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HAZARDS EVALUATION OF NUCLEAR FACILITY RELATED TRANSPORTATION ACCIDENTS

by
B. J. Garrick, Project Director
O. C. Baldonado, Principal Investigator
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Prepared for
U.S. ENVIRONMENTAL PROTECTION AGENCY
Rockville, Maryland 20852
Under
Contract No. 68-01-0555

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EPA Review Notice

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FOREWORD

The analyses presented in this report were made for the Office of Radiation Programs, Environmental Protection Agency, by Holmes and Narver, Inc., under contract. This report represents one of the first efforts to quantitatively assess the potential impact of the transportation of radioactive materials associated with the nuclear power industry through the year 2020. Technical data from numerous sources were collected and analyzed to produce the results reported herein. While not all of the radiological aspects of transportation analyzed in the report are covered in the detail which may be ultimately necessary, each area has received sufficient analysis to provide information useful in environmental impact statement reviews and other activities of the Agency. The results of this study will also provide an input into a planned EPA review of the need for additional protection standards for the transportation of radioactive materials.

Publication is made at this time so that the report will be available as a resource to the scientific community and the public generally. Because of the intended uses, the study may be of considerable interest to a large number of persons; therefore, it is likely that interested parties may wish to comment on the report, or certain aspects of it. Comments may be submitted to the Environmental Protection Agency, Office of Radiation Programs, Washington, D.C. 20460

W.D. Rowe, Ph.D.
Deputy Assistant Administrator
for Radiation Programs

ABSTRACT

A study was undertaken to determine the hazards from accidents to shipments of spent fuel, recycled plutonium, high level radioactive solidified waste, and noble gas between nuclear power reactors, chemical processing plants, fuel fabrication plants, and a Federal waste repository. Annual shipping data for these materials were projected for the period 1970 to 2020. In a given year, the shipping data was mapped by means of a fault tree model of the shipping containers, an empirical dispersion model, and a health effects model into a hazard vector with components denoting radiation released, environmental dose, population dose, lethal cases, and nonlethal effects.

Under the assumptions used in this study, the time variations of the maximum hazards are described as follows, using the annual population exposure to risk as the key index. For pure truck transportation, plutonium shipment accident exposure from severe accidents varies from 0.03 man-rems in 1980 down to 0.001 man-rems in 1990 and then up to 0.8 man-rems in 2020. For pure rail transportation, solid waste shipments present the greatest hazard in severe accidents varying from 0.0002 man-rems in 1990 to 0.004 man-rems in 2020. The least exposure results from pure truck shipment of spent fuel, ranging from 7×10^{-9} man-rems in 1970 to 1×10^{-5} man-rems in 2020 and pure rail shipment of noble gas, ranging from 1×10^{-6} man-rems in 1980 to 1×10^{-5} man-rems in 2020.

This report was submitted in fulfillment of Project No. 621901, Contract No. 68-01-0555, under the sponsorship of the Environmental Protection Agency.

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SECTION I

CONCLUSIONS

This study concerns transportation accident hazards in the nuclear power industry. While understanding that the nuclear power industry will grow over the next 50 years, some assumptions had to be made about the timely introduction of plutonium recycling programs, breeder reactor generators, fuel processing facilities, and waste disposal facilities in order to quantitatively describe the magnitude and rate of growth of the nuclear economy in time. Essentially all the information that was found on industry projections was derived from studies made at the Oak Ridge National Laboratory. The results of a computer program written at Oak Ridge that evaluates the growth of the industry on an economically competitive basis were particularly useful to this study.

This study treats only the transportation of spent fuel, fissile plutonium, high level radioactive solidified waste, and noble gas as significant movements of hazardous materials. The greatest shipping requirements in the year 2020 will be for the transportation of plutonium. Between 8 and 22 million shipment-miles will be required for plutonium then, while the requirements for spent fuel lie in the range of 6 to 14 million shipment-miles. In contrast, between 2. 1 and 2. 3 million shipment-miles will be required for solid waste movements and 0. 7 to 1. 0 million shipment-miles for noble gas shipping.

The evaluation of the radiation released from a container involved in an accident required a number of assumptions. Essentially five items of information were necessary to this evaluation: the amount of radiation carried in the container, the probability of the transport vehicle encountering an accident, the probability that the container encounters a rupturing force during the accident, the probability that the force is great enough to break the container, and the fraction of the contained radiation that will actually be released. An exhaustive supply of data with which to quantify these items is not available, so the numbers that were used for these items are by no means well established. In particular, difficulty was encountered in determining the probability of breaking force occurring in light and medium severity accidents. The accident severity classifications used in this study were arbitrarily based on collision velocity and duration of fires. By regulations, the shipping containers are required to withstand even severe accidents without loss of contents.

Five different components of a so-called hazard vector were discussed for each type of radioactive material. These components are the expected annual number of curies released from accidents, the number of acre-rems of environmental exposure (equivalent to the human absorption for a population density of one person per unit area), the number of man-rems of human exposure, the expected number of lethal cases resulting from the dose, and the number of nonlethal cancers resulting from the dose.

The results for the growth of these hazard vectors are summarized in Table 1. For clarity, only the numbers for the years 1980, 2000, and 2020 are given in Table 1, although hazard vectors for every fifth year of the 50-year period from 1970 to 2020 were calculated.

Under the assumptions made in this study, the projections to year 2020 indicate that the greatest hazards will result from pure truck shipments of plutonium and pure rail shipments of solid waste. The least hazards come from noble gas shipments in any transport mode mix, and the hazards from spent fuel shipments are intermediate.

Parametric studies were made to determine the effects of varying the mix of transport modes, the population density distribution, and the release probabilities of the containers. The results of the transport mix study indicate that from a safety point of view, hauling spent fuel and solid waste only by trucks is preferable, while hauling plutonium and noble gas only by rail cars is preferable to some other mix of rails, trucks, and barges.

The population density distribution was assumed to be uniform over isodose areas and to vary along a transport link. Such a distribution affects the calculations in this study in a linear manner. Each link distribution can be characterized by a multiplicative factor that modifies the average population density.

The release probabilities enter the calculation in a linear manner. Thus, inclusion of inferior containers in some parts of the transportation industry affects the resultant hazards linearly. Consequently, the accuracy of the release probability calculations are critical.

Lastly, an assessment of the hazards to be expected from an accident to a representative shipment was performed. The population distribution, the release fraction, and the method of calculating lethal and injurious effects of radiation absorbed by human beings are critical elements of this calculation. Assuming a right-of-way of about 1,000 feet, in which only two persons per square mile are found and a population density of 5 times the average outside the right-of-way area, about 70,000 man-rems

TABLE 1: SUMMARY OF HAZARD VECTORS FOR STUDY OF TRANSPORTATION OF NUCLEAR MATERIALS[a, b, c]

Material	Year	Curies Transported	Expected Curies Released	Expected Acre-Rems	Expected Man-Rems	Expected Fatalities	Expected Nonlethal Cancers
Spent Fuel	1980	1.02E+10	1.44E-6	5.15E-6	1.63E-5	2.71E-8	8.14E-10
	2000	8.43E+10	9.48E-6	3.39E-5	1.34E-4	2.23E-7	6.69E-9
	2020	1.92E+11	2.16E-5	7.74E-5	3.81E-4	6.36E-7	1.91E-8
Recycled Plutonium	1980	5.04E+8	5.48E-7	1.02E-3	3.23E-3	5.39E-6	1.62E-7
	2000	2.13E+8	1.85E-7	3.46E-4	1.36E-3	2.27E-6	6.82E-8
	2020	9.56E+8	8.32E-7	1.55E-3	7.65E-3	1.28E-5	3.83E-7
High Level Radioactive Solid Waste	1980	5.00E+6	3.04E-7	1.08E-6	3.43E-6	5.72E-9	1.71E-10
	2000	2.74E+9	1.46E-4	5.24E-4	2.07E-3	3.44E-6	1.03E-7
	2020	1.02E+10	4.98E-4	1.78E-3	8.78E-3	1.46E-5	4.39E-7
Noble Gas	1980	3.15E+7	4.81E-3	1.25E-6	3.94E-6	6.57E-9	1.97E-10
	2000	1.84E+8	2.46E-2	6.40E-6	2.52E-5	4.21E-8	1.26E-9
	2020	3.11E+8	3.80E-2	9.87E-6	4.87E-5	8.11E-8	2.43E-9

[a] The transport mix assumed is 20 percent trucks, 75 percent rails, and 5 percent barges.

[b] All accident severities are included.

[c] A population distribution is used such that 26.3 times the average population density in a particular year is exposed.

are expected from an accident to a solid waste shipment. This estimate is the maximum single accident hazard. Accidents to plutonium and spent fuel shipments produce 16,000 and 20,000 man-rems, respectively, and a noble gas shipment accident yields 110 man-rems.

SECTION II

RECOMMENDATIONS

Concerning the advisability of continuing a transportation program against beginning a program of constructing nuclear parks to minimize transportation requirements, the results of this study are not strongly conclusive. The probable hazard from transportation accidents appears to be acceptably low, but the consequences of an accident if it occurs are rather high.

As to minimizing the accident hazards, the results of this study support a recommendation to optimize the shipping schedules so that routes avoid population centers, shipments avoid violent weather conditions, shipment capacities be maximized while release fractions be minimized, the use of trucks be minimized, the shipment velocity be minimized, and the thermal insulation of containers be maximized. All these practices must be balanced at least partly against economic costs, and supposedly they are all in current effect.

Further studies would be profitable in the areas of fault tree determination of release probabilities, severity analysis of release fractions, real world dispersion, and dose response effects on health. These studies would not only be profitable for nuclear material transport processes, but also would benefit analysis of transportation of all hazardous materials.

Emphasis should be given to analyzing transportation accident statistics to determine probabilities of encountering particular physical conditions, e.g., crushing forces, shearing and stretching tensions, vibrations, excessive heat, pressure, puncturing impulses, etc. Material strength studies should be devoted to the determination of the probabilities that the physical forces will be large enough to break the containers. Conceivably these studies would incorporate test data already obtained with theoretical inquiries.

Little data exists of release fraction. This number is particularly frustrating since a light severity accident can produce a serious release and a severe accident can produce only a minor release or no release. Materials studies would be of use here, since the problem essentially is a determination of the bonding strength of a solid matrix.

Many dispersion models currently exist, but research in this area should still be encouraged.

Research in the health effects of radiation should be definitely encouraged, since the data base for dose response curves is small, because so many complicating factors exist, and because the ambient radiation levels from probable accidents will grow.

Similar studies to this one should be encouraged on a regional level. The demography and shipping distance data would have to be better established than in this study, however, for the hazards evaluations in a region to be of high value. Also, the projection of size, timing, and location of nuclear facilities would have to be obtained for the region under study. Some of the data used in this report would be useful in this regard, but a computer code similar to the economic model projection code in use at Oak Ridge National Laboratory would also be useful.

All these studies will undoubtedly contribute to a more accurate assessment of radiation hazards. The question is whether greater accuracy is worthwhile. The subject of radiation hazards is great enough in the public eye to justify the expenditure of time and money to conduct these studies. In addition, the studies would, or could, also contribute to technical knowledge in cask design for other hazardous materials, to a greater understanding of biological and physical processes, and to certain aspects of social research. For these reasons, the recommendations are proffered.

SECTION III

INTRODUCTION AND SUMMARY

INTRODUCTION

The energy demands of the United States are increasing. Traditional energy sources are being depleted, and this fact means that there will be an increase in the fraction of energy supplied by nuclear fuel. By the year 2020, nuclear fuel will provide as much as three-fourths of the electrical power of the United States. Electrical power represents as much as one-third of the total energy requirements of the country.

The increased use of nuclear fuel will result in more mining, fuel enrichment, fuel fabrication, fuel reprocessing, and nuclear waste disposal. The facilities required to carry out these activities will not necessarily be located within the same area. It will be necessary, therefore, to transport the nuclear fuel in a variety of forms and levels of radioactivity as it goes through the fuel cycle. An increase in total transportation of nuclear fuel and radioactive materials is anticipated. Radiation hazards are expected during transportation.

The radiation burden consists of a fixed and a probable component. The fixed radiation burden consists of effects from routine, accident-free operation. The probable burden is that associated with accidents. The purpose of this study is to assess the hazards from the probable burden of nuclear facility related transportation accidents.

EPA OBJECTIVES FOR THE STUDY

The responsibility for assessing and minimizing the detrimental environmental impact from most of man's activities rests with the EPA. As a part of these responsibilities, EPA has undertaken the assessment of the total environmental impact resulting from the production of nuclear power. The transportation of nuclear materials may represent a significant fraction of the total impact resulting from the nuclear power industry. As the nuclear transportation industry grows, a larger burden of radioactivity will have to be borne by the public and the environment. Thus, more regulatory controls will be required; and since the EPA is charged with the responsibility of protecting the environment, they are interested in assessing the magnitude of the radiation burden. The purpose of the present study is to help the EPA gain base information to use in establishing policies for the government of the transportation of radioactive materials generated by the nuclear power industry.

In the present study, the radiation burden from transportation accidents and its consequences are analyzed. A subsequent study of the routine shipment radiation burden and consequences is in process. These two studies will help identify any potential transportation impacts which may be considered unacceptable. Steps may then be taken to minimize these impacts.

The question naturally arises: If the radiation burden from transportation is excessive, would it be better to cluster nuclear facilities on the same sites or on nearby sites than to pursue a more random siting policy? If the clustering course is adopted, then size is an added constraint to those already limiting the choice of sites. As it is, finance, security, radiation level, cooling capability, land area, visibility, and power transmission must be considered before a suitable site can be used. Other questions come up in connection with minimizing risks and hazards. For instance, decisions must be made as to whether the shielding and impact resistance of shipment containers are sufficient.

Additional objectives of the present study are to obtain a perspective of important variables and to document the useful literature. In particular, accident frequencies, container designs, and variations in usage of the transport modes of trucks, rail cars, and barges are investigated. The pertinent studies that are documented may be divided into two categories: predictions on the transportation systems leading to the environmental impact and assessments of the effects of those impacts.

FEATURE CONTRIBUTIONS OF THE STUDY

Several items which differentiate the study from others are listed as follows:

1. Of several assessments of the environmental impact of transportation accidents, the present study involves shipments of radioactive material.

2. The work represents an extension of the scope of the AEC "Environmental Survey of Transportation of Radioactive Materials to and from Nuclear Power Plants" by treating transportation accidents to the year 2020.

3. Fault tree analysis is used to evaluate, in the absence of accident experience, the probability with which a transportation accident results in a release of radiation or a release of radioactive material.

4. A parametric model of the nuclear power transportation industry is established to allow future studies and updating.

5. The hazard from nuclear transportation accidents is formulated quantitatively in terms of a hazard vector field.

The methodology developed has been applied in other areas involving safety and reliability. The study begins from a projected transportation picture and generates the environmental impact of radiation releases during accidents. By changing parameters related to the transport modes, transport paths, shipping containers, and properties of the shipped materials, a series of environmental impact scenarios are simulated.

STUDY METHODOLOGY

The method used in this study is essentially a mapping mechanism. Figure 1 contains a diagram which illustrates the overall action of the mapping. The idea is to map a function, the amount of radioactive material being shipped, into a vector space which quantitatively describes the hazards. The amount of material being shipped is a function of several variables concerning the nuclear power and transportation industries.

Risk is the probability that existing conditions will lead to accidents that result in damage or loss. The consequence of these conditions is an important ingredient of hazard. In fact, hazard is taken to be the risk times the consequence. Values of hazard and risk depend upon the accidents, the container designs, the materials being shipped, the radiation doses resulting from these accidents and releases, and the health damage caused by these releases.

The overall view described by Figure 1 is given in more detail in Figure 2. A series of calculations produce the final mapping. First, the radioactivity of the material being shipped is calculated from such variables as the number and power of nuclear generators, the capacity of chemical processors, the number of metric tons of fuel burned and the isotope composition of the residues. Second, the probability of radiation release from a given accident is calculated by means of fault tree analysis. Third, the radiation released from probable accidents is calculated by means of a dispersion model. The results of this calculation are estimates of the dose to the environment (area-dose) measured in units such as acre-rems, and the whole body dose to the population measured in man-rems. Finally, an estimate of the lethal and injurious effects of the radiation to humans is generated by a health effects model.

