.02E-06	3.13E-05	4.01E-08	1.75E-10	3.53E-05
Ra226 LSA	4.02E-04	3.13E-05	4.01E-06	1.75E-08	4.37E-04
U238 LSA	1.56E-04	3.13E-05	2.24E-06	6.83E-09	1.90E-04
Misc Drum	1.40E-06	3.13E-05	2.01E-08	6.11E-11	3.27E-05
Misc LSA	1.40E-05	3.13E-05	2.01E-07	6.11E-10	4.55E-05

Table F-5. Non-Dispersal Accident Risk Components (Cask Shipments)

RURAL

Isotope	D_{area}	D_{veh}	D_{work}	$NDAD_{Total}$	Prob • $NDAD_T$
Am241 Cask	3.73E-07	2.93E-06	6.56E-05	6.89E-05	6.89E-12
Co58 Cask	1.72E-05	9.41E-05	2.11E-03	2.22E-03	2.22E-10
Co60 Cask	3.57E-05	1.95E-04	4.37E-03	4.60E-03	4.60E-10
Cs134 Cask	2.60E-05	1.42E-04	3.19E-03	3.36E-03	3.36E-10
Cs137 Cask	3.73E-06	2.93E-05	6.56E-04	6.89E-04	6.89E-11

Table F-5. (continued)

RURAL

Isotope	D_{area}	D_{veh}	D_{work}	$NDAD_{Total}$	Prob • $NDAD_T$
Ir192 Cask	1.24E-06	6.76E-06	1.51E-04	1.59E-04	1.59E-11
Nb94 Cask	2.60E-05	1.42E-04	3.19E-03	3.36E-03	3.36E-10
Ni59 Cask	1.85E-05	1.01E-04	2.27E-03	2.39E-03	2.39E-10
Ra226 Cask	2.54E-05	1.39E-04	3.11E-03	3.27E-03	3.27E-10

SUBURBAN

Isotope	D_{area}	D_{veh}	D_{work}	$NDAD_{Total}$	Prob • $NDAD_T$
Am241 Cask	7.46E-06	7.48E-06	6.56E-05	8.05E-05	8.05E-12
Co58 Cask	3.44E-04	2.40E-04	2.11E-03	2.69E-03	2.69E-10
Co60 Cask	7.14E-04	4.98E-04	4.37E-03	5.58E-03	5.58E-10
Cs134 Cask	5.21E-04	3.64E-04	3.19E-03	4.07E-03	4.07E-10
Cs137 Cask	7.46E-05	7.48E-05	6.56E-04	8.05E-04	8.05E-11
Ir192 Cask	2.47E-05	1.73E-05	1.51E-04	1.93E-04	1.93E-11
Nb94 Cask	5.21E-04	3.64E-04	3.19E-03	4.07E-03	4.07E-10
Ni59 Cask	3.71E-04	2.59E-04	2.27E-03	2.90E-03	2.90E-10
Ra226 Cask	5.07E-04	3.54E-04	3.11E-03	3.97E-03	3.97E-10

URBAN

Isotope	D_{area}	D_{veh}	D_{work}	$NDAD_{Total}$	Prob • $NDAD_T$
Am241 Cask	2.61E-05	2.40E-05	6.56E-05	1.16E-04	1.16E-11
Co58 Cask	1.20E-03	7.71E-04	2.11E-03	4.08E-03	4.08E-10
Co60 Cask	2.50E-03	1.60E-03	4.37E-03	8.47E-03	8.47E-10
Cs134 Cask	1.82E-03	1.17E-03	3.19E-03	6.18E-03	6.18E-10
Cs137 Cask	2.61E-04	2.40E-04	6.56E-04	1.16E-03	1.16E-10
Ir192 Cask	8.65E-05	5.54E-05	1.51E-04	2.93E-04	2.93E-11
Nb94 Cask	1.82E-03	1.17E-03	3.19E-03	6.18E-03	6.18E-10
Ni59 Cask	1.30E-03	8.30E-04	2.27E-03	4.40E-03	4.40E-10
Ra226 Cask	1.78E-03	1.14E-03	3.11E-03	6.02E-03	6.02E-10

Table F-6. Atmospheric Dispersion Data

Ellipse #	Total Area	Δ Area	χ	ΔCi Deposited	ΔA • χ
1	4.59E+02	4.59E+02	9.66E-02	1.90E-01	4.43E+01
2	1.53E+03	1.07E+03	4.96E-03	4.98E-02	5.31E+00
3	3.94E+03	2.41E+03	1.79E-03	2.99E-02	4.31E+00
4	1.25E+04	8.56E+03	5.78E-04	5.92E-02	4.95E+00
5	3.04E+04	1.79E+04	1.90E-04	1.62E-02	3.40E+00
6	6.85E+04	3.81E+04	9.16E-05	3.53E-02	3.49E+00
7	1.76E+05	1.08E+05	3.77E-05	7.07E-02	4.05E+00
8	4.46E+05	2.70E+05	1.47E-05	5.29E-02	3.97E+00
9	8.59E+05	4.13E+05	7.10E-06	4.97E-02	2.93E+00
10	2.55E+06	1.69E+06	3.07E-06	5.98E-02	5.19E+00
11	4.45E+06	1.90E+06	1.44E-06	4.85E-02	2.74E+00
Totals		4.45E+06	1.04E-01	6.62E-01	8.47E+01

Table F-7. Resuspension Dose Factors

Isotope	η	λ	RDF
Am241	1.90E-03	4.14E-06	3.28E+00
Cl36	1.90E-03	6.16E-09	3.28E+00
Co60	2.26E-03	3.61E-04	2.91E+00
Cr51	2.68E-02	2.49E-02	1.16E+00
Cs137	1.96E-03	6.32E-05	3.21E+00
Nb94	1.90E-03	9.49E-08	3.28E+00
Ni59	1.90E-03	2.37E-08	3.28E+00
P32	5.04E-02	4.85E-02	1.09E+00
Pu241	2.04E-03	1.44E-04	3.12E+00
Ra226	1.90E-03	1.18E-06	3.28E+00
S35	9.78E-03	7.88E-03	1.44E+00
Sr90	1.96E-03	6.54E-05	3.20E+00
Th232	1.90E-03	1.36E-13	3.28E+00
U238	1.90E-03	4.20E-13	3.28E+00
Misc	2.85E-03	9.49E-04	2.52E+00

Table F-8. Dispersal Accident Risk Components (LSA & Drum Shipments)

RURAL

Isotope	D_{WB}	D_{inh}	D_{gnd}	$ADAD_{Total}$	Prob • $ADAD_T$
Am241	6.71E-01	4.16E+02	1.24E-06	4.17E+02	4.17E-05
Cl36	4.57E-01	2.17E-02	8.77E-07	4.79E-01	4.79E-08
Co60	7.64E+01	1.92E-02	2.90E-05	7.64E+01	7.64E-06
Cr51	8.78E-01	3.10E-04	1.08E-08	8.78E-01	8.78E-08
Cs137	1.72E+01	1.43E-01	2.07E-05	1.73E+01	1.73E-06
Nb94	4.80E+01	1.75E-02	9.19E-05	4.80E+01	4.80E-06
Ni59	3.23E+01	8.76E-03	6.20E-05	3.23E+01	3.23E-06
P32	0.00E+00	7.17E-03	0.00E+00	7.17E-03	7.17E-10
Pu241	6.71E-01	1.03E+01	5.16E-07	1.10E+01	1.10E-06
Ra226	4.71E+01	1.75E+02	8.94E-05	2.22E+02	2.22E-05
S35	0.00E+00	3.85E-03	0.00E+00	3.85E-03	3.85E-10
Sr90	0.00E+00	9.36E+00	0.00E+00	9.36E+00	9.36E-07
Th232	3.05E-02	8.76E+02	5.85E-08	8.76E+02	8.76E-05
U238	4.33E-01	4.17E+00	8.31E-07	4.60E+00	4.60E-07
Misc	1.56E+01	6.72E-03	2.76E-06	1.56E+01	1.56E-06

SUBURBAN

Isotope	D_{WB}	D_{inh}	D_{gnd}	$ADAD_{Total}$	Prob • $ADAD_T$
Am241	1.34E+01	8.33E+03	2.49E-05	8.34E+03	8.34E-04
Cl36	9.15E+00	4.34E-01	1.75E-05	9.58E+00	9.58E-07
Co60	1.53E+03	3.85E-01	5.79E-04	1.53E+03	1.53E-04
Cr51	1.76E+01	6.19E-03	2.16E-07	1.76E+01	1.76E-06
Cs137	3.43E+02	2.85E+00	4.13E-04	3.46E+02	3.46E-05
Nb94	9.59E+02	3.50E-01	1.84E-03	9.59E+02	9.59E-05
Ni59	6.46E+02	1.75E-01	1.24E-03	6.46E+02	6.46E-05
P32	0.00E+00	1.43E-01	0.00E+00	1.43E-01	1.43E-08
Pu241	1.34E+01	2.06E+02	1.03E-05	2.19E+02	2.19E-05
Ra226	9.41E+02	3.50E+03	1.79E-03	4.44E+03	4.44E-04
S35	0.00E+00	7.69E-02	0.00E+00	7.69E-02	7.69E-09

Table F-8. (continued)

SUBURBAN

Isotope	D_{WB}	D_{inh}	D_{gnd}	$ADAD_{Total}$	Prob • $ADAD_T$
Sr90	0.00E+00	1.87E+02	0.00E+00	1.87E+02	1.87E-05
Th232	6.10E-01	1.75E+04	1.17E-06	1.75E+04	1.75E-03
U238	8.66E+00	8.34E+01	1.66E-05	9.21E+01	9.21E-06
Misc	3.12E+02	1.34E-01	5.52E-05	3.12E+02	3.12E-05

URBAN

Isotope	D_{WB}	D_{inh}	D_{gnd}	$ADAD_{Total}$	Prob • $ADAD_T$
Am241	4.69E+01	2.91E+04	8.71E-05	2.92E+04	2.92E-03
Cl36	3.20E+01	1.52E+00	6.14E-05	3.35E+01	3.35E-06
Co60	5.35E+03	1.35E+00	2.03E-03	5.35E+03	5.35E-04
Cr51	6.15E+01	2.17E-02	7.57E-07	6.15E+01	6.15E-06
Cs137	1.20E+03	9.98E+00	1.45E-03	1.21E+03	1.21E-04
Nb94	3.36E+03	1.23E+00	6.43E-03	3.36E+03	3.36E-04
Ni59	2.26E+03	6.13E-01	4.34E-03	2.26E+03	2.26E-04
P32	0.00E+00	5.02E-01	0.00E+00	5.02E-01	5.02E-08
Pu241	4.69E+01	7.21E+02	3.61E-05	7.68E+02	7.68E-05
Ra226	3.30E+03	1.23E+04	6.26E-03	1.56E+04	1.56E-03
S35	0.00E+00	2.69E-01	0.00E+00	2.69E-01	2.69E-08
Sr90	0.00E+00	6.55E+02	0.00E+00	6.55E+02	6.55E-05
Th232	2.13E+00	6.13E+04	4.09E-06	6.13E+04	6.13E-03
U238	3.03E+01	2.92E+02	5.81E-05	3.22E+02	3.22E-05
Misc	1.09E+03	4.70E-01	1.93E-04	1.09E+03	1.09E-04

Appendix G

UNIT RISK FACTORS

Appendix G

Unit Risk Factors

Table G-1. Risk Factors: Person-Rem per Kilometer

		ACCIDENT-FREE RISK FACTORS			ACCIDENT RISK FACTORS		
Isotope	**Package**	**Rural**	**Suburban**	**Urban**	**Rural**	**Suburban**	**Urban**
Am241	Cask	2.27E-05	2.27E-05	3.13E-05	6.89E-12	8.05E-12	1.16E-11
Am241	LSA	2.34E-05	3.52E-05	9.12E-05	4.17E-05	8.34E-04	2.92E-03
Cl36	LSA	2.43E-05	5.08E-05	1.66E-04	4.79E-08	9.58E-07	3.35E-06
Co58	Cask	2.28E-05	2.33E-05	3.40E-05	2.22E-10	2.69E-10	4.08E-10
Co60	Cask	2.28E-05	2.39E-05	3.70E-05	4.60E-10	5.58E-10	8.47E-10
Co60	Drum	2.59E-05	8.21E-05	3.17E-04	7.64E-06	1.53E-04	5.35E-04
Co60	LSA	2.91E-05	1.42E-04	6.02E-04	7.64E-06	1.53E-04	5.35E-04
Cr51	LSA	2.31E-05	2.91E-05	6.21E-05	8.78E-08	1.76E-06	6.15E-06
Cs134	Cask	2.28E-05	2.36E-05	3.54E-05	3.36E-10	4.07E-10	6.18E-10
Cs137	Cask	2.27E-05	2.29E-05	3.18E-05	6.89E-11	8.05E-11	1.16E-10
Cs137	Drum	2.29E-05	2.52E-05	4.32E-05	1.73E-06	3.46E-05	1.21E-04
Cs137	LSA	2.41E-05	4.77E-05	1.51E-04	1.73E-06	3.46E-05	1.21E-04
Ir192	Cask	2.27E-05	2.28E-05	3.14E-05	1.59E-11	1.93E-11	2.93E-11
Nb94	Cask	2.28E-05	2.36E-05	3.54E-05	3.36E-10	4.07E-10	6.18E-10
Nb94	Drum	2.51E-05	6.61E-05	2.40E-04	4.80E-06	9.59E-05	3.36E-04
Nb94	LSA	2.74E-05	1.09E-04	4.48E-04	4.80E-06	9.59E-05	3.36E-04
Ni59	Cask	2.28E-05	2.33E-05	3.42E-05	2.39E-10	2.90E-10	4.40E-10
Ni59	Drum	2.44E-05	5.36E-05	1.80E-04	3.23E-06	6.46E-05	2.26E-04
Ni59	LSA	2.60E-05	8.44E-05	3.28E-04	3.23E-06	6.46E-05	2.26E-04
P32	LSA	0.00E+00	0.00E+00	0.00E+00	7.17E-10	1.43E-08	5.02E-08
Pu241	Drum	2.28E-05	2.34E-05	3.42E-05	1.10E-06	2.19E-05	7.68E-05
Pu241	LSA	2.34E-05	3.52E-05	9.12E-05	1.10E-06	2.19E-05	7.68E-05
Ra226	Cask	2.28E-05	2.36E-05	3.53E-05	3.27E-10	3.97E-10	6.02E-10
Ra226	LSA	2.73E-05	1.07E-04	4.37E-04	2.22E-05	4.44E-04	1.56E-03
S35	LSA	0.00E+00	0.00E+00	0.00E+00	3.85E-10	7.69E-09	2.69E-08
Sr90	LSA	0.00E+00	0.00E+00	0.00E+00	9.36E-07	1.87E-05	6.55E-05
Th232	LSA	0.00E+00	0.00E+00	0.00E+00	8.76E-05	1.75E-03	6.13E-03
U238	LSA	2.46E-05	5.58E-05	1.90E-04	4.60E-07	9.21E-06	3.22E-05
Misc	Drum	2.27E-05	2.30E-05	3.27E-05	1.56E-06	3.12E-05	1.09E-04
Misc	LSA	2.29E-05	2.57E-05	4.55E-05	1.56E-06	3.12E-05	1.09E-04

Table G-2. Risk Factors: Person-Rem per Mile

		ACCIDENT-FREE RISK FACTORS			ACCIDENT RISK FACTORS		
Isotope	**Package**	**Rural**	**Suburban**	**Urban**	**Rural**	**Suburban**	**Urban**
Am241	Cask	3.65E-05	3.65E-05	5.04E-05	1.11E-11	1.30E-11	1.87E-11
Am241	LSA	3.77E-05	5.66E-05	1.47E-04	6.71E-05	1.34E-03	4.70E-03
Cl36	LSA	3.91E-05	8.18E-05	2.67E-04	7.71E-08	1.54E-06	5.39E-06
Co58	Cask	3.67E-05	3.75E-05	5.47E-05	3.57E-10	4.33E-10	6.57E-10
Co60	Cask	3.67E-05	3.85E-05	5.95E-05	7.40E-10	8.98E-10	1.36E-09
Co60	Drum	4.17E-05	1.32E-04	5.10E-04	1.23E-05	2.46E-04	8.61E-04
Co60	LSA	4.68E-05	2.29E-04	9.69E-04	1.23E-05	2.46E-04	8.61E-04
Cr51	LSA	3.72E-05	4.68E-05	9.99E-05	1.41E-07	2.83E-06	9.90E-06
Cs134	Cask	3.67E-05	3.80E-05	5.70E-05	5.41E-10	6.55E-10	9.95E-10
Cs137	Cask	3.65E-05	3.69E-05	5.12E-05	1.11E-10	1.30E-10	1.87E-10
Cs137	Drum	3.69E-05	4.06E-05	6.95E-05	2.78E-06	5.57E-05	1.95E-04
Cs137	LSA	3.88E-05	7.68E-05	2.43E-04	2.78E-06	5.57E-05	1.95E-04
Ir192	Cask	3.65E-05	3.67E-05	5.05E-05	2.56E-11	3.11E-11	4.72E-11
Nb94	Cask	3.67E-05	3.80E-05	5.70E-05	5.41E-10	6.55E-10	9.95E-10
Nb94	Drum	4.04E-05	1.06E-04	3.86E-04	7.72E-06	1.54E-04	5.41E-04
Nb94	LSA	4.41E-05	1.75E-04	7.21E-04	7.72E-06	1.54E-04	5.41E-04
Ni59	Cask	3.67E-05	3.75E-05	5.50E-05	3.85E-10	4.67E-10	7.08E-10
Ni59	Drum	3.93E-05	8.63E-05	2.90E-04	5.20E-06	1.04E-04	3.64E-04
Ni59	LSA	4.18E-05	1.36E-04	5.28E-04	5.20E-06	1.04E-04	3.64E-04
P32	LSA	0.00E+00	0.00E+00	0.00E+00	1.15E-09	2.30E-08	8.08E-08
Pu241	Drum	3.67E-05	3.77E-05	5.50E-05	1.77E-06	3.52E-05	1.24E-04
Pu241	LSA	3.77E-05	5.66E-05	1.47E-04	1.77E-06	3.52E-05	1.24E-04
Ra226	Cask	3.67E-05	3.80E-05	5.68E-05	5.26E-10	6.39E-10	9.69E-10
Ra226	LSA	4.39E-05	1.72E-04	7.03E-04	3.57E-05	7.15E-04	2.51E-03
S35	LSA	0.00E+00	0.00E+00	0.00E+00	6.20E-10	1.24E-08	4.33E-08
Sr90	LSA	0.00E+00	0.00E+00	0.00E+00	1.51E-06	3.01E-05	1.05E-04
Th232	LSA	0.00E+00	0.00E+00	0.00E+00	1.41E-04	2.82E-03	9.87E-03
U238	LSA	3.96E-05	8.98E-05	3.06E-04	7.40E-07	1.48E-05	5.18E-05
Misc	Drum	3.65E-05	3.70E-05	5.26E-05	2.51E-06	5.02E-05	1.75E-04
Misc	LSA	3.69E-05	4.14E-05	7.32E-05	2.51E-06	5.02E-05	1.75E-04

Appendix H

VERIFICATION OF THE NETWORK OPTIMIZATION ALGORITHM

Appendix H

Verification of the Network Optimization Algorithm

To verify its accuracy, the algorithm was tested with a simple network (figure H-1). The link weights shown are assumed to be independent of the nodes chosen as origin or destination. The destination is node T, S1 and S2 are source nodes.