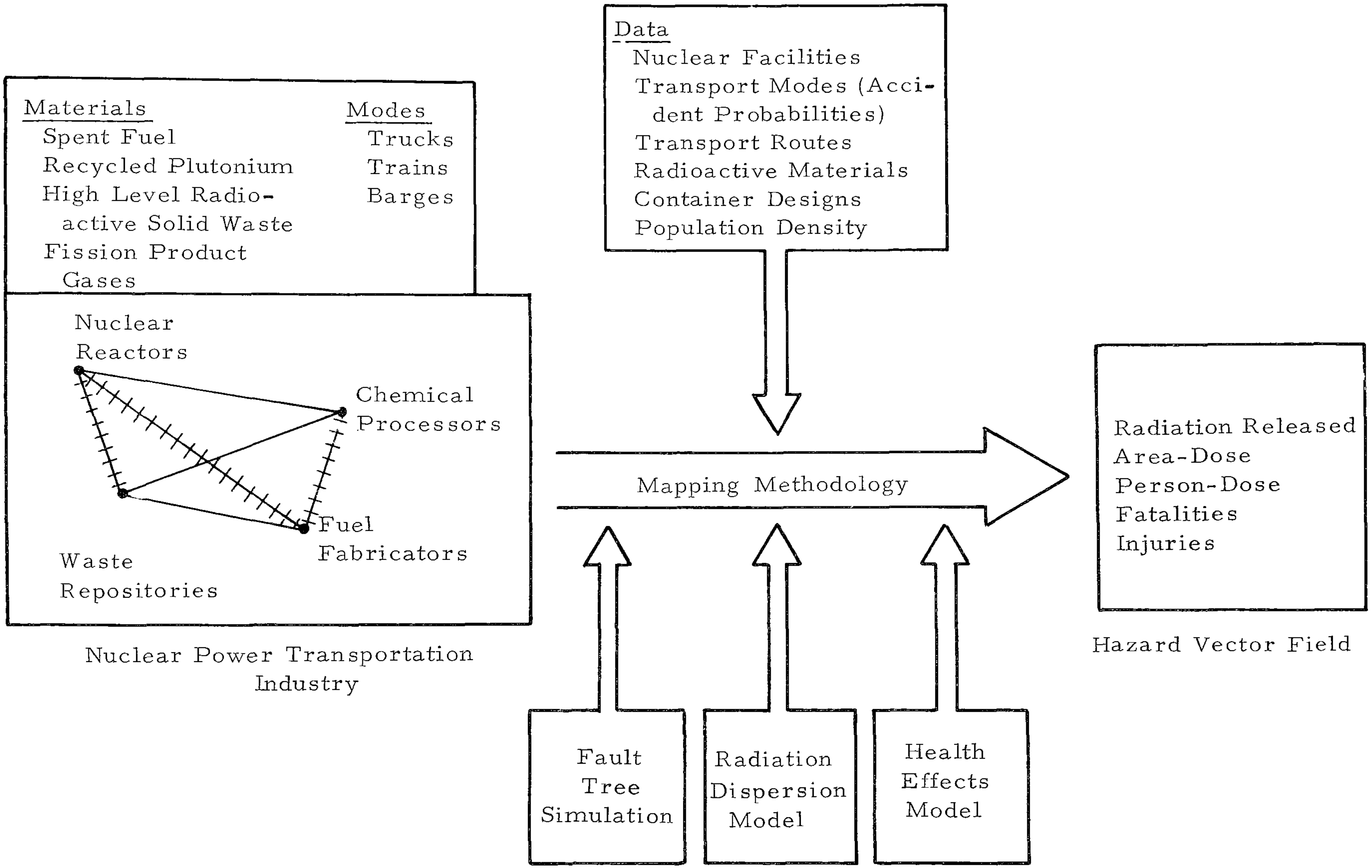


FIGURE 1: OVERALL ORGANIZATION OF EVALUATION OF HAZARD FROM ACCIDENTS IN THE NUCLEAR POWER TRANSPORTATION INDUSTRY

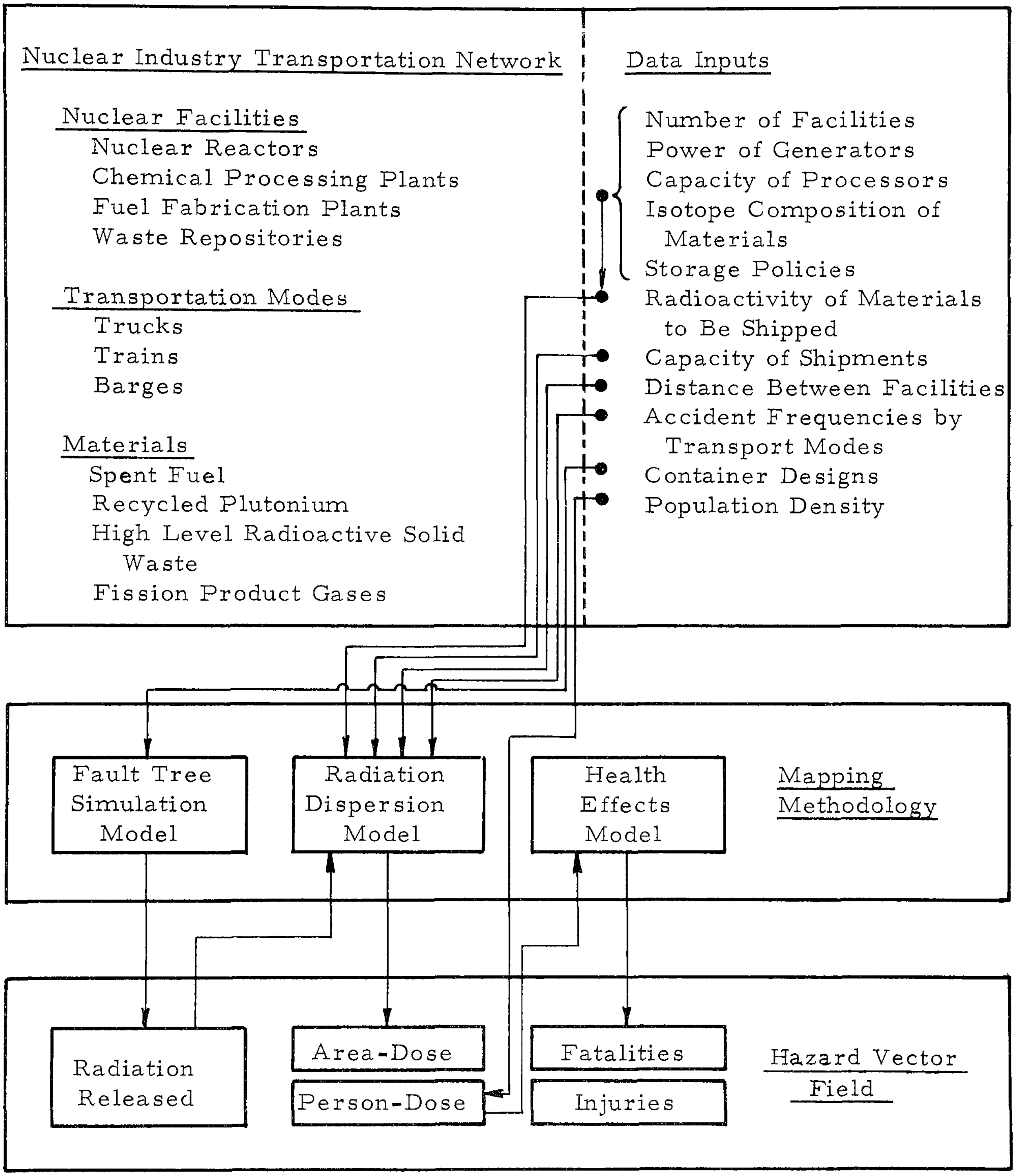


FIGURE 2: DETAILED ORGANIZATION OF EVALUATION OF HAZARD FROM ACCIDENTS IN THE NUCLEAR POWER TRANSPORTATION INDUSTRY

The fault tree simulation model is based on the representation of the shipping container as a series of barriers that are breached with some computable probability. The use of a barrier model in a fault tree is a way to calculate the conditional probability that radioactive material is released, given that an accident has occurred. These fault trees require input data in the form of probabilities with which elementary events occur. Examples of elementary events are occurrence of puncture force greater than that which the barrier can withstand, or failure of a seal due to heat from a nearby fire. Such data are obtained from laboratory or field tests, distribution functions, statistical tabulations for similar events, and theoretical estimates. Once the fault tree has been completely drawn with elementary probabilities, the probability of the top event (release probability in this case) can be computed by Boolean algorithm or Monte Carlo simulation. Here the Monte Carlo method is used.

The radiation dispersion model of Figures 1 and 2 is an empirical linear relationship between the logarithm of radiation dose from the accident and the logarithm of area ultimately affected after diffusion and material transport. The population density is required to convert the environmental dose into the population dose.

The health effects model is derived from the collection of information on man's response to radiation. Although the body of information on this subject is not conclusive, the guide for low levels of radiation presently used by the EPA is used for this study. The absolute values of dose response in this guide are that one million person-rems absorbed annually will produce an excess of cases over other causes equal to the following:

1. 200 fatalities if the dose is to the whole body.

2. 200 nonlethal cancers if the dose is to the whole body.

3. 300 serious effects if the dose is restricted to the reproductive organs.

ELEMENTS INCLUDED IN THE STUDY

Nuclear facilities which produce radioactive materials requiring transportation are confined in this study to the following:

1. Nuclear power reactors.

2. Chemical processing plants.

3. Fuel fabrication plants.

4. Radioactive waste repositories.

The means of transportation which are considered in this study are:

1. Motor freight.

2. Rail freight.

3. Barge freight.

Significant radiation burdens are expected to arise from transport of the materials:

1. Spent fuel.

2. Recycled plutonium.

3. High level radioactive solidified waste.

4. Fission product gases.

Results of the analysis are represented in a five component vector field called the hazard vector field. Its components indicate:

1. The number of curies released from an accident.

2. The number of acre-rems of dose irradiated from the accident to the environment.

3. The number of man-rems of absorbed dose.

4. The number of fatalities resulting from the absorbed dose.

5. The number of injuries resulting from the absorbed dose.

In this study, a hazard vector is obtained for the continental United States. This vector is studied for the period 1970 to 2020. A hazard vector is generated at 5-year intervals, beginning in 1970. A different hazard vector is obtained upon varying the following parameters:

1. Capacities of shipments.
2. Number of shipments.
3. Average distance between facilities.
4. Transport mode mix.
5. Material cargo.
6. Physical nature of accidents.
7. Accident severity.
8. Container breachment probabilities.
9. Fraction of cargo released after container rupture.
10. Dispersion conditions.
11. Population density distribution.
12. Health dose responses.

The possible impact from transportation accidents in a nuclear power system is treated on an average basis. The use of regional uniform population densities and average distances between facilities is considered to be adequate for the assessment of accident hazard, since accidents are discrete, random events. The burden from radiation exposure during routine shipments, i.e., shipments free of accidents, is of a more continuous nature, and thus would require more detail in the spatial distribution of facilities and population.

In the present hazard analysis of accidents, the principal parameters varied are population density, transport mode mix, material cargo, and accident severity.

The severity of accidents is divided into light, medium, and severe categories. These classifications are arbitrary functions of the relative velocity of colliding vehicles and of the time duration of fires associated with accidents.

ORGANIZATION OF STUDY

In analyzing the potential hazards and risks associated with radiation release from nuclear transportation accidents, five steps can be identified.

First, a reasonable picture of the United States nuclear industry from 1970 to 2020 is required. This information is used in the second step to predict the amount and type of nuclear material transportation required. The third step is to determine the occurrence probabilities for the various types of accidents which can lead to release of radiation. Evaluation of the hazards based upon the amount of radiation released in each accident is the fourth step of the study. The fifth step consists of parametric studies of the hazards.

SECTION IV

THE UNITED STATES NUCLEAR INDUSTRY PICTURE TO YEAR 2020

To accurately evaluate the environmental impact of accidents occurring during transportation of nuclear material, it is necessary to know the numbers, origins, and destinations of the shipments; the types of vehicles and shipping containers used; and the expected population densities along the routes. These parameters are dependent on projections of the development of the nuclear industry and the population during the 50 years covered by this study.

The aspects of the nuclear industry which are considered are:

1. The magnitude of the installed nuclear power capacity.

2. The relative contributions of each type of reactor to this capacity.

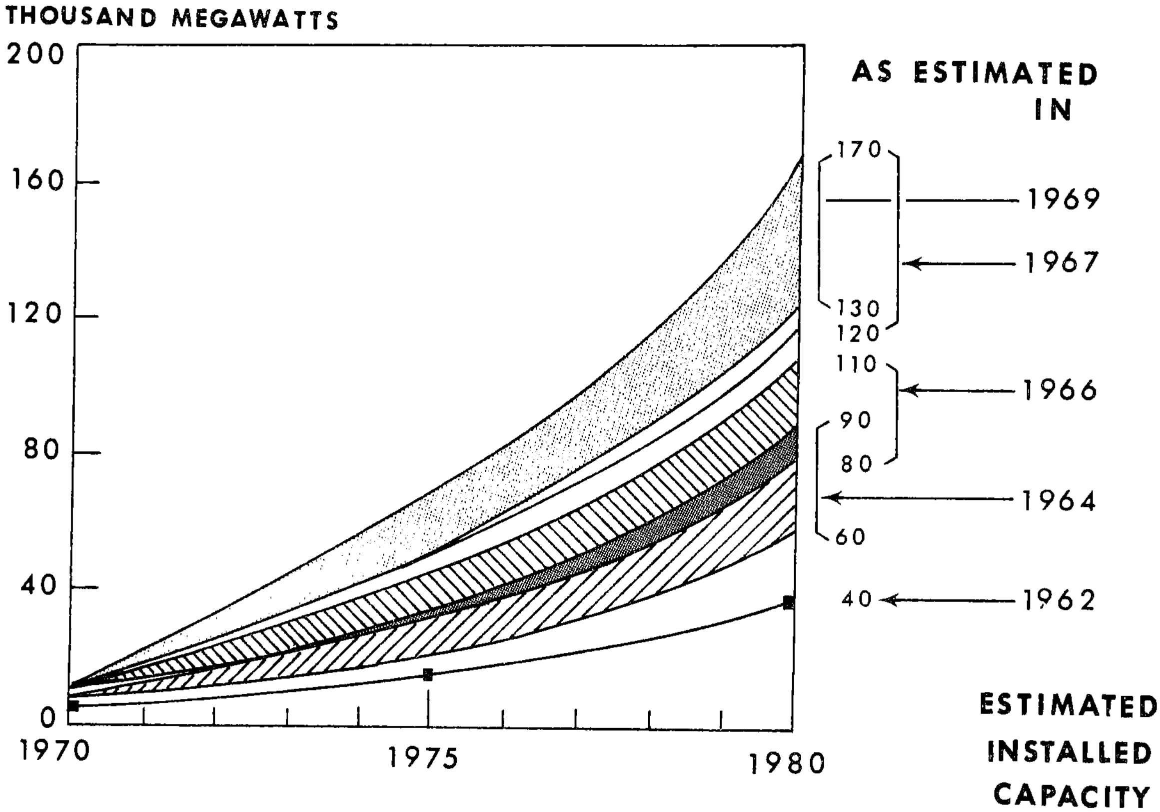
3. The long term disposal (or storage) policies for radioactive waste.

4. The economics of the fuel cycle.

Projections should be reevaluated periodically to make use of the most recent data. An example of an updated projection is given in Figure 3. This figure shows the AEC's forecasts of the nuclear generating capacity in the decade 1970 to 1980. The first estimate was made in 1962. The forecast was revised in 1964, 1966, 1967, and 1969; each time it was revised upward.

In the 50-year period of this study, society may change its pattern of energy consumption because of its desire to protect the environment. Technological breakthroughs may occur which will change the underlying assumption of the projections. The assumptions made are derived from opinions of scientists and engineers who work in the various areas. These limitations should be borne in mind when drawing any conclusions from this report.

The development of the United States nuclear industry over the next 50 years will be governed primarily by the demand for electrical energy. Military and scientific influences on the development of the nuclear industry are expected to be small compared to the influence of the domestic needs for more energy. In this section, the following aspects of the nuclear industry for the next 50 years are discussed:



Reference: "The Nuclear Industry - 1970," U. S. Atomic Energy Commission

FIGURE 3: NUCLEAR ELECTRIC PLANTS

1. Total energy demand in the United States between 1970 and 2020.

2. Ways in which the energy demand will be met.

3. Numbers, sizes, and types of nuclear facilities needed to support the nuclear energy requirements.

These items will be discussed for each of the six U. S. Federal Power Commission (FPC) National Power survey regions shown in Figure 4. These regions were modified slightly to follow state lines except for the areas around Pittsburgh, Pennsylvania, and St. Louis, Missouri. The Pittsburgh area is included in the East Central region and the St. Louis area is included in the West Central region. The boundary of these two areas corresponds to the Standard Metropolitan Statistical Areas.

POPULATION GROWTH IN THE UNITED STATES

The most obvious of the forces governing energy demand is the growth of the United States population. Table 2 shows the population of the United States in 1970 and the projected populations through the year 2020. This projection is based on an average of 2,775 children per 1,000 women at end of child bearing and a net annual immigration of 400,000. This birth rate is higher than that recently released by the Census Bureau. They report a rate of 2,040 children per 1,000 women (Reference 3). Figure 5 shows how the population projections are affected by the birth rate. The Census Bureau's latest estimate for the year 2000 is shown by the bar on Figure 5.

The population of the United States is expected to increase significantly during the next 50 years. The population in 2020, based on current projections, will be about 79 percent higher than in 1970. Thus, if the per capita energy demand remains constant, an increase of 79 percent in the overall energy demand is expected by the year 2020.

Population density is more suitable for calculating population risks than the population itself since the radiation dosage is dependent on the spatial dispersion of radiation or radioactive material. The exposure to risk is calculated from the product of dose as a function of area, the area itself, and the population density. The United States population density projections are derived from Table 2 and displayed in Table 3.