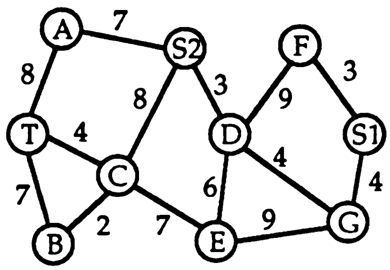

Figure H-1. Test Network

Stepping through the algorithm, the network is initialized by setting the temporary labels to ∞. The destination node is given the permanent label 0 and all nodes connected to it are found, receiving temporary labels equal to their weight plus the permanent label of T. C has the smallest temporary label, so it is made permanent. Listed below are the labels and predecessors for all nodes to this point in the process.

Table H-1. Test of Algorithm

Node	Temp. Label	Perm. Label	Predecessor
T	∞	-	-
S1	∞	-	-
S2	∞	-	-
A	∞	-	-
B	∞	-	-
C	∞	-	-
D	∞	-	-
E	∞	-	-
F	∞	-	-
G	∞	-	-

Node	Temp. Label	Perm. Label	Predecessor
T	-	0	-
S1	∞	-	-
S2	∞	-	-
A	∞	-	-
B	∞	-	-
C	∞	-	-
D	∞	-	-
E	∞	-	-
F	∞	-	-
G	∞	-	-

Node	Temp. Label	Perm. Label	Predecessor
T	-	0	-
S1	∞	-	-
S2	∞	-	-
A	8	-	T
B	7	-	T
C	4	-	T
D	∞	-	-
E	∞	-	-
F	∞	-	-
G	∞	-	-

Node	Temp. Label	Perm. Label	Predecessor
T	-	0	-
S1	∞	-	-
S2	∞	-	-
A	8	-	T
B	7	-	T
C	-	4	T
D	∞	-	-
E	∞	-	-
F	∞	-	-
G	∞	-	-

Since C is not S1, the origin desired, the algorithm continues by calculating new temporary labels for those nodes connected to C. Notice that node B has a new temporary label of 6, less than the value of the direct link to T. Next, the entire list of temporarily labeled nodes is scanned for the smallest value. In this case it is node B, which becomes permanently labeled. Since no temporarily labeled nodes are connected to B, the lists do not change and node A becomes permanently labeled.

Table H-1. (continued)

Node	Temp. Label	Perm. Label	Predecessor	Node	Temp. Label	Perm. Label	Predecessor
T	-	0	-	T	-	0	-
S1	∞	-	-	S1	∞	-	-
S2	12	-	C	S2	12	-	C
A	8	-	T	A	8	-	T
B	6	-	C	B	-	6	C
C	-	4	T	C	-	4	T
D	∞	-	-	D	∞	-	-
E	11	-	C	E	11	-	C
F	∞	-	-	F	∞	-	-
G	∞	-	-	G	∞	-	-
T	-	0	-	T	-	0	-
S1	∞	-	-	S1	∞	-	-
S2	12	-	C	S2	12	-	C
A	8	-	T	A	-	8	T
B	-	6	C	B	-	6	C
C	-	4	T	C	-	4	T
D	∞	-	-	D	∞	-	-
E	11	-	C	E	11	-	C
F	∞	-	-	F	∞	-	-
G	∞	-	-	G	∞	-	-
T	-	0	-	T	-	0	-
S1	∞	-	-	S1	∞	-	-
S2	12	-	C	S2	12	-	C
A	-	8	T	A	-	8	T
B	-	6	C	B	-	6	C
C	-	4	T	C	-	4	T
D	∞	-	-	D	∞	-	-
E	11	-	C	E	-	11	C
F	∞	-	-	F	∞	-	-
G	∞	-	-	G	∞	-	-

The only node with a temporary label connected to A is S2 but its weight through A is greater than through C so its temporary label does not change. E has the lowest temporary label so it becomes a permanent label. Connected to E are D and G which have their temporary labels lowered to 17 and 20 respectively. S2 now is permanently labeled, resulting in a new weight of 15 for D. This is the smallest value on the list of temporary labels, so it is made permanent.

Table H-1. (continued)

Node	Temp. Label	Perm. Label	Predecessor
T	-	0	-
S1	∞	-	-
S2	12	-	C
A	-	8	T
B	-	6	C
C	-	4	T
D	17	-	E
E	-	11	C
F	∞	-	-
G	20	-	E

Node	Temp. Label	Perm. Label	Predecessor
T	-	0	-
S1	∞	-	-
S2	-	12	C
A	-	8	T
B	-	6	C
C	-	4	T
D	17	-	E
E	-	11	C
F	∞	-	-
G	20	-	E

Node	Temp. Label	Perm. Label	Predecessor
T	-	0	-
S1	∞	-	-
S2	-	12	C
A	-	8	T
B	-	6	C
C	-	4	T
D	15	-	S2
E	-	11	C
F	∞	-	-
G	20	-	E

Node	Temp. Label	Perm. Label	Predecessor
T	-	0	-
S1	∞	-	-
S2	-	12	C
A	-	8	T
B	-	6	C
C	-	4	T
D	-	15	S2
E	-	11	C
F	∞	-	-
G	20	-	E

Node	Temp. Label	Perm. Label	Predecessor
T	-	0	-
S1	∞	-	-
S2	-	12	C
A	-	8	T
B	-	6	C
C	-	4	T
D	-	15	S2
E	-	11	C
F	24	-	D
G	19	-	D

Node	Temp. Label	Perm. Label	Predecessor
T	-	0	-
S1	∞	-	-
S2	-	12	C
A	-	8	T
B	-	6	C
C	-	4	T
D	-	15	S2
E	-	11	C
F	24	-	D
G	-	19	D

With D permanently labeled, F becomes accessible and its label is reduced to 24. G has weight 19 through D and retains that value for its permanent label. This leads to the labeling of S1 with a value of 23. Since this is the smaller of the two remaining temporary labels, it becomes a permanent label and the algorithm ends. The result for S1 then is a final weight of 23. The path to T can be traced by the predecessors: S1, G, D, S2, C, and finally, T.

Table H-1. (continued)

Node	Temp. Label	Perm. Label	Predecessor	Node	Temp. Label	Perm. Label	Predecessor
T	-	0	-	T	-	0	-
S1	23	-	G	S1	-	23	G
S2	-	12	C	S2	-	12	C
A	-	8	T	A	-	8	T
B	-	6	C	B	-	6	C
C	-	4	T	C	-	4	T
D	-	15	S2	D	-	15	S2
E	-	11	C	E	-	11	C
F	24	-	D	F	24	-	D
G	-	19	D	G	-	19	D

To complete the test, the algorithm needs to solve the path from S2. S2 is found on the list of permanent labels and so the algorithm does not solve the network again but merely reports the value of 12 and the path S2, C, T. If F were to be designated an origin, the algorithm proceeds from the temporary list above rather than reinitializing the network. Figure H-2 shows the permanent labels assigned to each node and the paths from each node to the destination. F is not included since the algorithm stopped before it was made permanent.

The solution is verified by enumerating all possible paths between S1 and T. Certain paths can be eliminated by inspection because of domination by alternative paths. For example, C-T will always be better than C-B-T and S1-F-D is always dominated by S1-G-D.

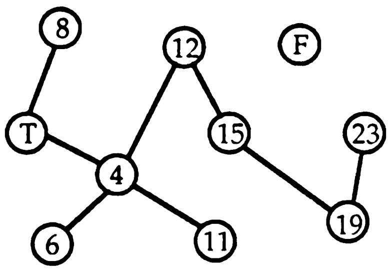

Figure H-2. Solution

Eliminating any path passing through nodes B or F leaves six possible paths:

S1-G-D-S2-A-T	4 + 4 + 3 + 7 + 8	= 26
S1-G-D-S2-C-T	4 + 4 + 3 + 8 + 4	= 23
S1-G-D-E-C-T	4 + 4 + 6 + 7 + 4	= 25
S1-G-E-D-S2-A-T	4 + 9 + 6 + 3 + 7 + 8	= 37
S1-G-E-D-S2-C-T	4 + 9 + 6 + 3 + 8 + 4	= 34
S1-G-E-C-T	4 + 9 + 7 + 4	= 24

So, the path chosen by the algorithm is the optimal solution. Enumeration is only practical with small networks, for the network modelling the MILLRWC, enumeration is not feasible and the algorithm quickly proves its worth.