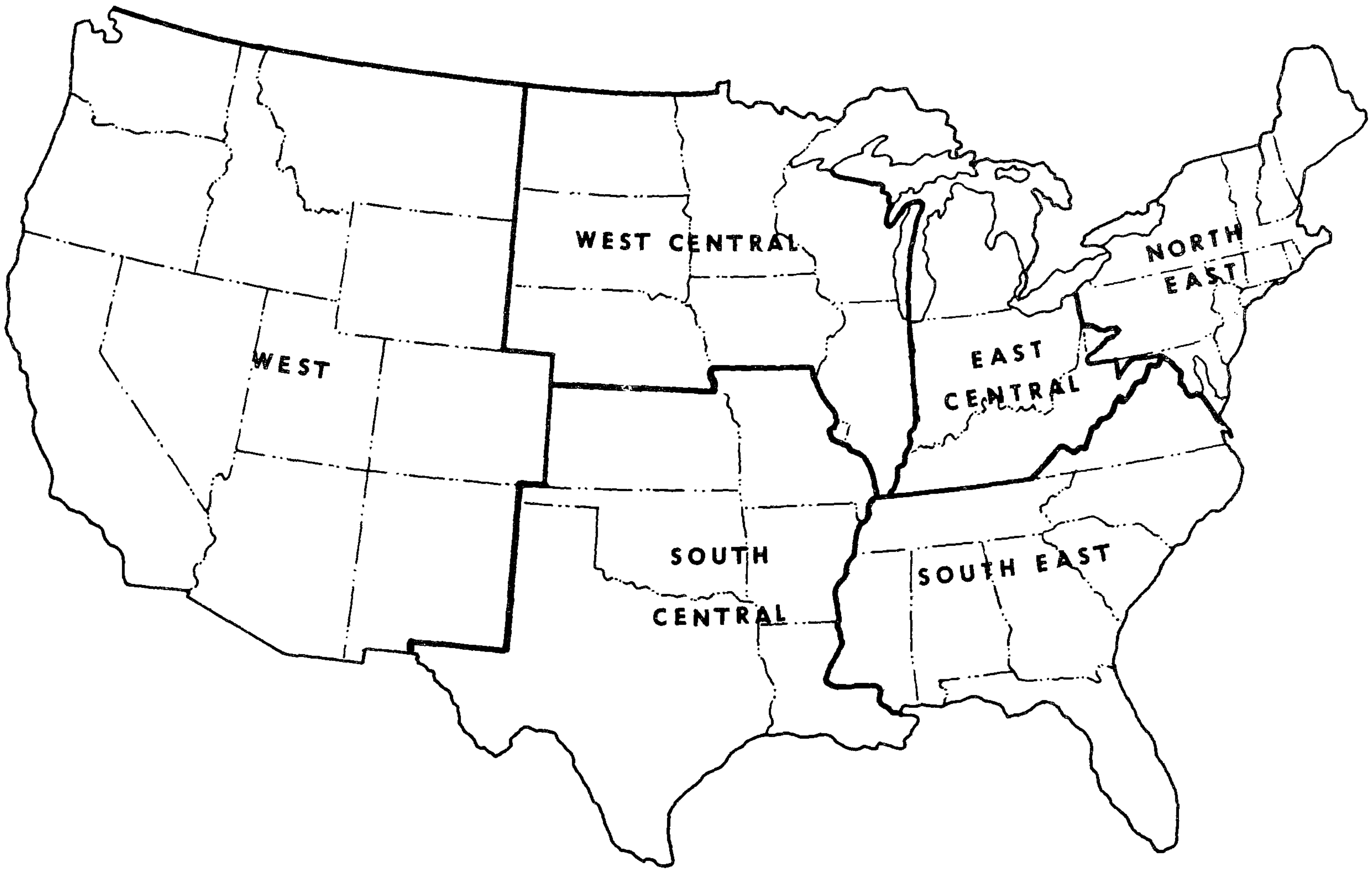


FIGURE 4

MODIFIED FEDERAL POWER COMMISSION NATIONAL POWER SURVEY REGIONS

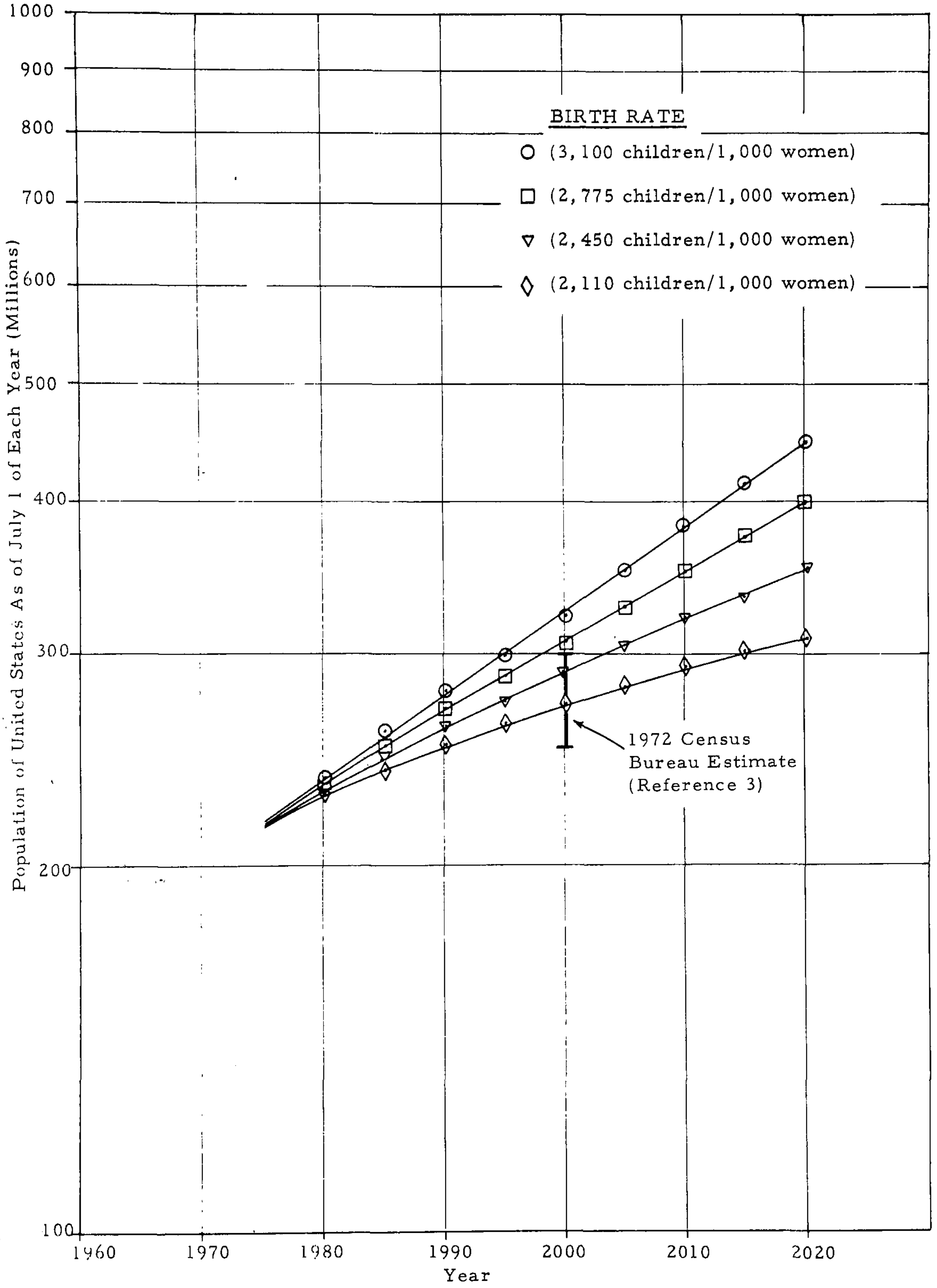


FIGURE 5: THE EFFECT OF FERTILITY ON THE PROJECTED UNITED STATES POPULATION (Reference 4)

TABLE 2: PROJECTED POPULATION OF THE UNITED STATES [a]

Year	Population in Modified FPC Regions, Millions [b]						Total Population, millions
	Northeast	East Central	Southeast	West Central	South Central	West	
1970	52.0	32.2	33.4	26.8	24.5	34.9	204
1975	55.4	34.0	35.6	28.4	26.2	38.9	218
1980	58.8	35.9	37.9	29.9	27.8	42.6	233
1985	63.1	38.3	40.6	32.0	29.8	47.0	251
1990	67.4	40.7	43.3	34.1	31.9	51.5	269
1995	70.0	42.0	45.0	35.6	33.2	54.8	281
2000	72.6	43.3	46.8	37.0	34.4	58.0	292
2005	76.6	45.3	49.5	38.2	36.4	63.7	310
2010	80.5	47.3	52.1	39.5	38.3	69.4	327
2015	85.0	49.8	54.5	42.0	39.8	74.8	346
2020	89.5	52.4	56.9	44.6	41.2	80.3	365
Percent Growth 1970-2020	72	63	70	67	68	130	79

[a] Derived from data for individual states in Reference 2.

[b] FPC Regions, modified to follow State boundaries (with the exception of the Pittsburgh and St. Louis areas). The population for the various states (Reference 2) were projected separately for each region. The west population includes Alaska and Hawaii.

TABLE 3: PROJECTED POPULATION DENSITY OF THE UNITED STATES

Year	Population Density in Modified FPC Regions Persons/Square Mile						National Average*
	North-east	East Central	South-east	West Central	South Central	West*	
1970	290.6	158.3	87.1	56.1	41.5	28.5	67.2
1975	309.6	167.2	92.8	59.4	44.3	31.6	72.1
1980	328.6	176.5	98.8	62.6	47.0	34.8	76.9
1985	352.6	188.3	105.8	67.0	50.4	38.5	82.8
1990	376.7	200.1	112.9	71.4	54.0	42.2	88.6
1995	391.2	206.5	117.3	74.5	56.2	44.9	92.4
2000	405.7	212.9	122.0	77.4	58.2	47.5	96.0
2005	428.1	222.8	129.0	79.9	61.6	52.2	102.0
2010	449.9	232.6	135.8	82.7	64.8	56.9	108.0
2015	475.0	244.9	142.1	87.9	67.3	61.4	114.0
2020	500.2	257.7	148.3	93.3	69.7	65.9	120.0

*Not including Alaska or Hawaii area or population.

ENERGY DEMAND IN THE UNITED STATES

The standard of living and life style in the United States requires large amounts of energy for each person. It has been estimated that while having 6 percent of the world's population, the United States consumes one third of the world's annual production of electrical energy.

Figure 6 shows the trend in energy demand per person in the United States projected over the next 50 years. It can be seen from this figure that the per capita demand will almost double by 2020.

The combination of increasing population and per capita energy demand is expected to cause a large increase in the demand for energy. This is shown in Figure 7. The total energy requirements will more than double over the next 50 years, with the demand for electrical energy contributing the largest portion of that growth. The electrical requirements projected to the year 2020 are presented in Table 4. The numbers in the second column in Table 4 correspond to the "Total Electric" curve of Figure 7. The third column in Table 4 lists the power at peak load to the year 2020. The effects of recent concern for the environment on the projections of energy demand is uncertain at this time and is not considered in this report.

EXPECTED WAYS TO MEET DEMAND BY FOSSIL AND NUCLEAR FUEL

The major role of nuclear fuel in satisfying the energy demands of the United States will be helping to provide adequate electricity. This role is shown in Figure 7 by the way the "Nuclear Electric" curve approaches the "Total Electric" curve. This same information is shown by the upper curve in Figure 8. Nuclear energy should supply over 80 percent of electrical energy requirements for the United States by the year 2020. The lower curve in Figure 8 shows the percent of generating capacity supplied by nuclear fuel. About 71 percent of the installed electrical power capacity in 2020 will be nuclear fueled. The nuclear power projections for the six FPC regions of Figure 4 and for the contiguous United States during the next 50 years are presented in Table 5.

REACTOR TYPES AND CHARACTERISTICS

Current designs of nuclear fueled electrical generating plants include two types of reactors -- converters and breeders. Both contain fissionable and fertile material. Fertile materials are isotopes which after capturing a neutron become fissionable material; for example,

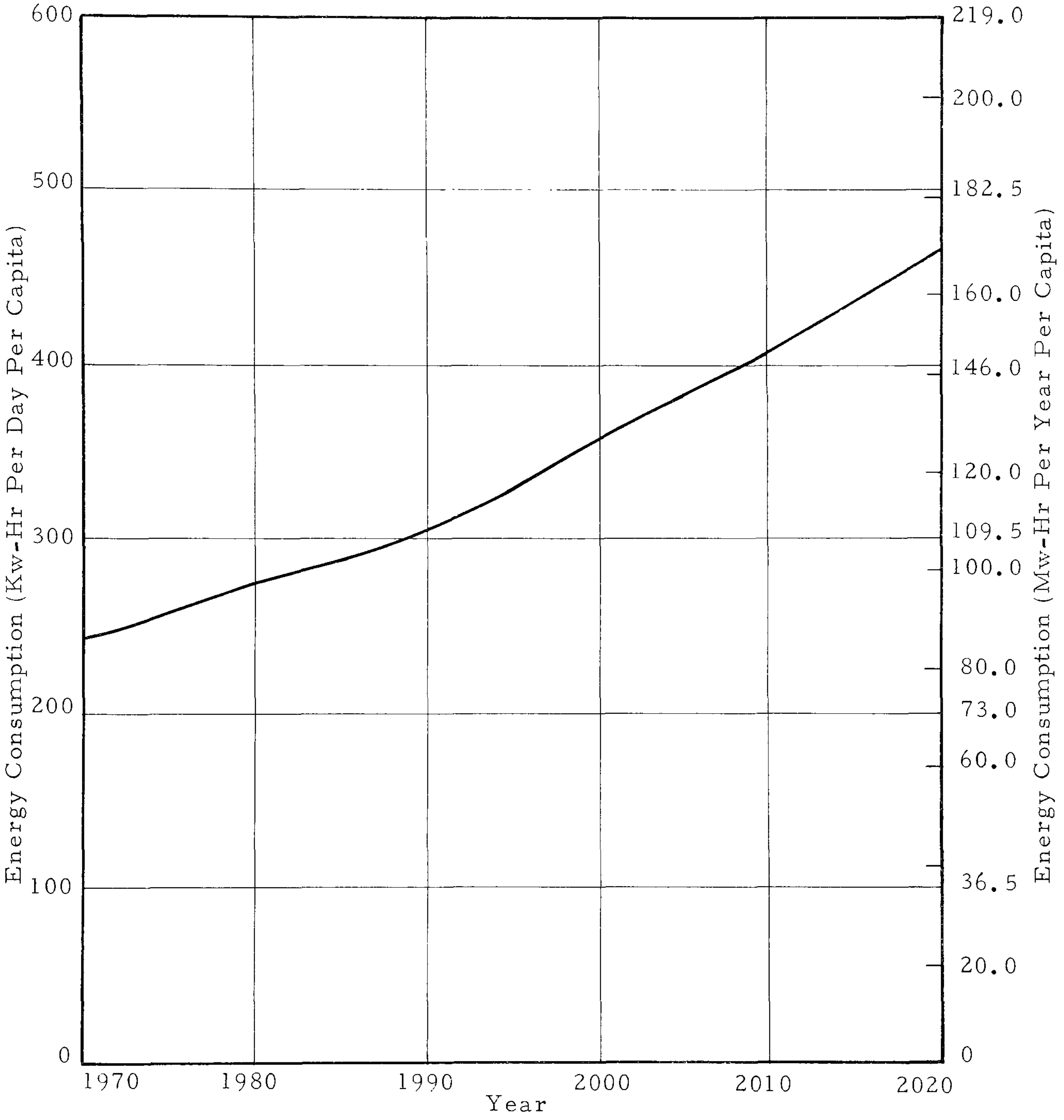


FIGURE 6: PROJECTION OF PER CAPITA ENERGY CONSUMPTION IN THE UNITED STATES (Reference 4)

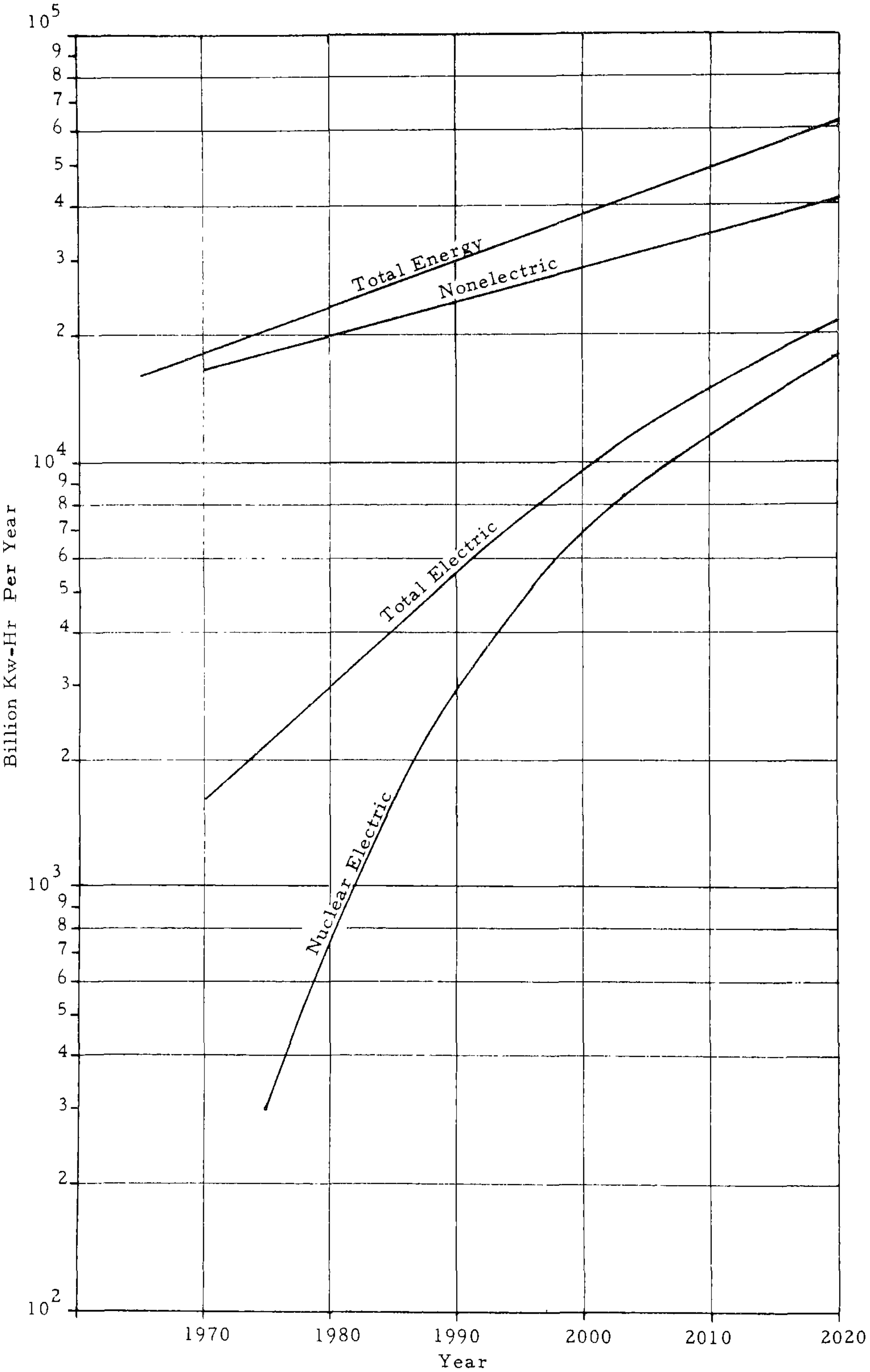


FIGURE 7: PROJECTION OF ENERGY DEMAND IN THE UNITED STATES (References 4, 5)

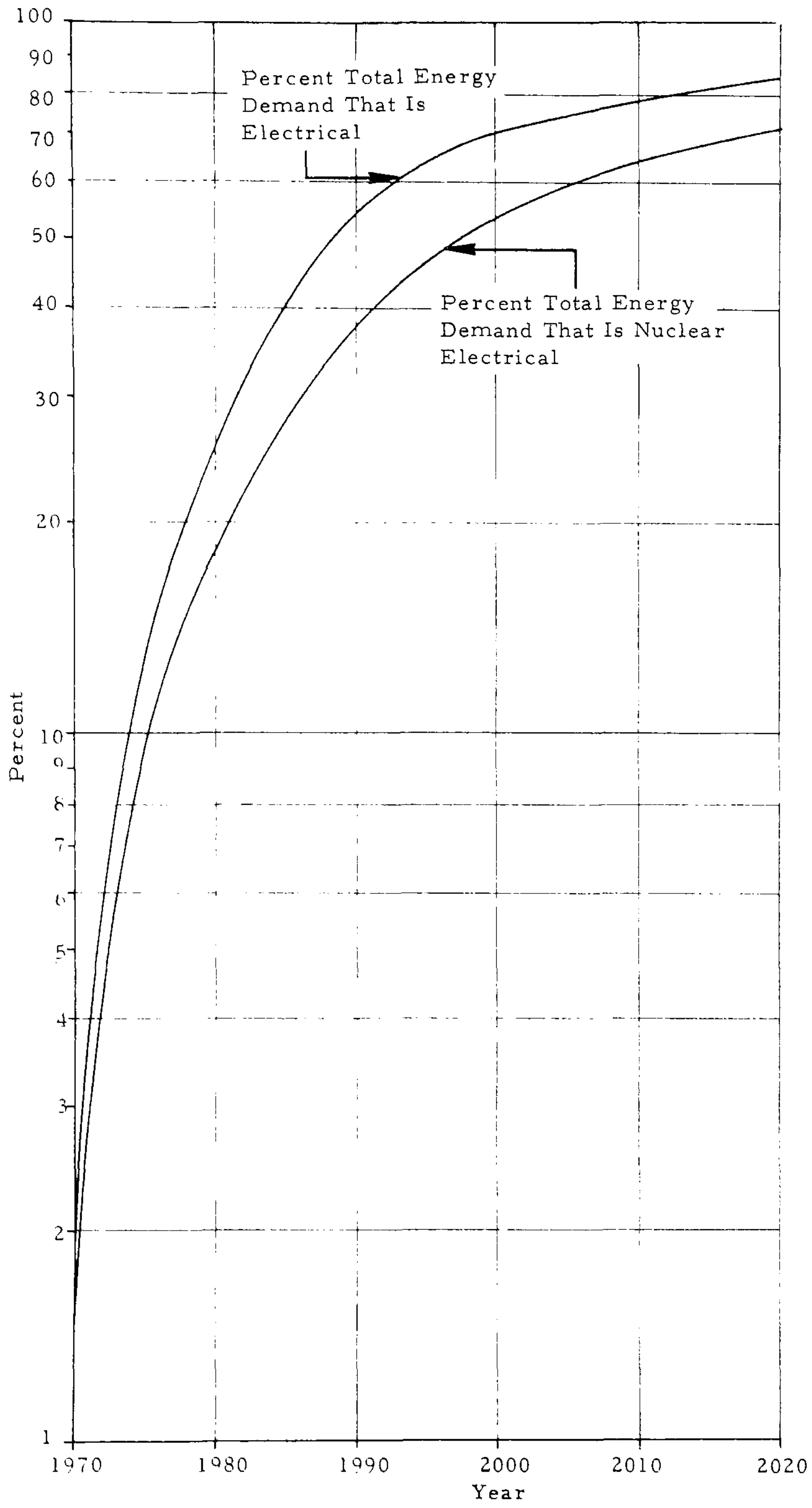


FIGURE 8: NUCLEAR POWER PLANTS' CONTRIBUTION TO INSTALLED CAPACITY AND ENERGY DEMAND (Reference 5)

TABLE 4: ANNUAL UNITED STATES ELECTRICAL ENERGY REQUIREMENTS (Reference 5)

Year	Annual Electrical Energy Use 10^9 Kw-Hour	Power Peakload 10^6 Kw
1970	1,603	336
1975	2,220	463
1980	2,972	628
1985	4,167	904
1990	5,459	1,197
1995	7,319	1,585
2000	9,650	2,090
2005	12,200	2,620
2010*	14,900	3,130
2015*	18,300	3,730
2020*	21,300	4,260

*Graphical extrapolation.

TABLE 5: PROJECTED REGIONAL DISTRIBUTION OF CENTRAL STATION NUCLEAR STEAM POWER PLANTS (Reference 5)

Calendar Year	FPC Region						Total United States
	North-east	East Central	South-east	West Central	South Central	West	
	Capacity of Nuclear Steam Power Plants, GWe (Net)						
1970	3	0	0	1	0	1	5
1975	14	5	12	8	1	5	45
1980	27	10	33	20	7	17	114
1985	54	23	66	38	22	42	245
1990	99	49	111	67	46	81	453
1995	159	81	182	111	75	132	740
2000	243	121	274	167	113	200	1,118
2005	290	218	330	224	210	289	1,562
2010*	383	285	427	302	229	384	2,010
2015*	462	396	513	382	311	481	2,545
2020*	519	515	590	456	397	563	3,040

*Graphical extrapolation.

U^{238} after capture becomes Pu^{239}. Both of the reactor types generate energy from fission and convert the fertile material into fissionable material, but the breeders produce more fissionable material than they consume. Reactors can also be classified by the coolant used to remove the heat and by the neutron energy at which the fissions occur. Most converters are light water thermal reactors (LWR). That is, they are cooled by light water and the neutrons are at thermal energy (0.025 ev). Another converter type is the high temperature gas cooled reactor (HTGR). For this reactor type, the coolant is helium gas. The breeders which are currently in the design stage are cooled by a liquid metal such as sodium. The energy of the neutrons which cause fission is about 10 Mev. These breeders are called liquid metal fast breeder reactors (LMFBR). The LWRs may be further classified by two designs and two uses of fuel. The two designs are the Pressurized Water Reactor (PWR) and the Boiling Water Reactor (BWR). LWRs can utilize enriched uranium as the fissionable material and be designated as LWR-U or they can utilize a combination of unenriched uranium and plutonium which was produced from fertile material and be designed as LWR-U, Pu.

Characteristics for the PWR-U; PWR-U, Pu; HTGR; and LMFBR types of reactors are listed in Table 6. These are expected to remain typical for the next 50 years. Proposed designs of LMFBRs have been submitted to the AEC by General Electric (GE) and Atomics International (AI). Data for the two designs are given in Table 6.

Fuel cycles for different reactor designs are pictured in Figures 9 through 11, and include all steps from ore mining to temporary storage of waste products. From the point of view of radiation safety in transportation, the most important links are those between reactors and chemical processing plants, between processors and waste repositories, between processors and fuel fabrication plants, and between fabricators and reactors. In this report, freight shipments along these links are divided into spent fuel, recycled plutonium, high level radioactive solidified waste, and fission product (noble) gas movements.

A possible source of electrical energy which still awaits a technological breakthrough is the fusion reactor. When it is developed, it will be an important part of the energy picture because of its clean operation, fuel recycling capability, huge fuel reservoir represented by the oceans, capability of direct conversion of fusion energy into electricity, and material decomposition possibilities. Since a workable fusion reactor is not foreseen for at least twenty years, the current study does not attempt to consider its potential contribution.

TABLE 6: CHARACTERISTICS OF TYPICAL PWRs, HTGRs, AND LMFBRs (Reference 5)

	PWR-U	PWR-U, Pu[a]	HTGR[b]	LMFBR	
				AI	GE
Electric Power, MWe (Net)	1,000	1,000	1,160	1,002	1,011
Thermal Power, MWt	3,077	3,077	3,000	2,400	2,417
Average Specific Power,[b] MW/Metric Ton	37.5	37.5	80.65	50.18	53.76
Average Burnup, MWd/Metric Ton	32,873	32,873	94,264	37,098[f]	41,792[f]
Refueling Interval, Days[c]	365.25	365.25	365.25	364	385
Steady State Charge					
Th, Kg	----	----	8,434	----	----
U-233, Kg	----	----	217	----	----
U-235, Kg	875.2	651.8	433	34	34
Total U, Kg	27,350	26,909	865.4	17,163	16,720
Fissile Pu, Kg[d]	----	270.3	----	1,196	786
Total Pu, Kg[e]	----	441.0	----	1,663	1,093
Total (U+Pu), Kg	----	27,350	----	18,826	17,813
Total (U+Pu+Th), Kg	----	----	9299.4		
Steady State Discharge					
Th, Kg	----	----	7,819	----	----
U-233, Kg	----	----	219.3	----	----
U-235, Kg	243.4	191.0	64.1	22	24
Total U, Kg	26,137	25,869	541.4	16,213	15,603
Fissile Pu, Kg[d]	180.1	273.1	2.1	1,395	1,111
Total Pu, Kg[e]	254.9	445.5	10.0	1,918	1,467
Total (U+Pu), Kg	26,392	26,314	551.4	18,131	17,069
Total (U+Pu+Th), Kg	----	----	8,370	----	----

[a] PWR with self-sustaining Pu recycle.
[b] Based upon full power and fuel charged.
[c] At 80 percent load factor.
[d] Pu-239 + Pu-241.
[e] Pu-238 + Pu-239 + Pu-240 + Pu-241 + Pu-242.
[f] Burnup per metric ton of fuel charged.

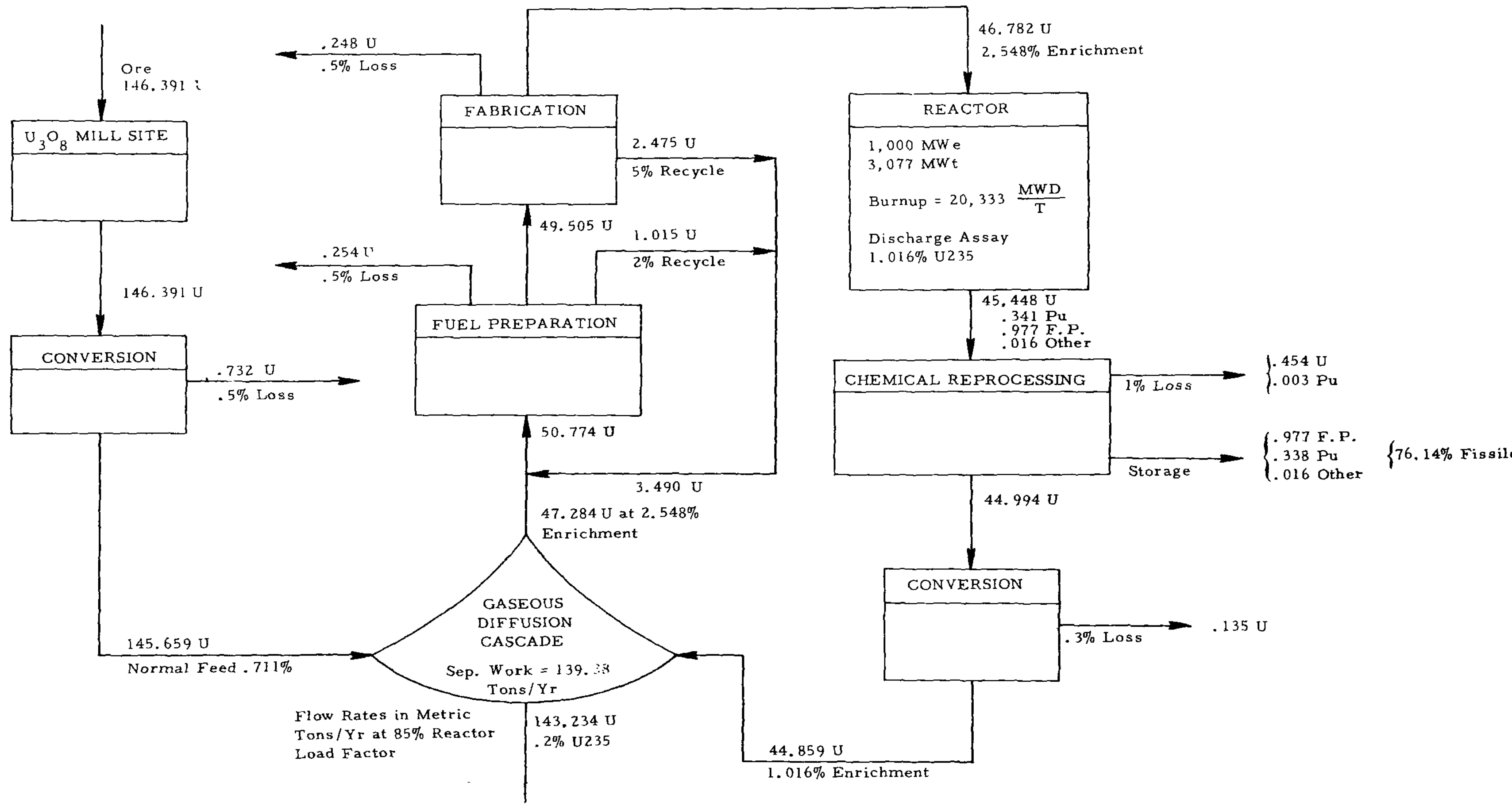


FIGURE 9: TYPICAL MATERIAL BALANCE FLOW SHEET OF A PWR (Reference 6)

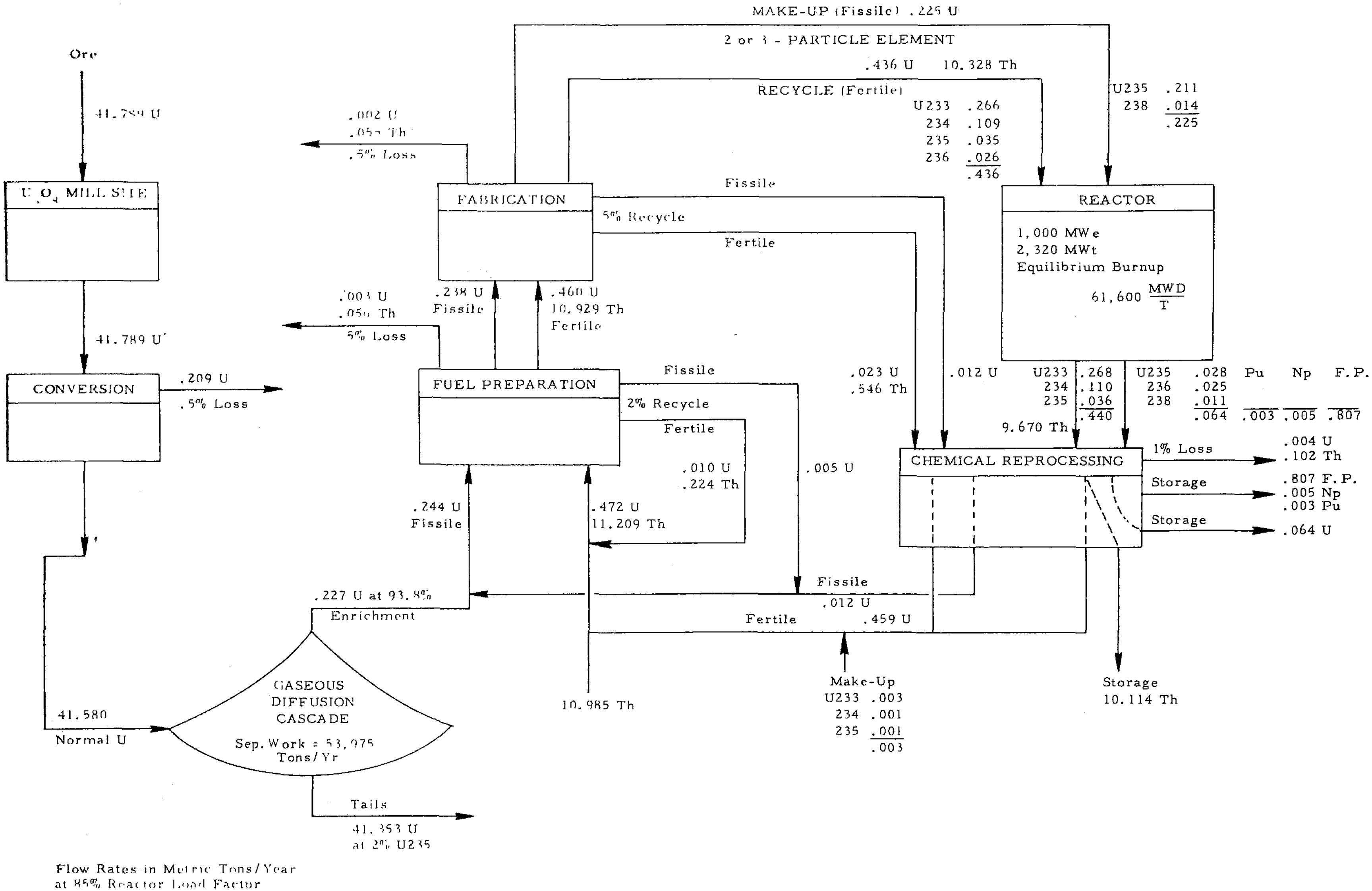


FIGURE 10: EQUILIBRIUM MATERIAL BALANCE FLOW SHEET OF AN HTGR (Reference 6)

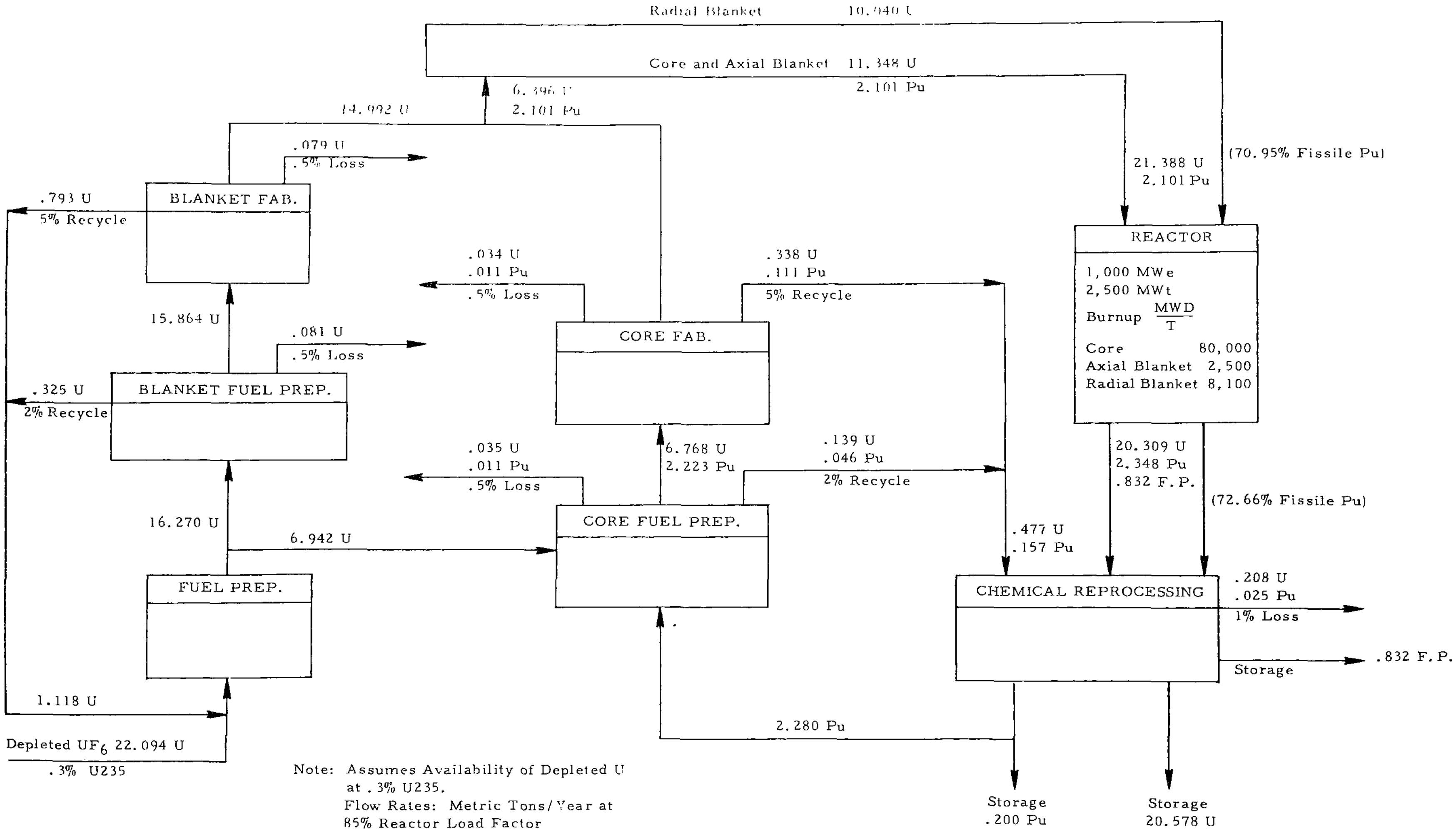


FIGURE 11: EQUILIBRIUM MATERIAL BALANCE FLOW SHEET OF AN LMFBR (Reference 6)

EXPECTED PERCENTAGE SUPPLIED BY LWR, HTGR, AND LMFBR

The increased demand for nuclear fueled electrical energy during the next 50 years will probably be met by the reactor types discussed in the previous section. Their expected relative contributions are shown in Table 7 and Figure 12 (Reference 5). The LWR should continue to be a significant electrical energy source for the remainder of this century. However, the bulk of the nuclear fueled generating capacity after the year 2000 will probably be supplied by the LMFBR. The HTGR should also play an important role. Of the installed nuclear electrical generating capacity in the year 2020 it is projected that 65 percent will be supplied by the LMFBR, 19 percent by the HTGR, and 16 percent by the LWR.