Appendix I

RISK AND COST OPTIMIZATION PROGRAM

Appendix I

Risk and Cost Optimization Program

```
REM   "Carrick 4.0"
REM
REM   Programmed by James T. Carrick
REM
REM   This software was created using the ZBasic™ Compiler.
REM   Portions of this code are Copyrighted ©, 1985 by Zedcor Inc.
REM
REM   This is a modification of the Dijkstra algorithm found on page 235
REM   of DISCRETE OPTIMIZATION ALGORITHMS by Syslo, Deo and Kowalik, as
REM   translated from their Pascal listing.
REM
REM   One modification is in the data structure.  Syslo, et. al. used a
REM   segment weight matrix requiring N x N entries where N = number of
REM   nodes.  This new structure is a linked adjacency list.  For each
REM   node a list of connecting nodes and segment weights is maintained.
REM   Associated with each node & weight is a link code, pointing to the
REM   next entry in the list for the originating node.  A second list is
REM   maintained containing the starting point in the adjacency list of
REM   each node.  These two lists require only N + (5 x M) memory
REM   locations where M = the number of segments.  So a network of 300
REM   nodes and 450 links will need only (300 x 2b)+(450 x 10b) = 5.1 Kb
REM   of memory as opposed to 300 x 300 x 4 bytes = 360 Kb for the weight
REM   matrix format.  Note that most of the weight matrix is composed of
REM   null entries, that is, representing no connection between nodes.
REM
REM   The random file containing the list of pointers for each node is
REM   called "Pointers."  Its format is 2 bytes for each pointer indexed
REM   by node number.
REM
REM   The random file containing the connecting nodes, weights and links
REM   is called "MidW Len, PopD, TrAcc."  Its format is 2 bytes for the
REM   connecting node number, 2 bytes for the weight, 2 bytes for the
REM   population density, 2 bytes for the truck accident rate and 2 bytes
REM   for the link number.  An arbitrary index is assigned to each entry.
REM   The index of the first entry for a particular node equals the value
REM   stored in "Pointers" for that node.  The value of LINKER equals the
REM   index of the following entry in the list.  If there are no other
REM   entries, LINKER = 0.
REM
REM   The second alteration is that the search algorithm has changed.
REM   When looking for the nodes adjacent to RECENT (the node most
REM   recently given a permanent label), this program only looks at the
REM   nodes linked to RECENT rather than looking at all the nodes or all
REM   the segments. This is a result of the structure of the data
REM   (adjacency list).  The search proceeds much faster, reducing the
REM   search by a factor of 15.
REM
GOSUB "Initialize"
TEXT 3,12,0,1
```

```
"Opening"
PRINT: PRINT: PRINT
PRINT "  This program analyzes the shipment of Low-Level Radioactive"
PRINT "  Waste in the Midwest Compact Region. The annual shipments"
PRINT "  from all waste generators in the region to a specified repository"
PRINT "  site are simulated. 2 alternative methods of evaluating the"
PRINT "  transportation of LLW are provided. They are:"
PRINT
PRINT "         1. Minimize the transportation cost,"
PRINT "         2. Minimize the radiological risk,"
PRINT
PRINT "  Please enter the number of the option you wish to use.   ";
INPUT Option%
"Decision"
WHILE (Option% < 1) OR (Option% > 2)
  PRINT
  PRINT "  Only alternatives 1 or 2 are available."
  PRINT "  Please enter the number of your selection again.   ";
  INPUT Option%
WEND
"OK"
ON Option% GOSUB "Cost", "Risk"
PRINT: PRINT
PRINT "  Would you like to use a different method of analysis";
INPUT Respond$
RRR$ = LEFT$(Respond$,1)
IF (RRR$ = "Y") OR (RRR$ = "y") THEN "Opening"
"Completion"
END

"Initialize"
REM
REM  Initialization of variables
REM
CLS
DIM Origin(62), ShipType(3), 7ShipType$(3), PopDens(3), 9PopDens$(3)
DIM AnnualShip(62,3)
i = 1
DO
  READ Origin(i)
  i = i+1
UNTIL i > 62
DATA 31,49,55,59,63,65,65,65,67,69
DATA 72,92,93,102,105,110,158,167,171,171
DATA 180,187,187,190,203,203,209,217,224,234
DATA 243,253,253,255,305,306,307,308,309,310
DATA 311,312,313,314,316,317,318,334,335,336
DATA 336,337,338,338,339,339,348,350,351,352
DATA 354,355
k = 1
DO
  READ ShipType(k), ShipType$(k), PopDens(k), PopDens$(k)
  k = k+1
UNTIL k > 3
DATA 1, Cask, 200, Rural, 2, LSA, 1000, Suburban, 3, Barrel, 3500, Urban
FOR i = 1 TO 62
  FOR k = 1 TO 3
    READ AnnualShip(i, k)
```

```
  NEXT k
NEXT i
DATA 0,1,0,0,1,0,0,1,0,0,1,0,0,1,0,0,13,0,5,11,0,0,17,0,0,1,0,1,0,0
DATA 0,1,0,1,14,0,1,1,0,0,1,0,0,1,0,1,1,0,0,7,0,0,1,0,3,0,0,0,1,0
DATA 0,2,0,0,1,0,4,1,0,0,3,0,0,6,0,0,2,0,0,1,0,0,2,0,0,1,0,0,1,0
DATA 0,3,0,0,1,0,0,1,0,0,3,0,0,1,0,2,0,0,0,1,0,0,1,0,0,1,0,0,1,0
DATA 0,1,0,0,1,0,0,1,0,0,1,0,0,1,0,0,1,0,0,1,0,8,4,10,4,4,1,17,4,23
DATA 0,1,0,20,1,6,3,1,1,0,1,0,3,7,8,2,2,2,7,2,5,4,13,10,8,4,44,33,5,11
DATA 5,0,7,28,4,34
DIM As(3)
DIM AccUnitRisk#(30,3), AFUnitConseq#(30,3), Offset(62,3)
DIM Attach(267), Ci!(267), Isotope(267)
REM
REM  Origin(i) = Node number of generator site. 62 sites
REM  Offset(Origin(i), Shipment Type(k)) = Points to first location
REM     in Isotope and Ci lists for shipment from Origin(i) and
REM     Shipment Type(1) for casks or (2) for LSA and (3) for barrels.
REM     One Offset for 62 Origins * 3 Shipment Types = 186.
REM  Isotope(m) = Identifies the index of an isotope and Shipment Type
REM     for the Origin pointed to by Offset(i,j).  30 combinations of
REM     isotopes and packaging are modeled.  Total of 267 shipments of
REM     isotopes and packages from 62 Origins are modeled for risk.
REM     The isotopes and packages are:
REM     1  Am241 Cask     2  Am241 LSA     3  C136 LSA      4  Co58 Cask
REM     5  Co60  Cask     6  Co60  Drum    7  Co60 LSA      8  Cr51 LSA
REM     9  Cs134 Cask    10  Cs137 Cask   11  Cs137 Drum   12  Cs137 LSA
REM    13  Ir192 Cask    14  Nb94  Cask   15  Nb94 Drum    16  Nb94 LSA
REM    17  Ni59  Cask    18  Ni59  Drum   19  Ni59 LSA     20  P32  LSA
REM    21  Pu241 Drum    22  Pu241 LSA    23  Ra226 Cask   24  Ra226 LSA
REM    25  S35   LSA     26  Sr90  LSA    27  Th232 LSA    28  U238 Drum
REM    29  Misc  Drum    30  Misc  LSA
REM  Ci(m) = Value for the curies of isotope shipped as designated in
REM     Isotope(m).
REM  Attach(m) = Points to the next Isotope(m) for any given Origin(i)
REM     and Shipment Type(k).
REM  AccUnitRisk#(n,p) = Unit Risk of an accident involving 1 curie of
REM     isotope and package n, over 1 mile of travel with Truck Accident
REM     Rate of 1 E-7, in population density zone p. 30 values for n
REM     correspond to the 30 combinations of isotopes and packages
REM     indexed by Isotope(m).
REM  AFUnitConseq#(n,p) = same as above except Accident-Free situation
REM
b = 1
DO
  a = 1
  DO
   READ AccUnitRisk#(a,b)
   a = a + 1
  UNTIL a > 30
  b = b + 1
UNTIL b > 3
DATA 1.13E-11, 6.71E-5, 7.71E-8, 3.64E-10, 7.55E-10
DATA 1.23E-5, 1.23E-5, 1.41E-7, 5.5E-10, 1.13E-10
DATA 2.78E-6, 2.78E-6, 2.61E-11, 5.5E-10, 7.72E-6
DATA 7.72E-6, 3.91E-10, 5.2E-6, 5.2E-6, 1.15E-9
DATA 1.77E-6, 1.77E-6, 5.36E-10, 3.57E-5, 6.2E-10
DATA 1.51E-6, 1.41E-4, 7.4E-7, 2.51E-6, 2.51E-6
DATA 1.75E-11, 1.34E-3, 1.54E-6, 5.65E-10, 1.17E-9
```

```
DATA 2.46E-4, 2.46E-4, 2.83E-6,  8.55E-10, 1.75E-10
DATA 5.57E-5, 5.57E-5, 4.06E-11, 8.55E-10, 1.54E-4
DATA 1.54E-4, 6.08E-10, 1.04E-4, 1.04E-4, 2.3E-8
DATA 3.52E-5, 3.52E-5, 8.32E-10, 7.15E-4, 1.24E-8
DATA 3.01E-5, 2.82E-3, 1.48E-5, 5.02E-5, 5.02E-5
DATA 3.48E-11, 4.7E-3, 5.39E-6, 1.12E-9, 2.32E-9
DATA 8.61E-4, 8.61E-4, 9.9E-6, 1.69E-9, 3.48E-10
DATA 1.95E-4, 1.95E-4, 8.01E-11, 1.69E-9, 5.41E-4
DATA 5.41E-4, 1.2E-9, 3.64E-4, 3.64E-4, 8.08E-8
DATA 1.24E-4, 1.24E-4, 1.64E-9, 2.51E-3, 4.33E-8
DATA 1.05E-4, 9.87E-3, 5.18E-5, 1.75E-4, 1.75E-4
b = 1
DO
  a = 1
  DO
    READ AFUnitConseq#(a,b)
    a = a + 1
  UNTIL a > 30
  b = b + 1
UNTIL b > 3
DATA 3.65E-5, 4.22E-5, 4.91E-5, 3.67E-5, 3.7E-5
DATA 5.5E-5, 7.35E-5, 3.94E-5, 3.69E-5, 3.67E-5
DATA 3.77E-5, 4.76E-5, 3.65E-5, 3.69E-5, 5E-5
DATA 6.36E-5, 3.67E-5, 4.62E-5, 5.58E-5, 0
DATA 3.69E-5, 4.22E-5, 3.69E-5, 6.29E-5, 0
DATA 0, 0, 5.13E-5, 3.67E-5, 5.97E-5
DATA 3.67E-5, 1.34E-4, 2.56E-4, 3.97E-5, 4.31E-5
DATA 3.62E-4, 6.87E-4, 8.67E-5, 4.14E-5, 3.75E-5