EXPECTED NUMBER AND LOCATION OF FUEL REPROCESSORS IN THE UNITED STATES

In the three fuel cycles (Figures 9 through 11) an important step is chemical fuel reprocessing. In this operation, the spent fuel from the reactor is put through a chemical process to separate the fission products and the cladding material from the still-fissionable material. The latter includes the original fuel which has not fissioned and the material newly created by the capture of neutrons by fertile material. The still-fissionable material is usually recycled. The fission products and the cladding materials are classified as radioactive waste and are (or will be) shipped to disposal and repository facilities. The fuel reprocessing load in the United States is projected to the year 2020 in Table 8. This table shows the reprocessing loads expected from LWR-U facilities; LWR-U, Pu facilities; HTGRs; and LMFBRs. It is anticipated that between 1990 and 1995, recycling of plutonium fuel for LWRs will cease. Many of the reprocessing plants expected to handle these loads will be able to handle reactor fuel from HTGRs and LMFBRs as well as LWRs. The anticipated increase in the number of fuel reprocessing plants for each FPC region over the next 50 years is shown in Table 9. The distribution of plants will follow the geographical distribution of nuclear reactors.

In Figure 13, the reprocessing load (Table 8), reprocessing capacity (Table 9), and installed generating capacity (Table 7) projections are compared. On a national basis the capacity of the reprocessors is always expected to exceed the reprocessing load. However, the load in a given FPC region may exceed the capacity in that region. An example of this is the South Central region. From Table 9 it can be seen that the first reprocessor should begin operation in the South Central region in 2003. Until then the spent fuel will have to be shipped to reprocessors in other regions.

TABLE 7: CONTRIBUTION OF THE LWR, HTGR, AND LMFBR TO THE UNITED STATES NUCLEAR ELECTRIC POWER GENERATING CAPACITY (Reference 5)

Year	Power Capacity (10^3 MWe)			
	LWR	HTGR	LMFBR	Total
1970	5(100)[a]	0	0	5
1975	45(100)	0	0	45
1980	112(98)	2(2)	0	114
1985	210(86)	35(14)	0	245
1990	345(76)	93(21)	15(3)	453
1995	476(64)	151(20)	113(16)	740
2000	546(49)	202(18)	370(33)	1,118
2005	533(34)	273(18)	756(48)	1,562
2010[b]	520(26)	350(17)	1,140(57)	2,010
2015[b]	500(20)	455(18)	1,590(62)	2,545
2020[b]	490(16)	590(19)	1,960(65)	3,040

[a] Number in parenthesis is percent of total.

[b] Graphical extrapolation.

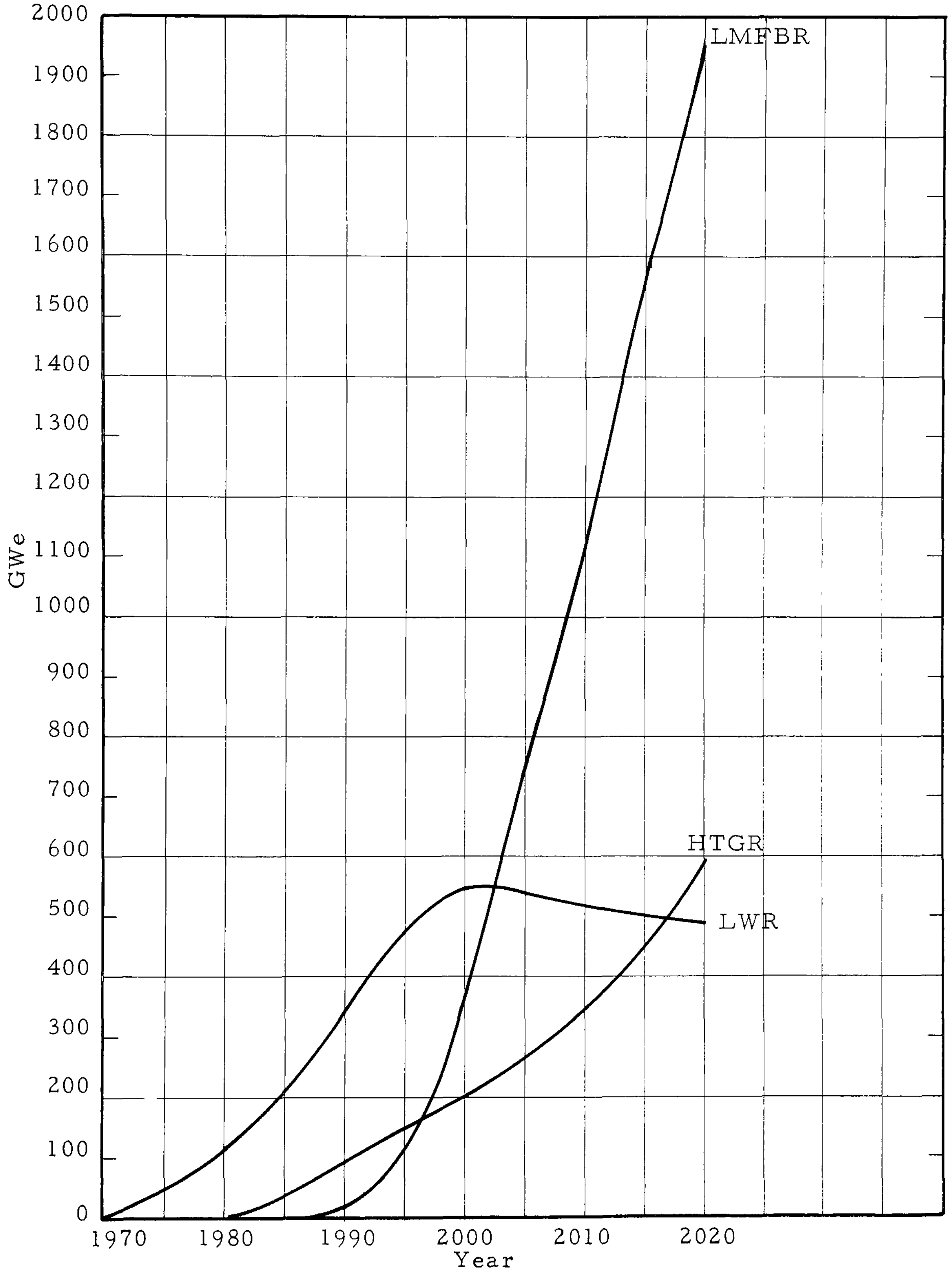


FIGURE 12: ELECTRICAL CONTRIBUTIONS OF VARIOUS REACTOR TYPES (Reference 5)

TABLE 8: ACTUAL REPROCESSING LOAD (Reference 5)

Year	Annual Load (Metric tons/year)				
	LWR-U	LWR-Pu	HTGR	LMFBR	Total
1970	0	0	0	0	0
1975	850	0	0	0	850
1980	2,126	269	7	0	2,402
1985	3,568	1,184	169	0	4,921
1990	7,284	366	590	175	8,415
1995	10,478	0	1,040	1,470	12,988
2000	11,042	0	1,415	5,123	17,580
2005	10,642	0	1,812	10,679	23,133
2010*	10,100	0	2,190	16,510	28,800
2015*	9,300	0	2,560	22,740	34,600
2020*	8,400	0	2,900	29,700	41,000

*Graphical extrapolation.

TABLE 9: PROJECTED REGIONAL DISTRIBUTION OF MULTIPURPOSE REPROCESSING PLANTS

WEST CENTRAL		
Capacity (MT/Yr)	Fuel Type	Operating Life
300	LWR	1973-1986
6,000	LWR HTGR LMFBR	1992-2006

EAST CENTRAL		
Capacity (MT/Yr)	Fuel Type	Operating Life
3,000	LWR LMFBR	1983-1997
6,000	LWR HTGR LMFBR	2000-2014

NORTHEAST		
Capacity (MT/Yr)	Fuel Type	Operating Life
300	LWR	1966-1974
780	LWR	1974-1988
3,000	LWR	1987-2001
6,000	LWR LMFBR	1998-2012

WEST		
Capacity (MT/Yr)	Fuel Type	Operating Life
3,000	LWR HTGR LMFBR	1990-2004
6,000	LWR HTGR LMFBR	2002-2016

SOUTH CENTRAL		
Capacity (MT/Yr)	Fuel Type	Operating Life
6,000	LWR LMFBR	2003-2017

SOUTHEAST		
Capacity (MT/Yr)	Fuel Type	Operating Life
1,500	LWR HTGR	1976-1990
1,500	LWR	1980-1994
6,000	LWR HTGR	1995-2009
6,000	LMFBR	2005-2019

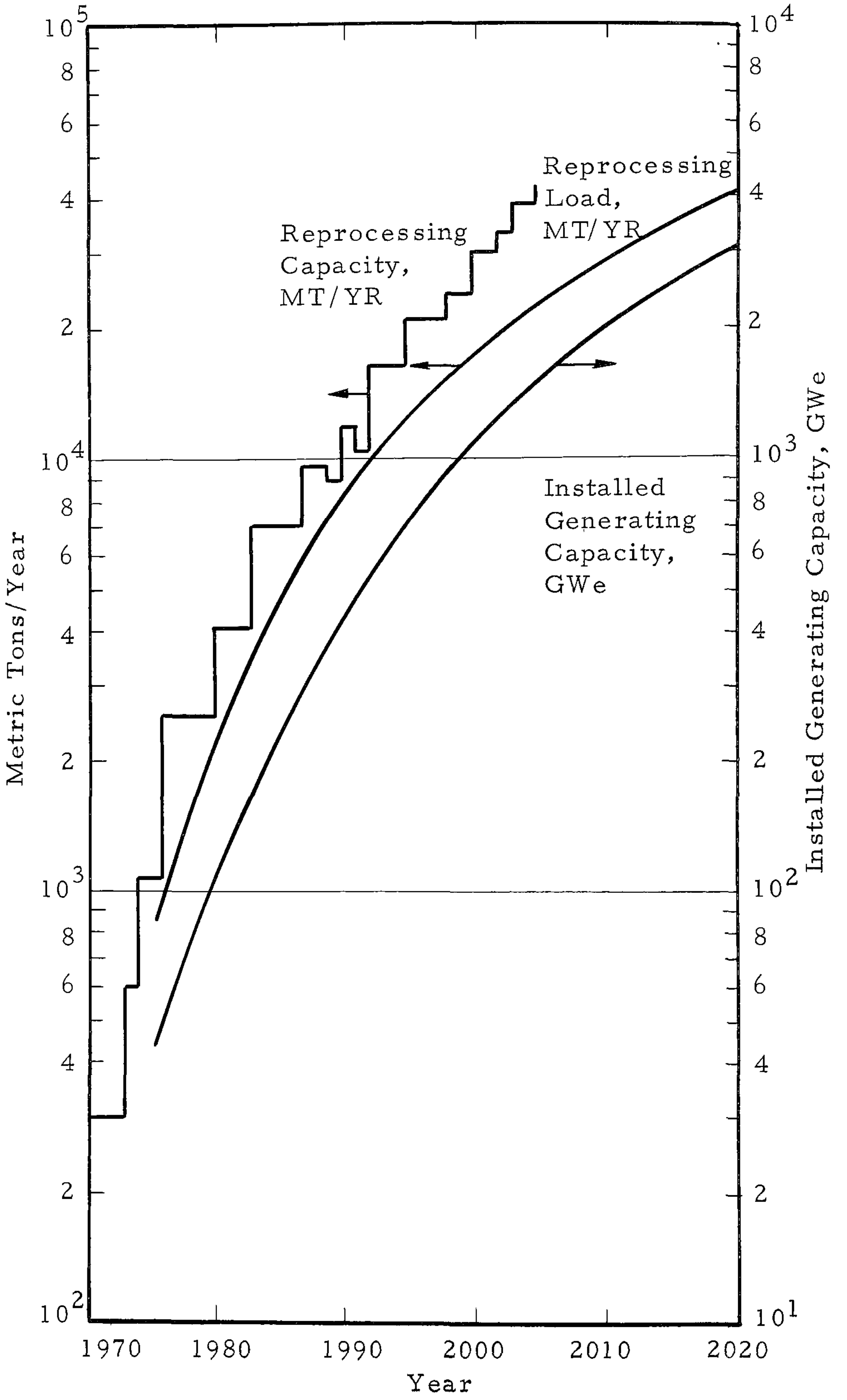


FIGURE 13: PROJECTION OF REPROCESSING LOAD AND CAPACITY IN THE UNITED STATES (Reference 5)

EXPECTED NUMBER AND LOCATION OF WASTE REPOSITORIES

All commercial high-level waste will originally be sent to a retrievable surface storage facility. Such facilities might be located at the AEC's facilities, such as Hanford, Oak Ridge, or Nevada. They are expected to be used primarily as holding facilities until such time as more permanent waste management methods are available.

Permanent waste repositories are in the development stage. One location in southeastern New Mexico is being examined as a possible site. A first coring sample of the salt bed information is expected to be taken in 1973 to allow a choice to be made between sites in New Mexico and Kansas. It is not anticipated that pilot plant operations will be started prior to 1982, while regular operation of the facility on a nonexperimental basis is not expected to take place before 1993. It is anticipated that if this project is successful and the salt formation disposal technique becomes publicly accepted, at least one other national disposal site will be in operation by the year 2020 (Reference 14).

Ocean dumping will not be utilized extensively as a waste deposit scheme because of difficulty in proving that ocean dumping is not harmful; the almost impossible recovery of the materials once dumped; the difficulty of imposing appropriate environmental controls; and Public Law 92-532, which prohibits ocean disposal of high level radioactive waste.

To obtain a definite transportation scenario, however, this study assumes that a repository will begin operation in 1980 in southeastern New Mexico.

SECTION V

NUCLEAR TRANSPORTATION FORECASTS (1970 TO 2020)

NUCLEAR FUEL PICTURE

Forecasts of the growth of the nuclear power industry in the United States in the next 50 years indicate that the volume of radioactive material produced by the nuclear power generation process will increase.

The principal components of this material are:

1. Spent fuel elements containing radioactive fission products, plutonium, and uranium.

2. Plutonium separated from spent fuel and incorporated into new fuel elements to be charged to nuclear reactors.

3. Fission products separated from spent fuel in the form of highly radioactive liquids (1-2.5 x 10^4 Ci/liter) requiring containment for 10^3 -10^6 years.

4. Fission products separated from spent fuel in the form of liquids of low and intermediate level radioactivity ($<10^{-4}$ Ci/liter and 10^{-4} -1 Ci/liter) requiring evaporation and/or ion exchange treatment.

5. Fission product gases separated from spent fuel.

In this study, shipments of spent fuel, recycled plutonium, solidified forms of highly radioactive liquid wastes, and fission product gases (principally noble gases) are treated as the significant hazards. The low and intermediate level wastes involve a greater number of shipments, but the risk of accidental radiation hazards from these shipments is disregarded in this study because of the low radioactivity involved. A possible management strategy for the gaseous wastes is to store them temporarily and then release them to the atmosphere. The longest lived component of fission gases is Kr-85, which has a half life of 10.7 years, so 107 years of temporary storage would be required for a reduction of radioactivity level to about 0.1 percent of the original level. In this study, the premise is adopted that such release provides an unacceptable solution, and shipments of fission gases are assumed to be part of the transportation scenario.

The number of shipments of these significantly hazardous materials is expected to increase from about 200 in 1975 to perhaps 60,000 in 2020. As more power reactors, processing plants, fuel fabrication plants, and waste repositories are built, the average shipping distance for the waste will decrease. However, the number of shipment-miles is not expected to decrease since the number of shipments outweighs the distance factor. This point will be discussed later.

Estimates to the year 2020 of the amount of fuel which will be used by the different nuclear reactors are presented in Table 10. The data in Table 10 is a revision of previously reported estimates (References 12 and 13). The latest estimates were generated by the Oak Ridge Systems Analysis Code, which was not available for the first projection (Reference 12).

This latest forecast assumes the introduction of fast breeder reactors (represented in Table 10 by the LMFBR column) in about 1987. Up until that time the use of LWRs will grow and recycling of Pu for use as LWR fuel is expected to be economically advantageous. After introduction of LMFBRs, the Pu recycling operation will be curtailed, but LWRs will be an increasing power source until about 1995, after which time they will fall into disuse. After 1995, the power burden is expected to fall on the fast breeders and the increasingly favorable HTGR. Overall, the total amount of fuel fabricated is expected to triple between 1975 and 1980 from 1,600 metric tons (MT) to 4,600 MT. It is expected to triple again by 1990 to 11,800 MT and a third time by 2015 to 37,600 MT. The amount of irradiated fuel that is to be processed would experience similar growth.

Shipments of plutonium are of special interest because this material is highly toxic and highly radioactive. In Table 10 data for the years between 1978 and 1990 are described in detail to show the plutonium reprocessing cycle for the LWR more clearly. In this table, the data in the columns marked LWR-U refer to the amounts of uranium used in LWRs. The data in the columns labeled LWR-Pu refer to the amounts of plutonium used in LWRs in the recycling program. No plutonium is included in the HTGR columns, but plutonium is counted in the LMFBR columns. From Table 6 the averages between AI and GE follow-on designs give 7.48 percent of the "Fabricated" numbers and 9.59 percent of the "Processed" numbers as plutonium.

All the numbers for processed fuel in Table 10 represent quantities of uranium, plutonium, and thorium in the spent fuel that is shipped to the reprocessing plant. Since startup cycles and recycling of fuel introduce nonuniformities in the amount of radiation exposure, the numbers

TABLE 10: ANNUAL NUCLEAR FUEL (U, Pu) PICTURE (Reference 5)

Year	Fuel (Metric Tons)									
	LWR-U		LWR-Pu		HTGR		LMFBR		Total	
	Fabricated[a]	Processed	Fabricated	Processed	Fabricated	Processed	Fabricated	Processed	Fabricated	Processed
1970	403.2	15.0							403.2	15.0
1975	1,566.2	566.9							1,566.2	566.9
1978	2,276.9	1,406.5	775.3						3,502.2	1,406.5
1980	2,987.6	1,937.0	801.2	113.5	117.4				4,585.9	2,050.5
1982	3,545.8	2,661.3	1,163.0	494.9	316.3	4.5			5,025.1	3,160.7
1984	4,796.7	3,020.5	1,085.5	876.1	507.7	29.7			6,389.9	3,926.3
1986	6,722.0	3,911.3	542.7	985.1	698.4	102.6			7,963.1	4,999.0
1988	8,404.5	5,222.1	180.9	762.6	913.8	227.5	225.9		9,725.1	6,212.2
1990	10,141.2	6,912.2		381.3	1,089.7	392.3	580.4	112.7	11,811.3	7,798.5
1995	11,759.0	10,279.8			1,429.2	869.0	3,179.7	1,165.0	16,367.9	12,313.8
2000	11,417.9	11,107.3			1,854.4	1,308.5	7,814.3	4,453.2	21,086.6	16,869.0
2005	9,745.8	10,287.2			2,293.6	1,664.0	14,467.8	9,671.1	26,507.2	21,622.3
2010[b]	8,000.0	9,400.0			2,800.0	2,000.0	21,000.0	14,800.0	31,800.0	26,200.0
2015[b]	6,300.0	8,600.0			3,300.0	2,400.0	28,000.0	20,000.0	37,600.0	31,000.0
2020[b]	4,600.0	7,200.0			3,800.0	2,800.0	35,000.0	25,200.0	43,400.0	35,200.0

[a] Processed tonnage data is prorated to uniform burnup of 33,000 megawatt-days per metric ton of uranium.