DATA 5.6E-5, 2.32E-4, 3.69E-5, 4.14E-5, 2.74E-4
DATA 5.1E-4, 3.99E-5, 2.06E-4, 3.73E-4, 0
DATA 4.15E-5, 1.34E-4, 4.12E-5, 4.99E-4, 0
DATA 0, 0, 2.95E-4, 3.89E-5, 5.97E-5
DATA 5.07E-5, 5.21E-4, 1.11E-3, 6.55E-5, 8.18E-5
DATA 1.63E-3, 3.19E-3, 2.93E-4, 7.32E-5, 5.5E-5
DATA 1.45E-4, 9.93E-4, 5.13E-5, 7.32E-5, 1.2E-3
DATA 2.35E-3, 6.66E-5, 8.66E-4, 1.67E-3, 0
DATA 7.39E-5, 5.21E-4, 7.26E-5, 2.29E-3, 0
DATA 0, 0, 1.3E-3, 6.15E-5, 1.63E-4
b = 1
DO
  a = 1
  DO
    READ Offset(a,b)
    a = a + 1
  UNTIL a > 62
  b = b + 1
UNTIL b > 3
DATA 0,0,0,0,0,0,10,0,0,16,0,18,21,0,0,0,0,0,35,0
DATA 0,0,43,0,0,0,0,0,0,0,0,0,0,0,0,71,0,0,0,0
DATA 0,0,0,0,0,0,0,88,104,117,0,134,147,0,163,176,190,205,219,234
DATA 251,256
DATA 1,0,3,0,6,7,11,13,15,0,0,20,23,26,0,28,32,0,0,38
DATA 40,0,46,49,53,0,0,58,59,0,61,62,0,66,0,0,0,0,0,76
DATA 78,0,0,84,0,0,0,92,107,121,0,137,150,162,166,180,193,209,224,237
DATA 0,258
DATA 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
DATA 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0
DATA 0,0,0,0,0,0,0,98,112,127,0,142,156,0,171,185,199,214,229,244
```

```
DATA 254,263
a = 1
DO
  READ Attach(a)
  a = a + 1
UNTIL a > 267
DATA 0,0,4,0,0,0,8,9,0,0,12,0,14,0,0,0,0,19,0,0
DATA 22,0,24,25,0,0,0,29,30,31,0,33,0,0,36,37,0,39,0,41
DATA 0,0,44,45,0,47,48,0,50,51,52,0,54,55,0,0,0,0,0,0
DATA 0,63,64,0,0,67,68,69,0,0,72,0,0,0,0,77,0,79,80,81
DATA 0,0,0,0,0,0,0,89,90,91,0,93,94,95,96,97,0,99,100,101
DATA 102,103,0,105,106,0,108,109,110,111
DATA 0,113,114,115,116,0,118,119,120,0
DATA 122,123,124,125,126,0,128,129,130,131
DATA 132,0,0,135,136,0,138,139,140,141
DATA 0,143,144,145,146,0,148,149,0,151
DATA 152,153,154,155,0,157,158,159,160,161
DATA 0,0,164,165,0,167,168,169,170,0,172,173,174,175,0,177,178,179,0,181
DATA 182,183,184,0,186,187,188,189,0,191
DATA 192,0,194,195,196,197,198,0,200,201
DATA 202,203,204,0,206,207,208,0,210,211
DATA 212,213,0,215,216,217,218,0,220,221
DATA 222,223,0,225,226,227,228,0,230,231
DATA 232,233,0,235,236,0,238,239,240,241
DATA 242,243,0,245,246,247,248,249,250,0
DATA 252,253,0,255,0,257,0,259,260,261
DATA 262,0,264,265,266,267,0
a = 1
DO
  READ Ci!(a)
  a = a + 1
UNTIL a > 267
DATA .001,0,.001,.012,0,.001,.114,.150,.062,200
DATA .181,.036,.002,.294,.001,210,0,2.5,1.2,.069
DATA 5.3,3.8,.003,.032,.018,.001,0,9.5,410,30
DATA .018,.049,.003,0,13.67,6.667,.004,.001,.001,.001
DATA .13,0,1.1,1,20,.008,.16,.012,.027,.026
DATA .093,.007,.022,.088,.003,0,0,.027,.001,0
DATA .047,.001,.031,.032,0,.001,.173,.001,.003,0
DATA 35,.25,0,0,0,.085,.074,.001,.001,.001
DATA .23,0,0,6.1,0,0,0,830,12.5,.004
DATA .7,10,7.143,.001,.012,.114,.025,10,7.143,.001
DATA .012,.264,.114,3.5,.725,.002,2.8,.580,.002,.112
DATA .01,2.8,.58,.002,.112,.01,295.9,9.706,.001,.247
DATA 8.519,6.111,.01,.008,.021,.001,8.519,6.111,.01,.008
DATA .021,.001,0,.55,.08,.001,1.571,.229,.001,.6
DATA .004,1.571,.229,.001,.06,.004,5.833,5.5,.004,8.75
DATA 8.25,.005,.065,.03,.001,8.75,8.25,.005,.065,.03
DATA .001,.002,8.5,2,.005,1.7,.4,.001,.073,.007
DATA 1.7,.4,.001,.073,.007,802,.45,.004,.7,1.013
DATA .225,.001,.042,.004,1.013,.225,.001,.042,.004,7.857
DATA 7.857,.005,7.857,7.857,.005,.059,.029,.001,7.857,7.857
DATA .005,.059,.029,.001,211.5,2.625,.001,.175,2,.456
DATA .002,.087,.008,2,.456,.002,.087,.008,9.375,1.813
DATA 50,31.25,.002,.302,5.208,.025,.001,.001,.302,5.208
DATA .025,.001,.001,20,14.09,.008,13.75,9.688,.001,.017
DATA .338,.069,.001,13.75,9.688,.001,.017,.338,.069,.001
DATA .89,8.6,13,.636,.929,13.04,9.286,9.605,6.842,.118
```

```
DATA .024,.001,9.605,6.842,.118,.024,.001
a = 1
DO
  READ Isotope(a)
  a = a + 1
UNTIL a > 267
DATA 30,0,8,30,0,30,8,20,25,10,24,26,2,28,30,5,0,5,10,26
DATA 5,10,19,22,26,30,0,3,20,25,30,20,30,0,1,10,23,12,30,8
DATA 30,0,1,5,10,24,26,30,8,20,25,30,8,20,30,0,0,8,30,0
DATA 8,3,7,30,0,7,8,12,30,0,5,13,0,0,0,7,26,7,12,24
DATA 27,0,0,26,0,0,0,5,10,14,17,7,12,16,19,22,26,6,11,15
DATA 18,21,26,5,10,17,7,12,19,22,26,6,11,18,21,26,5,10,14,17
DATA 7,12,19,22,26,30,6,11,18,21,26,29,0,5,10,17,7,12,19,22
DATA 26,6,11,18,21,26,5,10,17,7,12,19,22,26,30,6,11,18,21,26
DATA 29,8,5,10,17,7,12,19,22,26,6,11,18,21,26,5,10,14,17,7
DATA 12,19,22,26,6,11,18,21,26,5,10,17,7,12,19,22,26,30,6,11
DATA 18,21,26,29,5,10,14,17,7,12,19,22,26,6,11,18,21,26,4,5
DATA 9,10,17,7,12,22,26,30,6,11,21,26,29,5,10,17,7,12,16,19
DATA 22,26,30,6,11,15,18,21,26,29,5,9,10,6,11,5,10,7,12,22
DATA 26,30,6,11,21,26,29
REM
REM  Read files "Pointers" and "MidW Len, PopD, TrAcc"
REM
DIM FINAL%(355), PRED%(355), Pointer%(355), H%(355)
DIM NODE%(836), Length%(836), PopD%(836), TrAccRate%(836), LINKER%(836)
PRINT
OPEN "R", #2, "Pointers", 2
OPEN "R", #1, "MidW Len, PopD, TrAcc", 10
N% = 355
NUM% = 1
DO
  RECORD #2, NUM%
  READ #2, Pointer$;2
  LET Pointer%(NUM%) = CVI(Pointer$)
  P% = Pointer%(NUM%)
  IF P% = 1000 THEN "Null.Node"
  WHILE P% <> 0
    RECORD #1, P%
    READ #1, Connector$;2, Length$;2, PopD$;2, TrAccRate$;2, LINKER$;2
    LET NODE%(P%) = CVI(Connector$)
    LET Length%(P%) = CVI(Length$)
    LET PopD%(P%) = CVI(PopD$)
    LET TrAccRate%(P%) = CVI(TrAccRate$)
    LET LINKER%(P%) = CVI(LINKER$)
    P% = LINKER%(P%)
  WEND
  "Null.Node"
  H%(NUM%) = NUM%
  NUM% = NUM% + 1
UNTIL NUM% > N%
CLOSE #1,#2
Saver% = 0
C% = 1
WHILE C% < N% - Saver%
  IF Pointer%(C%) <> 1000 THEN "Ignore"
  WHILE Pointer%(N% - Saver%) = 1000
    Saver% = Saver% + 1
  WEND
```

```
  H%(C%) = H%(N% - Saver%)
  Saver% = Saver% + 1
  "Ignore"
  C% = C% + 1
WEND
REM
REM  Initialization process completed.
REM
RETURN

"Cost"
DIM DIST(355)
"NewSite1"
V% = 1
DO
  DIST(V%) = 9999
  FINAL%(V%) = 0
  PRED%(V%) = -1
  V% = V% + 1
UNTIL V% > N%
TotalCost! = 0
TotalDist! = 0
PRINT: PRINT: PRINT
INPUT " Which node is to be the location of the repository?   "; S%
DIST(S%) = 0
FINAL%(S%) = -1
Recent% = S%
PRINT
PRINT " Would you like the results for each generation site:"
PRINT
PRINT "        1. Not reported,"
PRINT "        2. Displayed on the screen,"
PRINT "        3. Printed on the line printer."
PRINT
PRINT " Please enter the number of your selection.   ";
INPUT ReportOut%
PRINT
IF ReportOut% = 3 THEN PRINT "   Please insure that the printer is turned on."
FOR ii% = 1 TO 62
  CaskCost! = 0
  BarrelCost! = 0
  TransCost! = 0
  CaskTariff! = 0
  BarrelTariff! = 0
  Decide = 2
  T% = Origin(ii%)
  REM
  REM  The next statement creates a loop which causes the problem to
  REM  be solved for all nodes until the destination node is solved.
  REM  The solution for the remainder of the network is not completed.
  REM
  WHILE FINAL%(T%) = 0
    REM
    REM  The following FOR loop finds all nodes connected to the current
    REM  node (designated as RECENT).  For all nodes connected to RECENT
    REM  and not yet permanently labelled, the total distance from the
    REM  source is calculated and temporarily stored for comparison.
    REM
```

```
    Z = Pointer%(Recent%)
    WHILE Z <> 0
      IF FINAL%(NODE%(Z)) <> 0 THEN "UPWARD1"
      NEWLABEL = DIST(Recent%) + Length%(Z)
      IF NEWLABEL >= DIST(NODE%(Z)) THEN "UPWARD1"
      DIST(NODE%(Z)) = NEWLABEL
      PRED%(NODE%(Z)) = Recent%
      "UPWARD1"
      Z = LINKER%(Z)
    WEND
    REM
    REM  The next DO loop sorts through the nodes adjacent to RECENT and
    REM  chooses the node nearest RECENT (the node currently being
    REM  examined.)
    REM
    TEMP = 9999
    U% = 1
    DO
      IF ((FINAL%(H%(U%))=0) AND (DIST(H%(U%))<TEMP)) THEN "SHORTEST1"
        ELSE "AGAIN1"
      "SHORTEST1"
      Y% = H%(U%)
      TEMP = DIST(H%(U%))
      "AGAIN1"
      U% = U% + 1
    UNTIL U% > (N% - Saver%)
    REM
    REM  Once the node closest to RECENT is determined, it is made part
    REM  of the set of permanently labelled nodes by giving it a FINAL
    REM  value of -1 and it is assigned the temporary title of RECENT.
    REM  The process continuesby solving for the node nearest the newly
    REM  crowned RECENT.
    REM
    IF TEMP > 9998 THEN "FINIS1"
    FINAL%(Y%) = -1
    Recent% = Y%
    "FINIS1"
  WEND
  IF DIST(T%) < 100 THEN Decide = 1
  ON Decide GOSUB "ShortDist", "LongDist"
  TransCost! = CaskCost!/100 + BarrelCost!/100
  TotalCost! = TotalCost! + TransCost!
  TotalDist!=TotalDist!+(DIST(T%)*(AnnualShip(ii%,1)+AnnualShip(ii%,2)
    +AnnualShip(ii%,3)))
  ON ReportOut%-1 GOSUB "Displayed", "Printed"
NEXT ii%
PRINT " The TOTAL COST of shipping LLW to"; S%; "is: $"; TotalCost!
PRINT
PRINT USING " #.### ^^^^ "; TotalDist!;
PRINT "vehicle-miles are required for annual shipments to"; S%
PRINT: PRINT
INPUT "  Would you like to examine another repository site?   "; Reply$
AA$ = LEFT$(Reply$,1)
IF (AA$ = "Y" OR AA$ = "y") THEN "NewSite1"
RETURN

"LongDist"
IF AnnualShip(ii%,1) = 0 THEN "Barrels1"
```

```
CaskTariff! = INT((3140 * DIST(T%)^(-.484)) + .5)
IF DIST(T%) > 600 THEN CaskTariff! = 142
CaskCost! = AnnualShip(ii%,1) * ((CaskTariff! * 2 * DIST(T%)) + (100000
  * INT((2 * DIST(T%)/500))+.5) + 200000)
"Barrels1"
BarrelTariff! = INT((4290 * DIST(T%)^(-.4799)) + .5)
IF DIST(T%) > 1000 THEN BarrelTariff! = 156
BarrelCost! = (AnnualShip(ii%,2) + AnnualShip(ii%,3)) * BarrelTariff! *
  DIST(T%)
RETURN

"ShortDist"
REM
REM  Distances less than 100 miles are charged for 100 miles of
REM  shipping.
REM
CaskTariff! = 338
BarrelTariff! = 471
CaskCost! = AnnualShip(ii%,1) * ((CaskTariff! * 200) + 200000)
BarrelCost! = (AnnualShip(ii%,2) + AnnualShip(ii%,3))*BarrelTariff!*100
RETURN

"Displayed"
WIDTH 70
DEF TAB = 7
TEXT 4,9,0,1
IF S% = T% THEN "Soon"
PRINT
PRINT "The path between node"; T%; "and node"; S%; "is:"
PRINT T%,
PRINT PRED%(T%),
X% = PRED%(T%)
WHILE X% <> S%
  PRINT PRED%(X%),
  X% = PRED%(X%)
WEND
PRINT
PRINT "The distance between nodes"; T%; "and"; S%; "is:"; DIST(T%)
PRINT
"Soon"
PRINT "The cost of transporting LLW between"; T%; "and"; S%; "is: $"; TransCost!
PRINT: PRINT
TEXT 3,12,0,1
RETURN

"Printed"
TEXT 4,9,0,1
IF S% = T% THEN "Goon"
LPRINT
LPRINT "The path between node"; T%; "and node"; S%; "is:"
LPRINT T%,
LPRINT PRED%(T%),
X% = PRED%(T%)
WHILE X% <> S%
  LPRINT PRED%(X%),
  X% = PRED%(X%)
WEND
LPRINT
```

```
LPRINT "The distance between nodes"; T%; "and"; S%; "is:"; DIST(T%)
LPRINT
"Goon"
LPRINT "The cost of transporting LLW between"; T%; "and"; S%; "is: $"; TransCost!
LPRINT: LPRINT
TEXT 3,12,0,1
RETURN

"Risk"
DIM Risk#(355),RDist(355),RFinal(355),RPred(355),DDist(355)
"NewSite2"
TotalRisk# = 0
TotalDist! = 0
V = 1
DO
  RDist(V) = 9999
  RFinal(V) = 0
  RPred(V) = -1
  V = V + 1
UNTIL V > N%
PRINT: PRINT: PRINT
INPUT "  Which node is to be the location of the repository?    "; T%
PRINT
PRINT "  Would you like the results for each generation site:"
PRINT
PRINT "        1. Not reported,"
PRINT "        2. Displayed on the screen,"
PRINT "        3. Printed on the line printer."
PRINT
PRINT "  Please enter the number of your selection.    ";
INPUT ReportOut%
PRINT
IF ReportOut% = 3 THEN PRINT " Please insure that the printer is turned on."
RDist(T%) = 0
RFinal(T%) = -1
RRecent = T%
FOR ii% = 1 TO 62
  As(1) = AnnualShip(ii%,1)
  As(2) = AnnualShip(ii%,2)
  As(3) = AnnualShip(ii%,3)
  Chooser = 1
  IF (Offset(ii%,1)=0 AND Offset(ii%,2)=0 AND Offset(ii%,3)=0) THEN
    Chooser=2
  REM
  REM  If the shipment being modelled has risk factor equal to 0, then
  REM  the route selected will be the shortest distance route.  RRisk
  REM  optimizes risk while RDistance optimizes distance
  REM
  ON Chooser GOSUB "RRisk", "RDistance"
  TotalRisk# = TotalRisk# + Risk#
  TotalDist! = TotalDist! + (RLength * (As(1) + As(2) + As(3)))
  ON ((Chooser+1)*(ReportOut%-1)-1) GOSUB
    "Displayed2","Disp2a","Printed2","zip","Prin2a"
NEXT ii%
PRINT " The DOSE CONSEQUENCE of shipping LLW to"; T%; "is ";
PRINT USING "#.### ^^^^ "; TotalRisk#;
PRINT "person-rem."
PRINT
```

```
PRINT USING " #.### ^^^^ "; TotalDist!;
PRINT "vehicle-miles are required for annual shipments to"; T%
PRINT: PRINT
INPUT "  Would you like to examine another repository site?   "; Reply$
AA$ = LEFT$(Reply$,1)
IF (AA$ = "Y" OR AA$ = "y") THEN "NewSite2"
RETURN

"RRisk"
V% = 1
DO
  Risk#(V%) = 9E6
  FINAL%(V%) = 0
  DDist(V%) = 0
  PRED%(V%) = -1
  V% = V% + 1
UNTIL V% > N%
S% = Origin(ii%)
Risk#(S%) = 0
FINAL%(S%) = -1
Recent% = S%
WHILE FINAL%(T%) = 0
  Z = Pointer%(Recent%)
  WHILE Z <> 0
    IF FINAL%(NODE%(Z)) <> 0 THEN "UPWARD2"
    AccConseq# = 0
    AFConseq# = 0
    Conseq# = 0
    ST% = 1
    DO
      REM
      REM  Risk is calculated for each link (population density zone) for
      REM  all shipment types.
      REM
      PP% = Offset(ii%,ST%)
      WHILE PP% <> 0
        AccConseq# = AccConseq# + Ci!(PP%) *
          (AccUnitRisk#(Isotope(PP%),PopD%(Z)) * TrAccRate%(Z) *
          Length%(Z) * As(ST%))
        AFConseq# = AFConseq# + Ci!(PP%) *
          (AFUnitConseq#(Isotope(PP%),PopD%(Z)) * Length%(Z) * As(ST%))
        Conseq# = Conseq# + AccConseq# + AFConseq#
        PP% = Attach(PP%)
      WEND
      ST% = ST% + 1
    UNTIL ST% > 3
    NEWLABEL# = Risk#(Recent%) + Conseq#
    IF NEWLABEL# >= Risk#(NODE%(Z)) THEN "UPWARD2"
    Risk#(NODE%(Z)) = NEWLABEL#
    PRED%(NODE%(Z)) = Recent%
    DDist(NODE%(Z)) = DDist(Recent%) + Length%(Z)
    "UPWARD2"
    Z = LINKER%(Z)
  WEND
  TEMP# = 9E6
  U% = 1
  DO
    IF ((FINAL%(H%(U%))=0) AND (Risk#(H%(U%))<TEMP#)) THEN "SHORTEST2"
```

```
    ELSE "AGAIN2"
   "SHORTEST2"
   Y% = H%(U%)
   TEMP# = Risk#(H%(U%))
   "AGAIN2"
   U% = U% + 1
  UNTIL U% > (N% - Saver%)
  IF TEMP# >= 9E6 THEN "FINIS2"
  FINAL%(Y%) = -1
  Recent% = Y%
  "FINIS2"
WEND
Risk# = Risk#(T%)
RLength = DDist(T%)
RETURN

"RDistance"
S% = Origin(ii%)
WHILE RFinal(S%) = 0
  RZ = Pointer%(RRecent)
  WHILE RZ <> 0
   IF RFinal(NODE%(RZ)) <> 0 THEN "RUPWARD"
   RNEWLABEL = RDist(RRecent) + Length%(RZ)
   IF RNEWLABEL >= RDist(NODE%(RZ)) THEN "RUPWARD"
   RDist(NODE%(RZ)) = RNEWLABEL
   RPred(NODE%(RZ)) = RRecent
   "RUPWARD"
   RZ = LINKER%(RZ)
  WEND
  RTEMP = 9999
  U = 1
  DO
   IF ((RFinal(H%(U))=0 AND RDist(H%(U))<RTEMP)) THEN "RSHORTEST" ELSE
    "RAGAIN"
   "RSHORTEST"
   RY = H%(U)
   RTEMP = RDist(H%(U))
   "RAGAIN"
   U = U + 1
  UNTIL U > (N% - Saver%)
  IF RTEMP > 9998 THEN "RFinis"
  RFinal(RY) = -1
  RRecent = RY
  "RFinis"
WEND
Risk# = 0
RLength = RDist(S%)
RETURN

"Displayed2"
WIDTH 70
DEF TAB = 7
TEXT 4,9,0,1
IF S% = T% THEN "Soon2"
PRINT
PRINT "The path between node"; S%; "and node"; T%; "is:"
PRINT T%,
PRINT PRED%(T%),
```

```
X% = PRED%(T%)
WHILE X% <> S%
 PRINT PRED%(X%),
 X% = PRED%(X%)
WEND
PRINT
"Soon2"
PRINT " The consequence of transporting LLW between"; S%; "and"; T%; "is"
PRINT USING " #.### ^^^^ "; Risk#;
PRINT "person-rem."
PRINT
PRINT USING " #.### ^^^^ "; (RLength * (As(1) + As(2) + As(3)));
PRINT "vehicle-miles are required for annual shipments to"; T%
PRINT: PRINT
TEXT 3,12,0,1
RETURN

"Disp2a"
WIDTH 70
DEF TAB = 7
TEXT 4,9,0,1
IF S% = T% THEN "Soon2a"
PRINT
PRINT "The path between node"; S%; "and node"; T%; "is:"
PRINT S%,
PRINT RPred(S%),
X% = RPred(S%)
WHILE X% <> T%
 PRINT RPred(X%),
 X% = RPred(X%)
WEND
PRINT
"Soon2a"
PRINT " The consequence of transporting LLW between"; S%; "and"; T%; "is"
PRINT USING " #.### ^^^^ "; Risk#;
PRINT "person-rem."
PRINT
PRINT USING " #.### ^^^^ "; (RLength * (As(1) + As(2) + As(3)));
PRINT "vehicle-miles are required for annual shipments to"; T%
PRINT: PRINT
TEXT 3,12,0,1
RETURN

"zip"
RETURN

"Printed2"
TEXT 4,9,0,1
IF S% = T% THEN "Goon2"
LPRINT
LPRINT "The path between node"; S%; "and node"; T%; "is:"
LPRINT T%,
LPRINT PRED%(T%),
X% = PRED%(T%)
WHILE X% <> S%
 LPRINT PRED%(X%),
 X% = PRED%(X%)
WEND
```

```
LPRINT
"Goon2"
LPRINT " The consequence of transporting LLW between"; S%; "and"; T%; "is"
LPRINT USING " #.### ^^^^ "; Risk#(T%);
LPRINT "person-rem."
LPRINT
LPRINT USING " #.### ^^^^ "; (RLength * (As(1) + As(2) + As(3)));
LPRINT "vehicle-miles are required for annual shipments to"; T%
LPRINT: LPRINT
TEXT 3,12,0,1
RETURN

"Prin2a"
TEXT 4,9,0,1
IF S% = T% THEN "Goon2a"
LPRINT
LPRINT "The path between node"; S%; "and node"; T%; "is:"
LPRINT S%,
LPRINT RPred(S%),
X% = RPred(S%)
WHILE X% <> T%
  LPRINT RPred(X%),
  X% = RPred(X%)
WEND
LPRINT
"Goon2a"
LPRINT " The consequence of transporting LLW between"; S%; "and"; T%; "is"
LPRINT USING " #.### ^^^^ "; Risk#(T%);
LPRINT "person-rem."
LPRINT
LPRINT USING " #.### ^^^^ "; (RLength * (As(1) + As(2) + As(3)));
LPRINT "vehicle-miles are required for annual shipments to"; T%
LPRINT: LPRINT
TEXT 3,12,0,1
RETURN
```