[b] Approximations to linear extrapolations after year 2005.

for processed fuel in Table 10 are calculated under the assumption that all the fuel is irradiated by the same amount, i. e., 33,000 megawatt-days exposure.

RADIOACTIVE WASTE PICTURE

Generation of Waste

Analysis of waste treatment processes for LWR, HTGR, and LMFBR fuel has led to figures of merit for specific volumes of solid waste produced from each metric ton of uranium (MTU) charged to the reactors. They are:

Reactor Type	Specific Solid Waste (ft^3/MTU)
LWR	2
HTGR	6
LMFBR	3

Calculated values for the volumes of wastes actually committed from the processors are given in Table 11.

An industry-wide projection of the amount of radioactivity generated by the processing of high level waste is given in Table 12. The total amount is projected to increase from 2.5×10^6 Curies (2.5 MCi) to 9.1 MCi between 1975 and 1980, to 35.25 MCi by 1990, and to 148.3 MCi by 2005.

For at least two reasons, no liquid wastes are considered in the transportation picture (Reference 14). As a policy, the AEC restricts disposal practices for liquid wastes that have high levels of radioactivity. Consequently, the transportation of highly radioactive liquid wastes is prohibited. The other reason is economic--adequate liquid container fabrications are too expensive to admit the notion of transporting liquids.

Solid wastes consist of solidified aqueous products, solvent cleanup materials, cladding hulls, alpha contaminated solids, and fission products. The fission products and part of the other wastes are classified as high level radioactive wastes. The alpha contaminated waste may be partitioned into low level and intermediate level segments.

TABLE 11: ANNUAL VOLUME COMMITMENT OF HIGH LEVEL RADIOACTIVE SOLIDIFIED WASTE (Reference 5)

Year	Waste Volume (Cubic Feet)			
	LWR	HTGR	LMFBR	Total
1973	100.0	0.0	0.0	100.0
1975	1,700.0	0.0	0.0	1,700.0
1980	4,789.6	39.6	0.0	4,829.2
1985	9,504.0	1,015.8	0.0	10,519.8
1990	15,300.6	3,537.6	526.2	19,364.4
1995	20,956.2	6,240.6	4,408.8	31,605.6
2000	22,083.0	8,490.6	15,369.3	45,942.9
2005	21,284.4	10,872.6	32,035.2	64,192.2
2010*	20,500.0	13,200.0	48,600.0	82,300.0
2015*	19,700.0	15,600.0	65,200.0	100,500.0
2020*	18,900.0	18,000.0	81,800.0	102,500.0

*Approximations to linear extrapolation after year 2005.

TABLE 12: ANNUAL RADIOACTIVITY GENERATION OF HIGH LEVEL RADIOACTIVE SOLIDIFIED WASTE (Reference 5)

Year	Radioactivity (10^9 Curies)			
	LWR	HTGR	LMFBR	Total
1973	0.128	0.0	0.0	0.128
1975	2.501	0.0	0.0	2.501
1980	9.102	0.0	0.0	9.102
1985	20.008	0.277	0.0	20.284
1990	32.364	1.800	1.085	35.249
1995	45.344	3.986	11.374	60.705
2000	48.994	6.002	43.820	98.816
2005	45.377	7.633	95.257	148.267
2010*	41.8	9.2	146.6	197.6
2015*	38.2	10.8	197.0	246.0
2020*	34.6	12.4	248.4	295.4

*Approximations to linear extrapolation after year 2005.

A projection of the amount of solid wastes of low and intermediate levels of radioactivity (<1 Ci/liter of liquid from which the solid was formed) which will be shipped over the next 50 years is given in Table 13. As indicated above, these solids are not included as a significant radioactive transport hazard.

Gaseous wastes are products of fission. The principal nuclides are Kr-85, Xe-131m, and I-131, with the radiation from Kr-85 outweighing that from the other gases. After a year's cooling time, a metric ton of uranium fuel contains 0.0108 MCi of Kr-85, with the other nuclides standing in the ratio (Reference 8):

$$Kr : Xe : I = 1 : 10^{-9} : 1.83 \times 10^{-12}.$$

The amount of iodine gas radiation becomes insignificant, so the terms fission product gas and noble gas are used interchangeably. Of the fission gases, Kr is the least chemically hazardous in terms of human health and has a half life of 10.7 years. Consequently, the gas could be ventilated to the atmosphere after being stored to allow radioactive decay.

Such releases would not provide a satisfactory solution to the radiation burden that is forecast from the production of fission gases. Transport of gaseous wastes from reactors or fuel reprocessing centers to repositories where they may be held in long term storage would be more satisfactory. Research is being conducted to find a feasible method of entraining the gases in a solid matrix for transport purposes. When such solidification processes are available, the shipments of gases would be counted as shipments of high level radioactive solid wastes. Such shipments would probably be safer than shipments of pressurized cylinders of gas since the amount of gas released in an accident would be much less.

For purposes of estimating the risk, the management of gaseous waste is assumed to include transport of gases in pressurized cylinders, and not to involve controlled releases of the gases produced in fission or chemical processes.

Shipping of Significant Nuclear Materials

The major factors in transportation of nuclear materials are:

1. Spent fuel shipped from power reactor to chemical processing plant.

2. Recycled plutonium shipped from processor to fuel fabricator.

TABLE 13: ANNUAL SHIPPING DATA FOR LOW AND INTERMEDIATE LEVEL RADIOACTIVE SOLID WASTE (Reference 7)

Year	Number of Shipments			
	Alpha Contaminated Wastes	Cladding Hulls	Nonalpha Contaminated Solids	Intermediate Level Alpha Contaminated Solids
1970	1*	0*	17*	4*
1975	7*	2*	111*	27*
1980	350	54	6,700	1,730
1985	700	150	10,000	2,300
1990	1,000	280	13,900	2,900
1995	1,800	650	22,000	7,000
2000	2,500	990	30,000	10,600
2005	3,100	1,250	33,000	12,000
2010	3,800	1,500	36,000	14,000
2015	4,400	1,750	39,000	16,000
2020	5,000	2,000	42,000	18,000

* Values of 1,000 MT and 6,000 MT for wastes shipped in 1970 and 1975 were taken from Reference 1, 1971. These wastes were assumed to include no high level wastes. It was assumed further that these wastes were shipped in ATMX-500 rail cars of 90,000 lb. capacity (Reference 11). The shipments were then partitioned among the columns as follows: 5% alpha, 1% hulls, 76% nonalpha, 18% intermediate. This distribution agrees approximately with the 1980 and 1985 distributions.

3. Radioactive solids transported from processor to repository.

4. Gaseous wastes transported from reactor or processor to repository.

Currently, between 50 and 600 MT of fuel are being discharged from power reactors in the United States (References 1 and 12). From estimates made at Oak Ridge National Laboratory (References 5, 12, 13, 17, and 19), from 50 to 660 MT of uranium and plutonium will be shipped in the form of spent fuel elements in 1973. Seventeen MT of fuel for LWRs were estimated to be discharged for the plutonium recycling program in 1973 (Reference 12) and from 4 to 9 MT of fissile plutonium are expected to be recovered in 1975 (References 12, 20, and 17). Consequently, between 4 and 9 MT fissile Pu will be shipped in 1975. Only 100 to 300 MT of high level radioactive solidified wastes are expected to be generated by the reprocessing plants in 1973 (References 5, 12, and 13), but this amount of waste is not expected to be transported to a Federal repository until 1983. The radioactivity associated with this amount of waste is estimated to be 130 to 210 MCi. An estimate of about 1.7 MCi (Reference 10) has been made for the radioactivity represented by the production of fission (principally noble) gases in 1970. These gases are separated from the spent fuel mass in the chemical processing plants and are either held for radioactive decay or released at large stack heights for atmospheric dissipation. Shipments of these gases to repositories are assumed for this study.

Projections of shipments of these materials are studied in Figures 14 through 17. Shipments of all materials are expected to monotonically increase with time, with the exception of recycled plutonium. According to some estimates of the future movements of this material, the use of recycled plutonium in LWRs will decrease between 1985 and 1990, and the shipments of plutonium for LMFBRs will increase beginning about 1987. Consequently, a minimum appears in these curves for the year 1995.

In all the projections, approximate envelope curves were drawn to represent high and low possible magnitudes of shipments. Practically none of the estimates found in the literature or by personal communication extended to the year 2020. The later years of a projection were treated by linear extrapolation.

In Figure 14, the expected annual metric tonnages of spent fuel movements are shown. The oldest curve (Reference 12, ORNL-4451) indicates the shape of the curve is irregular and that the weight of spent fuel shipped will approximately increase eightfold in the period 1970 through 1985,