Appendix J

COST, RISK AND INDEX RESULTS: MODELLING THE MILLRWC

Appendix J

Cost, Risk and Index Results: Modelling the MILLRWC

Node	Location	Cost ($*E6)	Risk (P-rem*E3)	Cost Norm.	Risk Norm.	Combined Index
3	Fargo, ND	1.52	9.35	1.77	1.70	3.46
12	E Sioux Falls, SD	1.40	8.02	1.63	1.45	3.08
14	Sioux City, IA	1.36	8.24	1.58	1.49	3.07
17	Council Bluffs, IA	1.26	7.53	1.47	1.37	2.83
25	St. Joseph, MO	1.34	8.87	1.56	1.61	3.17
31	Kansas City, MO	1.30	8.22	1.51	1.49	3.00
49	SW Minneapolis, MN	1.21	6.31	1.41	1.14	2.55
55	NE St. Paul, MN	1.20	6.69	1.40	1.21	2.61
58	Barnum, MN	1.34	8.48	1.56	1.54	3.10
59	Duluth, MN	1.38	8.80	1.60	1.59	3.20
61	Albert Lea, MN	1.17	6.02	1.36	1.09	2.45
63	Marion, MN	1.13	6.51	1.31	1.18	2.49
65	Minneapolis, MN	1.21	7.36	1.41	1.33	2.74
67	Ames, IA	1.09	5.84	1.27	1.06	2.33
69	SE Des Moines, IA	1.09	5.89	1.27	1.07	2.34
72	Tiffin, IA	1.02	5.52	1.19	1.00	2.19
79	Joplin, MO	1.40	9.29	1.63	1.68	3.31
81	Springfield, MO	1.35	9.16	1.57	1.66	3.23
85	Cape Girardeau, MO	1.25	9.11	1.45	1.65	3.10
87	Hayti, MO	1.31	9.52	1.52	1.72	3.25
90	Charlestown, MO	1.24	8.92	1.44	1.62	3.06
92	St. Louis, MO	1.14	8.72	1.33	1.58	2.91
93	Columbia, MO	1.19	8.06	1.38	1.46	2.85
95	Rice Lake, WI	1.19	7.94	1.38	1.44	2.82
97	Eau Claire, WI	1.13	7.26	1.31	1.32	2.63
99	Tomah, WI	1.08	7.13	1.26	1.29	2.55
100	Portage, WI	1.02	7.59	1.19	1.38	2.56
101	Merrill, WI	1.18	9.01	1.37	1.63	3.01
102	Madison, WI	1.01	7.80	1.17	1.41	2.59
103	Beloit, WI	0.91	7.77	1.06	1.41	2.47
104	Green Bay, WI	1.10	9.15	1.28	1.66	2.94
105	Oshkosh, WI	1.07	8.67	1.24	1.57	2.82
110	Milwaukee, WI	0.95	8.12	1.10	1.47	2.58
112	Rockford, IL	0.90	6.87	1.05	1.24	2.29
120	Chicago Loop, IL	0.89	7.51	1.03	1.36	2.40
124	Joliet, IL	0.89	6.30	1.03	1.14	2.18
131	Galesburg, IL	1.01	6.08	1.17	1.10	2.28
133	S Bloomington, IL	0.97	6.43	1.13	1.17	2.29
134	Springfield, IL	1.05	7.10	1.22	1.29	2.51
138	Champaign, IL	0.97	6.68	1.13	1.21	2.34
139	Effingham, IL	1.01	7.24	1.17	1.31	2.49
144	Mt. Vernon, IL	1.09	8.06	1.27	1.46	2.73
145	Pulleys Mill, IL	1.18	8.59	1.37	1.56	2.93
147	E Gary, IN	0.86	7.30	1.00	1.32	2.32
153	Sault Ste. Marie, MI	1.28	12.05	1.49	2.18	3.67

Node	Location	Cost ($*E6)	Risk (P-rem*E3)	Cost Norm.	Risk Norm.	Combined Index
154	St. Ignace, MI	1.21	11.40	1.41	2.07	3.47
156	Clare, MI	1.00	9.82	1.16	1.78	2.94
157	Bay City, MI	1.01	10.32	1.17	1.87	3.05
158	East Lansing, MI	0.92	8.96	1.07	1.62	2.69
160	Jackson, MI	0.88	8.54	1.02	1.55	2.57
163	E Grand Rapids, MI	0.92	8.94	1.07	1.62	2.69
166	Reed City, MI	0.98	9.69	1.14	1.76	2.90
167	Muskegon, MI	0.95	8.71	1.10	1.58	2.68
168	Ludington, MI	1.03	9.53	1.20	1.73	2.92
169	Holland, MI	0.93	8.56	1.08	1.55	2.63
170	Benton Harbor, MI	0.89	8.15	1.03	1.48	2.51
171	Kalamazoo, MI	0.91	8.49	1.06	1.54	2.60
172	Marshall, MI	0.90	8.27	1.05	1.50	2.54
175	Flint, MI	0.97	9.80	1.13	1.78	2.90
176	Lapeer, MI	0.98	10.70	1.14	1.94	3.08
179	Brighton, MI	0.91	9.13	1.06	1.65	2.71
180	N Ann Arbor, MI	0.90	9.27	1.05	1.68	2.73
186	Wayne, MI	0.91	9.28	1.06	1.68	2.74
187	Southfield, MI	0.94	9.63	1.09	1.75	2.84
190	Detroit, MI	0.94	11.24	1.09	2.04	3.13
191	Sylvania, OH	0.90	8.54	1.05	1.55	2.59
193	Port Huron, MI	1.03	11.22	1.20	2.03	3.23
195	Muncie, IN	0.95	7.50	1.10	1.36	2.46
201	Veedersburg, IN	1.01	7.05	1.17	1.28	2.45
203	Indianapolis, IN	0.97	8.07	1.13	1.46	2.59
207	New Albany, IN	1.06	8.60	1.23	1.56	2.79
209	Ottawa Hills, OH	0.90	8.74	1.05	1.58	2.63
213	Amherst, OH	0.97	9.42	1.13	1.71	2.84
217	Cleveland, OH	1.00	10.48	1.16	1.90	3.06
222	Ashtabula, OH	1.05	10.94	1.22	1.98	3.20
224	Shaker Heights, OH	1.01	10.08	1.17	1.83	3.00
226	Streetsboro, OH	1.01	10.17	1.17	1.84	3.02
232	North Lima, OH	1.04	11.20	1.21	2.03	3.24
233	Bridgeport, OH	1.13	10.44	1.31	1.89	3.21
234	Akron, OH	1.02	11.08	1.19	2.01	3.19
239	Seville, OH	1.00	9.74	1.16	1.77	2.93
243	Columbus, OH	1.01	9.56	1.17	1.73	2.91
247	Cambridge, OH	1.07	10.12	1.24	1.83	3.08
248	Marietta, OH	1.14	10.62	1.33	1.92	3.25
249	Findlay, OH	0.94	8.67	1.09	1.57	2.66
252	Portsmouth, OH	1.17	10.26	1.36	1.86	3.22
253	Dayton, OH	0.97	9.59	1.13	1.74	2.87
255	Cincinnati, OH	1.00	9.32	1.16	1.69	2.85
265	Warrenton, IN	1.12	8.82	1.30	1.60	2.90
305	Charlotte, MI	0.92	8.54	1.07	1.55	2.62
306	Canton, OH	1.03	10.50	1.20	1.90	3.10
307	River Falls, WI	1.16	6.96	1.35	1.26	2.61
308	W Lafayette, IN	0.97	7.68	1.13	1.39	2.52
309	Stevens Point, WI	1.14	8.46	1.33	1.53	2.86
310	Bloomington, IN	1.03	7.94	1.20	1.44	2.64
311	South Bend, IN	0.88	7.72	1.02	1.40	2.42
312	Elkhart, IN	0.88	7.73	1.02	1.40	2.42

Node	Location	Cost ($*E6)	Risk (P-rem*E3)	Cost Norm.	Risk Norm.	Combined Index
313	Athens, OH	1.12	10.17	1.30	1.84	3.15
314	Clinton, IA	1.01	6.17	1.17	1.12	2.29
315	Le Claire, IA	0.99	5.86	1.15	1.06	2.21
316	Atlantic, IA	1.20	6.83	1.40	1.24	2.63
317	Springfield, OH	0.99	8.93	1.15	1.62	2.77
318	Mason City, IA	1.18	5.98	1.37	1.08	2.46
334	Monticello, MN	1.24	6.98	1.44	1.27	2.71
335	Red Wing, MN	1.15	6.91	1.34	1.25	2.59
336	Cedar Rapids, IA	1.07	5.88	1.24	1.07	2.31
337	Fulton, MO	1.19	8.14	1.38	1.48	2.86
338	Genoa, WI	1.11	6.83	1.29	1.24	2.53
339	Manitowoc, WI	1.07	8.72	1.24	1.58	2.82
340	Manitowoc, WI	1.07	8.72	1.24	1.58	2.82
348	Indian River, MI	1.18	11.09	1.37	2.01	3.38
350	Covert, MI	0.89	8.23	1.03	1.49	2.53
351	Bridgman, MI	0.88	7.69	1.02	1.39	2.42
352	Newport, MI	0.93	9.43	1.08	1.71	2.79
354	Oak Harbor, OH	0.91	8.92	1.06	1.62	2.68
355	North Perry, OH	1.02	10.89	1.19	1.97	3.16

Appendix K

COST, RISK AND INDEX RESULTS: MODELLING MICHIGAN

Appendix K

Cost, Risk and Index Results: Modelling Michigan

Node	Location	Cost ($*E5)	Risk (P-rem*E2)	Cost Norm.	Risk Norm.	Combined Index
147	E Gary, IN	2.46	7.56	1.14	1.64	2.78
153	Sault Ste. Marie, MI	3.45	11.33	1.60	2.45	4.05
154	St. Ignace, MI	3.32	10.22	1.54	2.21	3.75
155	Grayling, MI	2.63	8.45	1.22	1.83	3.05
156	Clare, MI	2.40	7.39	1.11	1.60	2.71
157	Bay City, MI	2.40	8.28	1.11	1.79	2.90
158	East Lansing, MI	2.21	6.24	1.02	1.35	2.38
159	S Lansing, MI	2.21	5.70	1.02	1.23	2.26
160	Jackson, MI	2.19	5.87	1.01	1.27	2.28
161	SW Lansing, MI	2.19	6.18	1.02	1.34	2.35
162	W Lansing, MI	2.21	6.28	1.02	1.36	2.38
163	E Grand Rapids, MI	2.25	6.43	1.04	1.39	2.43
164	N Grand Rapids, MI	2.25	6.68	1.04	1.45	2.49
165	Grand Rapids, MI	2.25	8.81	1.04	1.91	2.95
166	Reed City, MI	2.40	7.73	1.11	1.67	2.79
167	Muskegon, MI	2.38	6.77	1.10	1.47	2.57
168	Ludington, MI	2.82	8.29	1.31	1.79	3.10
169	Holland, MI	2.38	6.97	1.10	1.51	2.61
170	Benton Harbor, MI	2.36	7.18	1.09	1.55	2.65
171	Kalamazoo, MI	2.29	7.57	1.06	1.64	2.70
172	Marshall, MI	2.16	5.78	1.00	1.25	2.25
173	NW Flint, MI	2.31	9.78	1.07	2.12	3.19
174	NE Flint, MI	2.31	9.88	1.07	2.14	3.21
175	Flint, MI	2.30	7.27	1.07	1.57	2.64
176	Lapeer, MI	2.36	10.33	1.09	2.24	3.33
177	W Flint, MI	2.29	7.39	1.06	1.60	2.66
178	SW Flint, MI	2.30	6.39	1.06	1.38	2.45
179	Brighton, MI	2.28	5.70	1.06	1.23	2.29
180	N Ann Arbor, MI	2.26	5.70	1.05	1.23	2.28
181	Ann Arbor, MI	2.26	6.59	1.05	1.43	2.47
182	NE Ann Arbor, MI	2.27	5.54	1.05	1.20	2.25
183	SE Ann Arbor, MI	2.34	5.48	1.09	1.19	2.27
184	Farmington, MI	2.31	5.68	1.07	1.23	2.30
185	Livonia, MI	2.37	5.52	1.10	1.19	2.29
186	Wayne, MI	2.38	4.62	1.10	1.00	2.10
187	Southfield, MI	2.39	6.47	1.11	1.40	2.51
188	W Detroit, MI	2.38	9.91	1.10	2.15	3.25
189	Dearborn, MI	2.40	11.73	1.11	2.54	3.65
190	Detroit, MI	2.40	12.13	1.11	2.63	3.74
191	Sylvania, OH	2.42	5.50	1.12	1.19	2.31
192	Toledo, OH	2.44	5.14	1.13	1.11	2.24
193	Port Huron, MI	2.57	11.16	1.19	2.42	3.61
194	Fremont, IN	2.32	5.54	1.07	1.20	2.27
209	Ottawa Hills, OH	2.43	6.08	1.13	1.32	2.45
210	Maumee, OH	2.42	5.58	1.12	1.21	2.33

Node	Location	Cost ($*E5)	Risk (P-rem*E2)	Cost Norm.	Risk Norm.	Combined Index
303	N Lansing, MI	2.22	6.41	1.03	1.39	2.42
304	NW Lansing, MI	2.21	6.28	1.03	1.36	2.38
305	Charlotte, MI	2.19	6.31	1.02	1.37	2.38
311	South Bend, IN	2.41	7.41	1.12	1.60	2.72
312	Elkhart, IN	2.41	6.19	1.12	1.34	2.46
348	Indian River, MI	3.24	9.54	1.50	2.06	3.57
350	Covert, MI	2.38	7.04	1.10	1.52	2.63
351	Bridgman, MI	2.40	7.52	1.11	1.63	2.74
352	Newport, MI	2.41	4.62	1.12	1.00	2.12

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