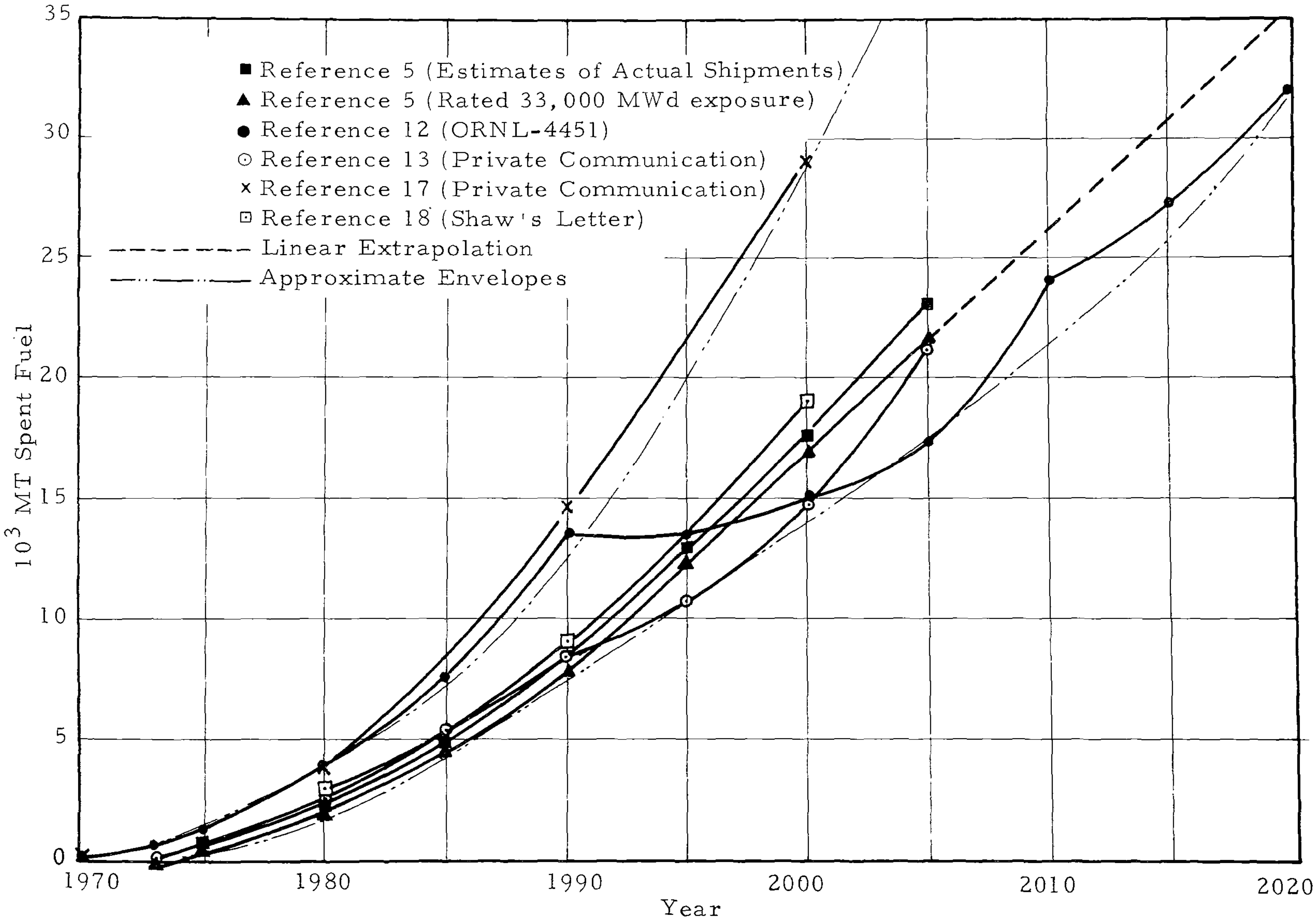


FIGURE 14: PROJECTIONS OF SHIPPED TONNAGE OF SPENT FUEL

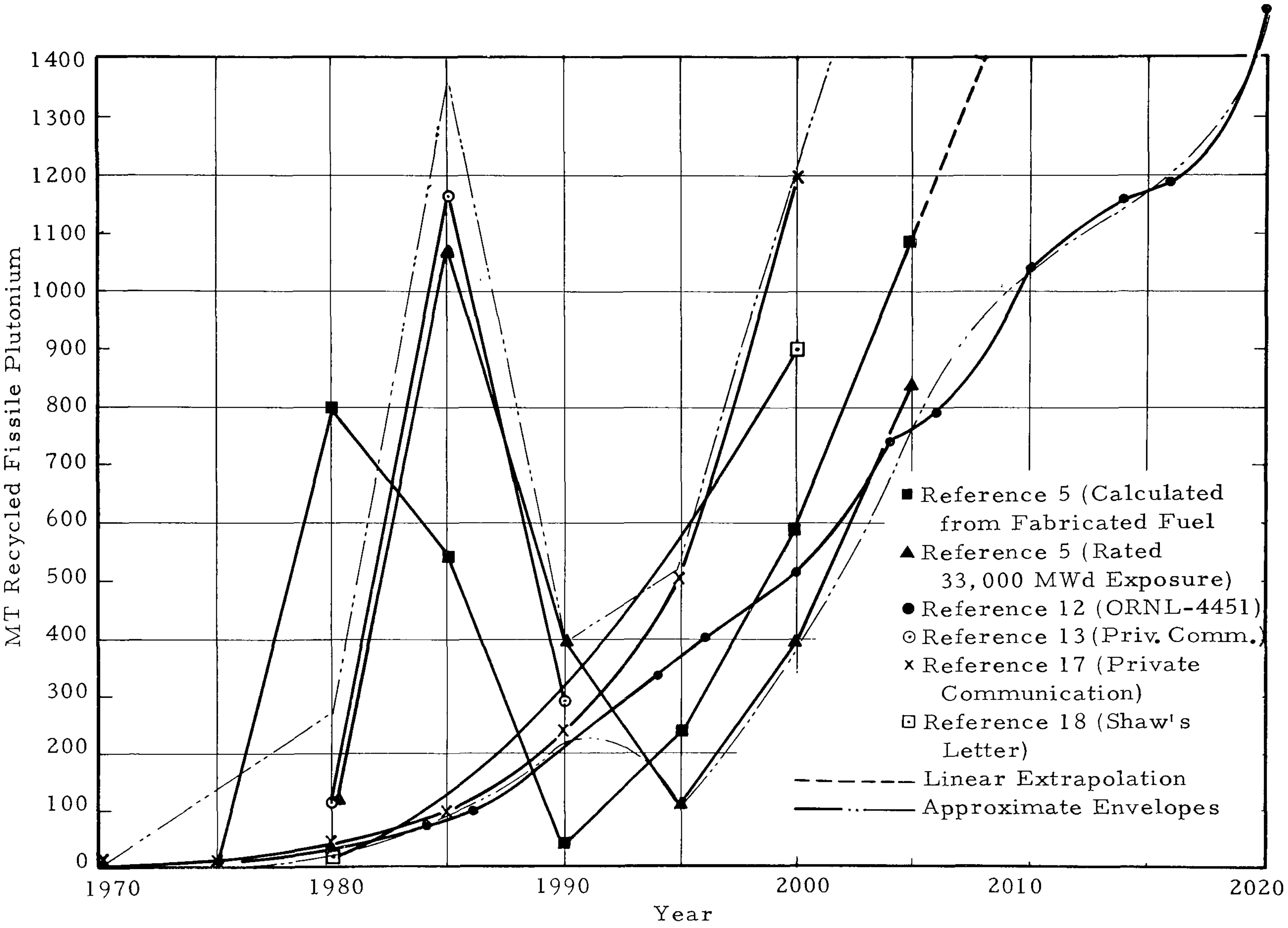


FIGURE 15: PROJECTIONS OF SHIPPED TONNAGE OF FISSILE PLUTONIUM

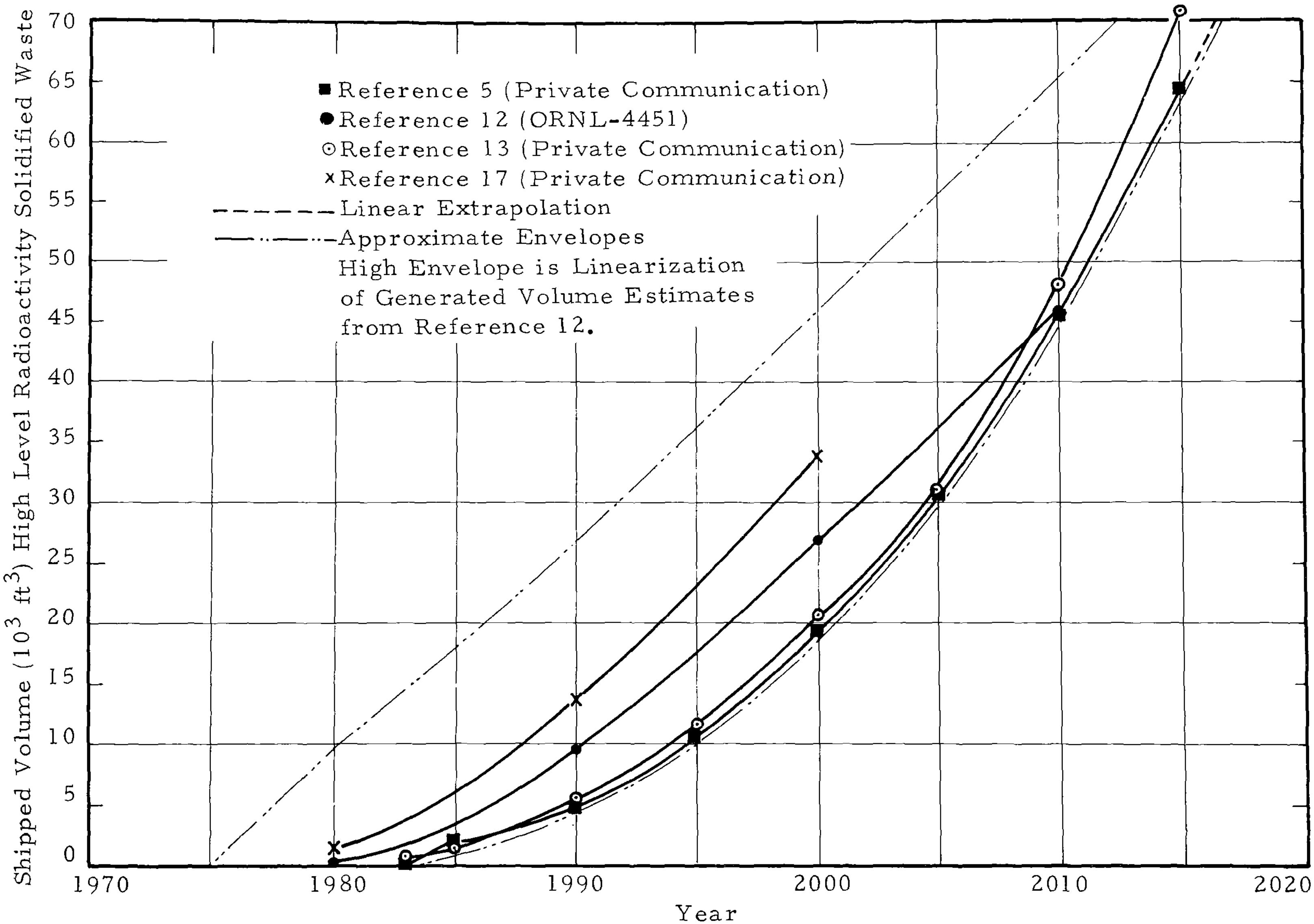


FIGURE 16: PROJECTIONS OF SHIPPED VOLUME OF HIGH LEVEL RADIOACTIVE SOLIDIFIED WASTE

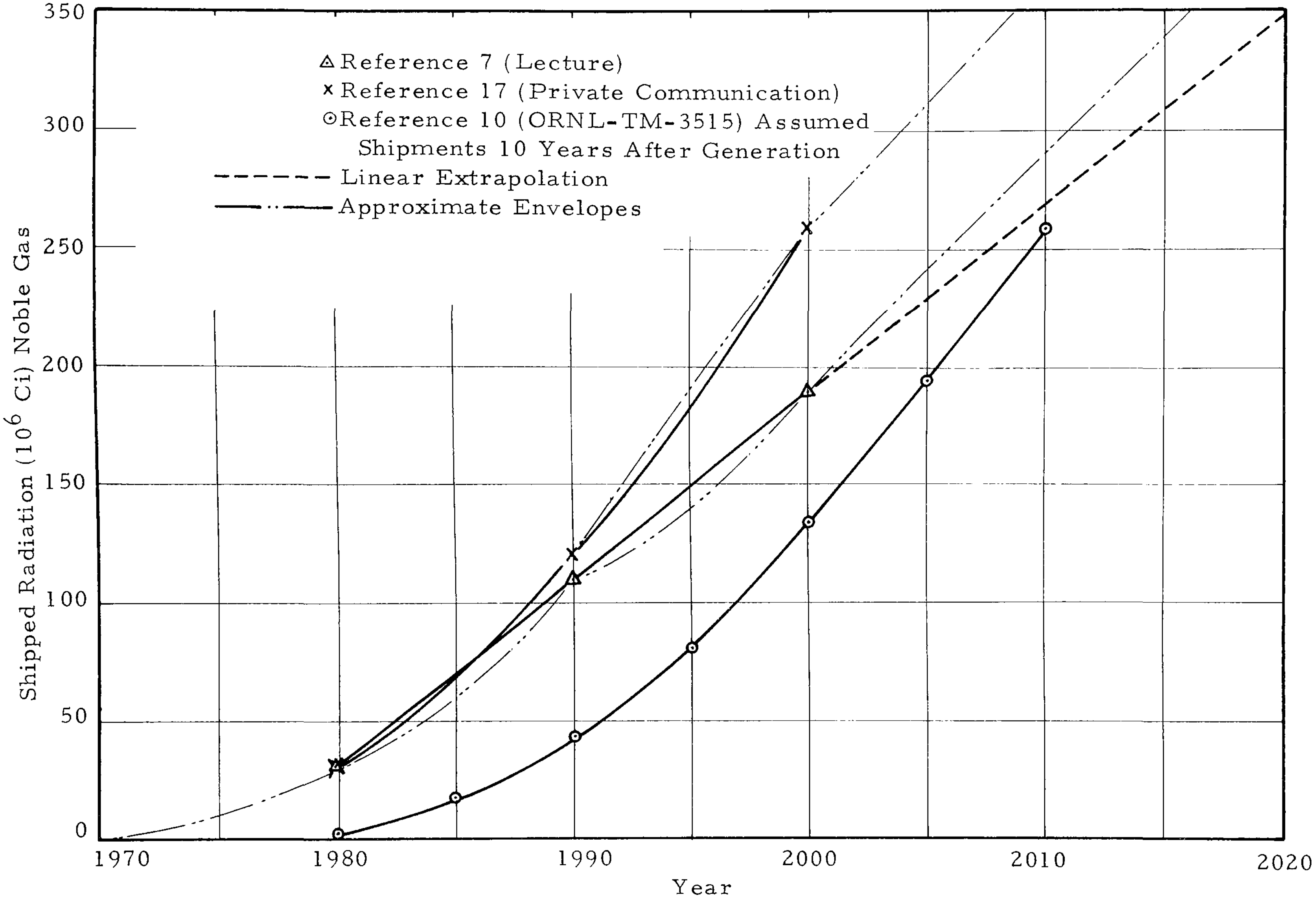


FIGURE 17: PROJECTIONS OF SHIPPED RADIATION OF NOBLE GASES

double during 1985 to 2000, and double again by 2020. A more recent estimate based on a computerized model of the nuclear economy, which model evidently was not available for the ORNL-4451 estimate (Reference 5, private communication), shows that the growth rate will not be quite as strong from 1970 to 1995, but will be stronger after 1995.

Probably the most applicable curve is the projection of shipped tonnage at rated exposure (33,000 MWd). This curve is linearly extrapolated in Figure 14 to represent the most suitable estimate of spent fuel shipments from 1970 to 2020. A table summarizing the shipment numbers for this estimate and for the high and low estimates is given in Table 14. For the most part, the high and low envelopes are straight lines passing through appropriate points of the data curves.

In Table 15, the shipments of spent fuel for the chosen estimate are described with different parameters. The radioactivity of the fuel is estimated using the factor 5×10^6 Ci/MT. The number of casks depends on the reactor mix in which the fuel is used and is here determined by an average cask capacity. No distinction is made for the differences in weights that may be transported by different modes. The mileage figures are based on Table 22 which will be discussed and shown later.

In Figure 15, the expected annual metric tonnage of recycled plutonium shipments are shown. As mentioned before, a minimum occurs in some projections because the LWR-Pu recycling program is expected to terminate near the time that the LMFBR usage increases. For the chosen estimate, the minimum occurs near 1990. The chosen estimate is calculated from the fuel fabrication data in Reference 5. Before 1985, only the LWR-Pu data is counted. After 1985, the LWR-Pu values are added to 7.5 percent (average of GE and AI designs) of the LMFBR fuel loadings.

Table 16 compares the chosen estimate with high and low estimates. Values of radioactivity and numbers of shipments used to describe the chosen projection of recycled plutonium transportation are included in Table 17. No distinctions of shipment capacities between transport modes are assumed in Table 17. The shipping distance data are obtained from Table 22.

In Figure 16, the expected annual shipped volumes of high level radioactivity solidified waste are shown. The chosen estimate is synonymous with the low estimate. For the high estimate, the values of Reference 12 (ORNL-4451) for the amounts of high level waste generated annually were linearized. Of course, the shipments are assumed to occur 10 years after generation, so the high estimate of shipments is rather arbitrary.

TABLE 14: COMPARISON OF HIGH, LOW, AND CHOSEN ESTIMATES OF SHIPPED TONNAGE OF SPENT FUEL

Year	Low Estimate	Chosen Estimate*	High Estimate
1970	0	15	0
1975	300	567	1,400
1980	1,800	2,050	4,000
1985	4,300	4,474	7,200
1990	7,500	7,798	12,500
1995	10,700	12,134	20,000
2000	14,100	16,869	29,000
2005	17,500	21,622	39,000
2010	21,400	26,200	49,000
2015	25,800	31,000	60,000
2020	32,200	35,200	70,400

*Reference 5, rated exposure of 33,000 MWd.

TABLE 15: ANNUAL SHIPPING DATA FOR SPENT FUEL

Year	Spent Fuel[a] (Metric Tons)	Radioactivity[b] (10^9 Curies)	Number of[c] Casks	Distance[d] (Miles)	Shipping Units (10^6 Cask-Miles)
1970	15	0.07	5	700	0.003
1975	567	2.84	191	600	0.115
1980	2,050	10.25	934	500	0.467
1985	4,474	22.37	1,612	450	0.806
1990	7,798	39.00	3,297	400	1.483
1995	12,314	61.57	7,463	400	2.985
2000	16,869	84.34	10,224	400	4.089
2005	21,622	108.11	12,100	400	4.805
2010	26,200	131.00	16,000	400	6.400
2015	31,000	155.00	19,000	400	7.600
2020	35,200	176.00	21,400	400	8.600

[a] Obtained from Total Processed column of Table 10, this report. The upper limit numbers for the period 1970-1985 are obtained from Reference 1, 1971.

[b] Assume 5×10^6 Ci/metric ton.

[c] Based upon an average of 3.133 to 1.65 metric tons of fuel/cask.

[d] Based on assumption of uniform geographical distribution of plants.

TABLE 16: COMPARISON OF HIGH, LOW, AND CHOSEN ESTIMATES OF SHIPPED TONNAGE OF RECYCLED FISSILE PLUTONIUM

Year	Low Estimate (MT)	Chosen* Estimate (MT)	High Estimate (MT)
1970	0	0	0
1975	0	0	0
1980	20	801.2	270
1985	90	542.7	1,360
1990	210	43.5	390
1995	110	238.5	520
2000	390	586.1	1,200
2005	750	1,085.1	1,930
2010	1,040	1,575	2,640
2015	1,170	2,100	3,360
2020	1,500	2,625	4,080

*Reference 5, calculated from fuel fabrication projection.

TABLE 17: ANNUAL SHIPPING DATA FOR PLUTONIUM[a]

Year	Plutonium[b] (Metric Tons)	Radioactivity[c] (10^9 Curies)	Number of[d] Shipments	Shipping[e] Distance (Miles)	Number of 10^6 Shipment-Miles
1970	-	-	-	700	-
1975	-	-	-	600	-
1980	801.2	0.504	10,680	500	5.34
1985	542.7	0.341	7,234	450	3.26
1990	43.5	0.016	580	400	0.23
1995	238.5	0.087	3,179	400	1.27
2000	586.1	0.213	7,813	400	3.12
2005	1085.1	0.395	14,464	400	5.78
2010	1575	0.573	20,995	400	8.40
2015	2100	0.765	27,993	400	11.20
2020	2625	0.956	34,991	400	14.00

[a] Plutonium considered to be shipped from chemical processing plants to fuel fabrication plants in dry solid form. These shipments are identical in quantity, though not in form with shipments from fabricators to reactors, since no losses are assumed during fabrication. The movements of plutonium from reactors to processors are accounted for in spent fuel shipments.

[b] Amount of plutonium shipped assumed to be equal to amount fabricated for recycle in LWRs. In LMFBRs (after 1985) amount of plutonium is taken to be 7.5 percent (average of GE and AI designs) of fuel fabricated.

[c] Based on 0.6285×10^6 Ci/MT for LWRs, representing 33,000 MWd/MT exposure and 150 days decay. In LMFBRs (after 1985), based on 0.3641×10^6 Ci/MT, representing mixed core and blanket fuel exposed to 41,200 MWd/MT and 90 days decay.

[d] Based on 2.5 kg Pu per container and 30 containers per shipment, or 13.33 shipments per MT.

[e] Average distance between processors and fabricators; assumed to be equal to average distance between reactors and processors.

Generally, all the estimates for high level solid waste shipping have similar curvature. The highest estimate (References 7 and 17) has from 2 to 3 times as much volume being shipped in 1990 and 2000 as does the lowest estimate (References 5 and 13). The chosen projection indicates that the volume will increase fivefold in the period 1985 to 1990, double during 1990 to 1995, double during 1995 to 2000, increase by 150 percent during 2000 to 2005, increase by another 150 percent by 2010, and increase at a rate of about 20, 000 ft^3 every 5 years thereafter.

The comparison between high, low, and chosen projections of high level solidified waste shipping is given in Table 18. The description of waste transportation in terms of radioactivity, number of containers, number of shipments, and shipping distance is given in Table 19. As with the other tables of this kind, no distinctions in shipment capacities by transport mode are made and the distance data are obtained from Table 22.

In Figure 17, the expected annual shipped radiation of fission gases are shown. The most complete estimate in the literature refers to the amount of radiation generated in North America in the era 1970 to 2000 (Reference 10). For perspective, this curve is displayed in Figure 17 under the assumption that the radiation was shipped 10 years after generation.

The other estimates for noble gas are linearizations based on projections made for the years 1980, 1990, and 2000. The chosen estimate is taken from Reference 7, and after 2000 is assumed to be lower than the "low" estimate.

Generally, one would expect the radiation carried by shipments of noble gas to increase at a rate of about 50 to 130 MCi every 10 years. Tables comparing the estimates and giving additional transportation data for the chosen projection for noble gas are presented in Tables 20 and 21.

To facilitate discussion of the next 50 years in the nuclear transportation industry for the United States, a uniform geographical distribution of power reactors and fuel fabricators is assumed. Current plans include three processing plants, one in western New York, another in northern Illinois, one in South Carolina, and a repository for which a location has not yet been determined (Reference 14). To obtain an idea of the distance of shipments to the repository, the location which has been discussed for southeastern New Mexico was assumed. Additional processing plants may be built in the west and south central Federal Power Commission survey regions, beginning service in 1990 and 2003, respectively. Based on these assumptions, the approximate mileage figures for different types of radioactive material shipments are summarized in Table 22.

TABLE 18: COMPARISON OF HIGH, LOW, AND CHOSEN ESTIMATES OF SHIPPED VOLUME OF HIGH LEVEL RADIOACTIVITY SOLIDIFIED WASTE

Year	Low Estimate (10^3 ft^3)	Chosen* Estimate (10^3 ft^3)	High Estimate (10^3 ft^3)
1970	0	0	0
1975	0	0	0
1983	0.1	0.1	9.73
1985	1.7	1.7	18.315
1990	4.83	4.83	26.9
1995	10.52	10.52	36.45
2000	19.365	19.365	46.0
2005	31.61	31.61	55.55
2010	45.945	45.94	65.1
2015	64.195	64.195	74.65
2020	82.445	84.445	84.2

* Reference 5

TABLE 19: ANNUAL SHIPPING DATA FOR HIGH LEVEL RADIOACTIVE SOLID WASTE[a] (Reference 5)

Year	Volume ($10^3 ft^3$)	Radioactivity (10^9 Curies)	No. of Containers[b]	No. of Shipments[c]	Shipping Distance (Miles)	No. of 10^6 Container-Miles	No. of 10^6 Shipment-Miles
1970	0	0	0	0	-	0	0
1975	0	0	0	0	-	0	0
1980	.05	.005	1	1	2,500	0	.002
1985	1.70	.178	271	23	2,500	.678	.057
1990	4.83	.651	769	65	2,200	1.922	.143
1995	10.52	1.506	1,676	140	2,200	3.687	.308
2000	19.36	2.742	3,084	257	2,200	6.784	.565
2005	31.60	4.496	5,033	420	2,200	11.072	.924
2010	45.94	6.364	7,316	610	2,000	16.095	1.220
2015	64.19	8.309	10,222	852	2,000	20.444	1.704
2020	82.40	10.250	13,121	1,094	2,000	26.242	2.188

[a] Assumed to have decayed 10 years before shipment.
[b] Based on 6.28 ft^3 solid waste/container (nominally 1 ft diameter, 10 ft long).
[c] Based on twelve containers/shipment.

TABLE 20: COMPARISON OF HIGH, LOW, AND CHOSEN ESTIMATES OF SHIPPED RADIATION OF FISSION (NOBLE) GASES

Year	Low Estimate (10^6 Ci)	Chosen* Estimate (10^6 Ci)	High Estimate (10^6 Ci)
1970	0	0	0
1975	10	0	10
1980	32	32	32
1985	60	63	60
1990	110	106	120
1995	140	144	190
2000	190	184	260
2005	240	218	330
2010	290	252	400
2015	340	284	470
2020	390	311	540

*Reference 7.

TABLE 21

ANNUAL SHIPPING DATA FOR NOBLE GAS (Reference 7)

Year	No. of Cylinders	Radioactivity[a] (10^9 Curies)	No. of[b] Shipments	Shipping Distance (Miles)	No. of 10^6 Shipment-Miles
1970	-	-	-	-	-
1975	-	-	-	-	-
1980	175	.032	30	2,500	.075
1985	350	.063	59	2,500	.147
1990	590	.106	99	2,200	.217
1995	800	.144	134	2,200	.294
2000	1,020	.184	170	2,200	.374
2005	1,210	.218	202	2,200	.444
2010	1,400	.252	234	2,000	.468
2015	1,580	.284	264	2,000	.528
2020	1,730	.311	289	2,000	.578

[a] Based on $.18 \times 10^6$ curies/cylinder.
[b] Based on six cylinders/shipment.

TABLE 22: APPROXIMATE AVERAGE SHIPPING DISTANCES

Year	Distance (Miles)	
	Spent Fuel[a] and Recycled Plutonium	Fission Product Gas[b] and Solid Waste
1970	700	-
1975	600	-
1980	500	2,500
1985	450	2,500
1990	400	2,200
1995	400	2,200
2000	400	2,200
2005	400	2,200
2010	400	2,000
2015	400	2,000
2020	400	2,000

[a] Assigned data for the assumed uniform geographical distribution of power reactors in the continental United States.

[b] Processing plants assumed in western New York, northern Illinois, South Carolina, center of West Federal Power Commission (FPC) Survey Region, and center of South Central FPC Survey Region. Repository assumed built in 1980 in southeastern New Mexico. The distances between facilities are approximate assignments.

A summary of data giving the number of shipments for the four significantly hazardous materials and for low level radioactive wastes is displayed in Table 23. These shipments are determined from container sizes and are not dependent on the capacities of different transport modes. If the data in this table are eventually realized, quite a transportation industry will evolve. An average of 31.9 shipments per day of highly radioactive material would be made in 1980. This number would decrease to 11.1 in 1990, but then would grow to 50.6 in 2000, 104.6 in 2010, and 163.6 in 2020. While the number of shipments of low level wastes increases from about 9,000 in 1980 to about 67,000 in 2020, its ratio to the number of high level shipments increases from about 0.8 to about 1.1 in the same time interval.

Of the high level shipments, solid wastes and fission gases are practically insignificant components in numbers, compared to the spent fuel and plutonium components. The growth of a breeder economy is reflected in the ratio of spent fuel shipments to plutonium shipments. In 1980 this ratio is 0.1, in 1990 it is 5.7, and in 2000 it is 1.3. Of course, these numbers are dependent on shipment capacities, which might be changed as regulation policy changes. These results are illustrated in Figure 18.

The amounts of radiation carried with the annual number of shipments are compared in Figure 19. The greatest radiation is carried by the spent fuel by at least a factor of 10.

A plot (Figure 20) of the shipment-miles data in Tables 15, 17, 19, and 21 shows that the increase in gas transportation is approximately linear, with the number (0.075×10^6 shipment-miles) increasing eightfold between 1980 and 2020. Spent fuel transportation can be roughly characterized by two linear growth segments. The 1970 figure (0.003×10^6 shipment-miles) increases sixtyfold by 1985, and the 1985 amount increases by a factor of 6 by 2020 (9.3×10^6 shipment-miles). The transportation of solid wastes is influenced by the spent fuel situation, increasing by a factor of 40 in two roughly linear growth segments from 0.06×10^6 shipment-miles in 1980 to 2.2×10^6 shipment-miles in 2020. As indicated above, plutonium shipment-miles exhibit a minimum because the LMFBR production begins about the time that LWR recycling of plutonium ends.

The 1980s decade should witness a decrease by a factor of about 20 in plutonium shipment-miles, but the period from 1990 to 2020 should experience an increase in this quantity by a factor of about 60. Both changes should be approximately linear as indicated in Figure 20.

TABLE 23: SUMMARY ANNUAL WASTE TRANSPORTATION PICTURE

Year	Low Level Radioactivity* (Number of Shipments)	High Level Radioactivity (Number of Shipments)				
		Spent Fuel (I)	Plutonium (II)	Solid Wastes (III)	Fission Gases (IV)	Sum (I + II + III + IV)
1970	22	5	---	---	---	5
1975	147	191	---	---	---	191
1980	8,834	934	10,680	1	30	11,645
1985	13,150	1,612	7,234	23	59	8,928
1990	18,080	3,297	580	65	99	4,041
1995	31,450	7,463	3,179	140	134	10,916
2000	44,590	10,244	7,813	257	170	18,484
2005	49,350	12,100	14,464	420	202	27,186
2010	55,300	16,360	20,995	610	234	38,199
2015	61,150	19,697	27,993	852	264	48,806
2020	67,000	23,334	34,991	1,094	289	59,708

* Low level radioactivity wastes include compacted quantities of both alpha contaminated and nonalpha contaminated refuse for both low and intermediate radioactivity levels. Cladding hulls, which are assumed to contain 0.05 percent of Pu in the fuel, are also included.

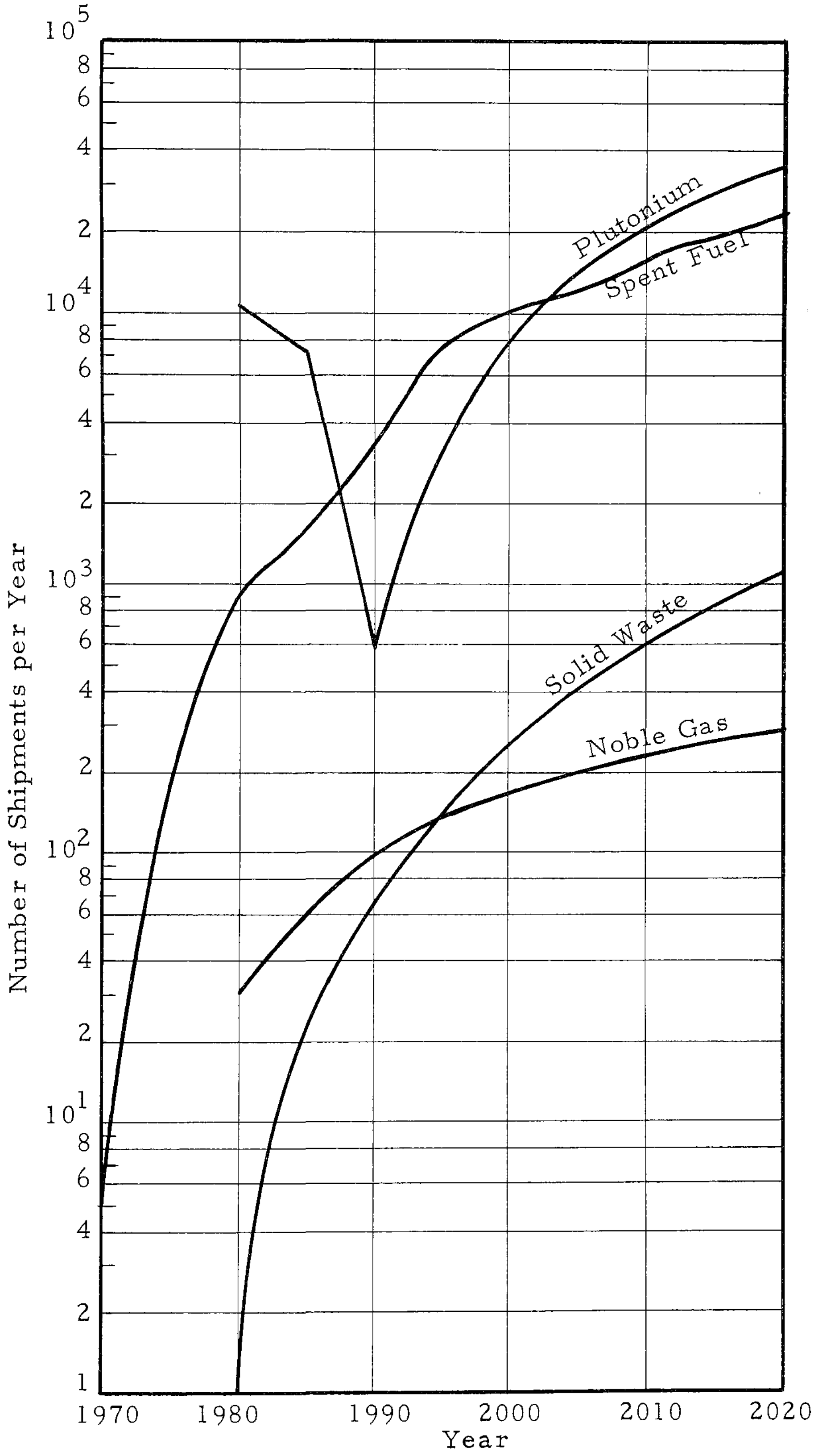


FIGURE 18: COMPARISON OF PROJECTIONS OF ANNUAL NUMBER OF SHIPMENTS

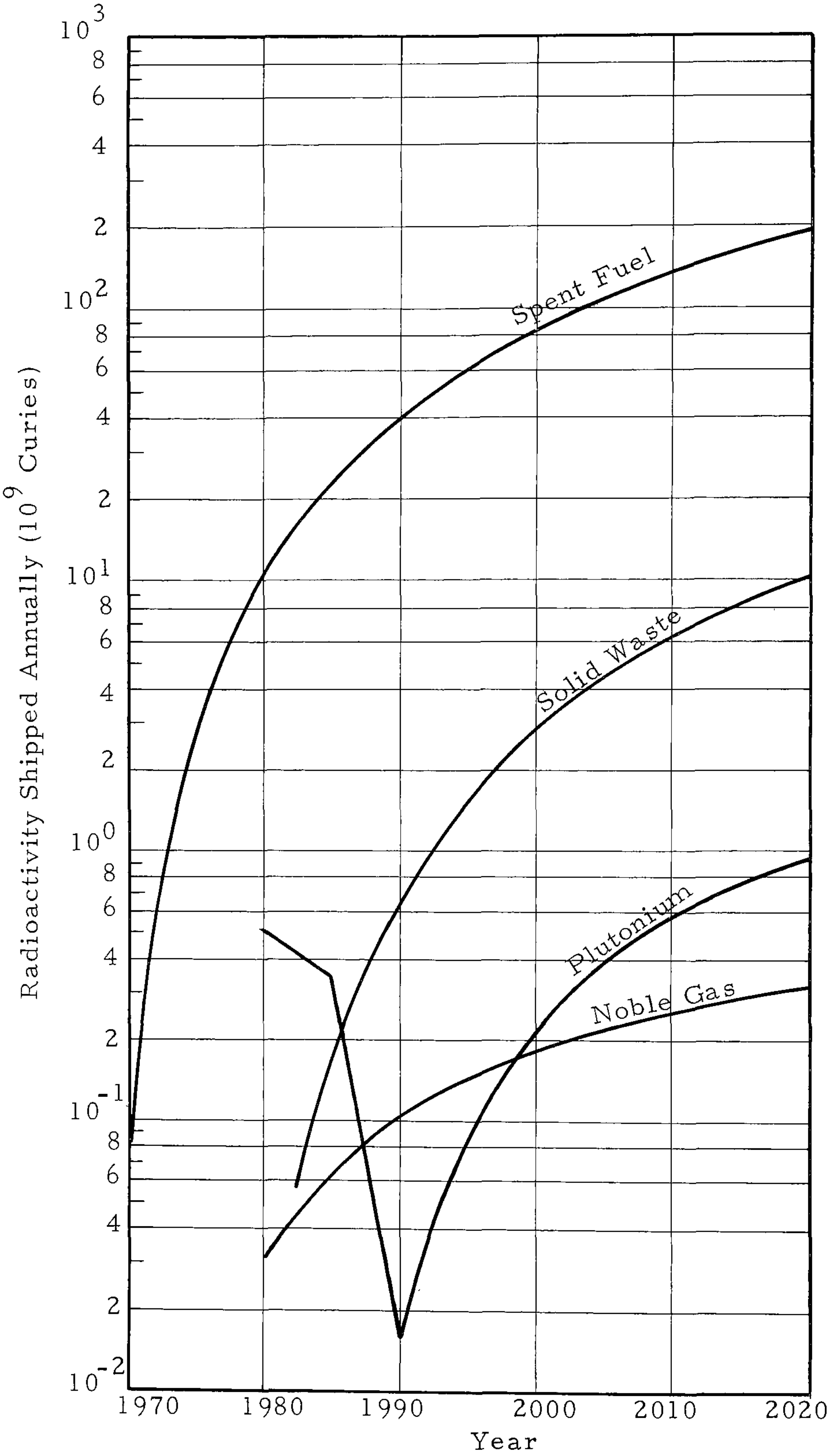


FIGURE 19: COMPARISON OF PROJECTIONS
OF ANNUAL RADIATION SHIPPED

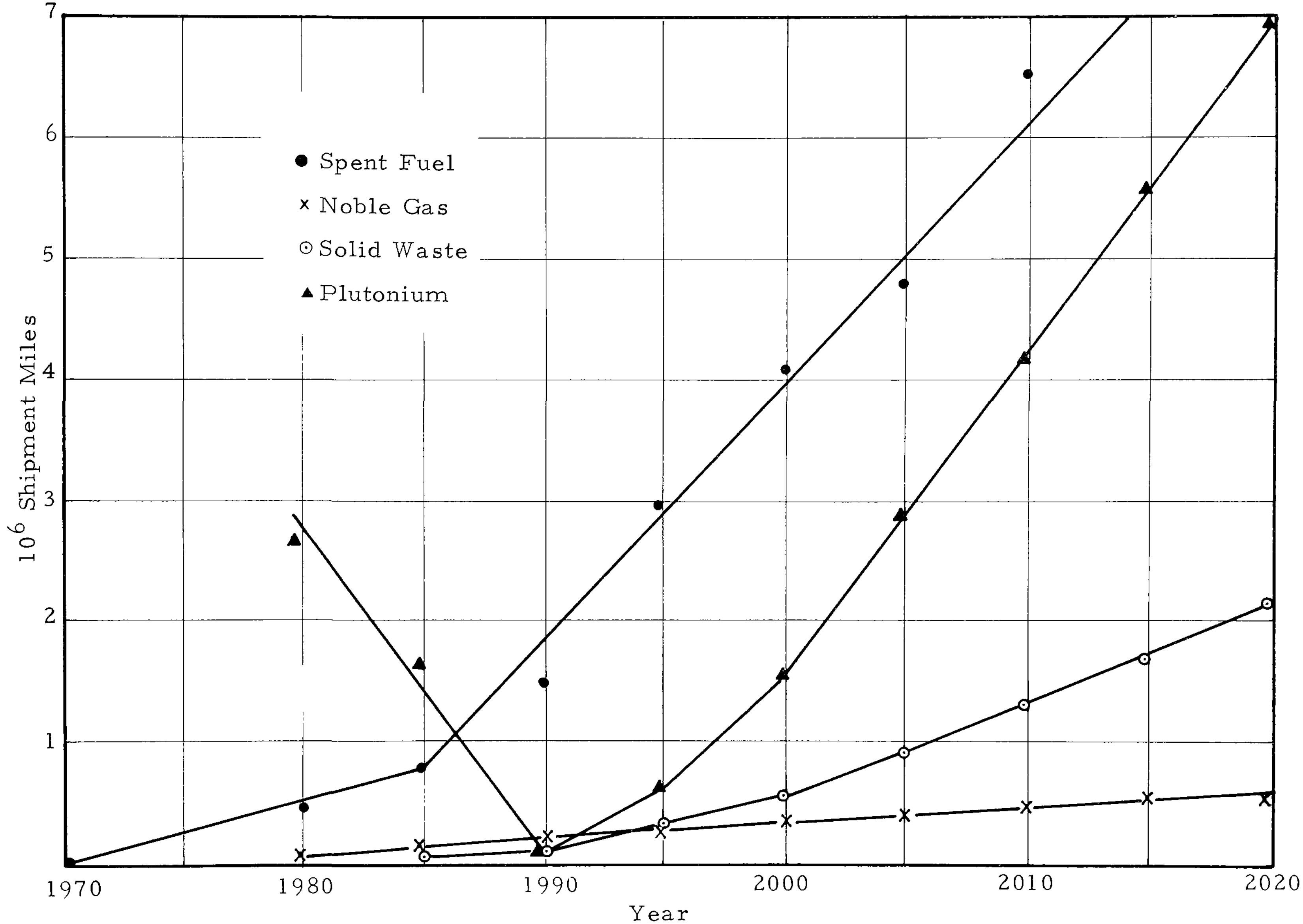


FIGURE 20: PROJECTED VARIATION OF NUMBER OF SHIPMENT-MILES IN TIME

SECTION VI

METHODOLOGY FOR ACCIDENT HAZARD ANALYSIS

Release of radioactivity is a hazard associated with the transportation of radioactive materials. It may occur routinely or accidentally. Evaluation of the accidental hazard depends on the probability of the occurrence of an accident severe enough to cause release and on the evaluation of the consequences of the release to the environment in the area of the accident.

The hazard of transportation accidents involving a cargo of a particular radioactive material may be calculated from the following quantities:

1. Number of curies of radiation carried in the shipment.

2. Probability of the shipment encountering an accident.

3. Probability that the accident results in a release of radioactivity or radioactive material.

4. Fraction of the cargo that is actually released.

5. Dose absorbed by a single person from the released part of the cargo.

6. Population distribution.

7. Health response to the absorbed dose.

RADIATION SOURCES ASSOCIATED WITH TRANSPORTATION ACCIDENTS

The number of curies Q carried in all the shipments of a particular material in a particular year by a particular transport mode is calculated from the product

$$Q_{\ell jm} = q_\ell S_{\ell j} b_m$$

where

q = the number of curies per shipment

S = the number of shipments

b = the fraction of shipments attributed to a transport mode

ℓ = the index distinguishing radioactive cargoes

j = the index distinguishing the year of shipment

m = the index distinguishing transport modes

These data are listed in Tables 15, 17, 19, and 21 for spent fuel, recycled plutonium, high level radioactive solidified wastes, and noble gases. Referring to Figure 1, these data for Q represent the intersection of the transportation and nuclear power generating industries.

PROBABILITY OF ACCIDENTS

The fraction P(A|S) giving the number of accidents that can be expected from a given number of shipments in given transport modes is calculated from the product

$$P(A|S)_{\ell jkms} = d_{\ell jk} a_{ms}$$

where

d = the distance traveled by the shipment

a = the accident probability per unit distance

k = the index distinguishing intervals of the transport route link that are described by different values of uniform population density

s = the index distinguishing accident severities.

Data for the shipping distances as functions of cargo and time are given in Table 22. Accident probability data will be discussed below.

Several government agencies continually accumulate statistics on accidents occurring in the major transportation systems in the United States. These accident statistics are expressed in terms of units which are products of the transportation units and unit distance of travel, such as ton-miles or shipment-miles. The accident statistics are observed fractions of all shipments that result in accidents. These fractions are interpreted as the probabilities that accidents occur.

In a recent AEC report (Reference 8), the recent accident statistics were conveniently classified by transport mode and by accident severity. The severity grades of minor, moderate, severe, extra severe, and extreme were obtained from various combinations of the relative velocities of colliding vehicles and the duration of fires. In the present study, the minor accidents are called light, the moderate accidents are called medium, and the three severe categories are lumped together and called severe. Consequently, the severe accident probabilities in this study are the sums of probabilities for severe, extra severe, and extreme conditions given in the AEC report. The resultant modal and severity analysis of accident probabilities are given in Table 24.

PROBABILITY (FAULT TREE SIMULATION MODEL) OF CONTAINER RUPTURE IN ACCIDENTS

The fraction of accidents resulting in ruptures of the shipping containers is determined from fault tree analysis of the shipping containers. This fraction is called the release probability and is denoted by $r_{\ell ms}$. A discussion of the fault tree methodology follows.

All accidents are considered to involve certain physical conditions, namely:

1. Impact
2. Puncture
3. Fire
4. Vibration

These conditions occur with different probabilities according to accident severity. Table 25 gives the modal and severity analysis of these physical conditions.

Inhibit conditions must be met for these probable physical conditions to cause failure of the shipping containers. That is, the forces generated by impact, puncture, or explosion must be of sufficiently large magnitude to break the container. Other possible modes of failure include human error, manifest in improper closure, and equipment reliability, such as valve and seal defects.

TABLE 24: ACCIDENT PROBABILITIES

Accident Severity	Collision Velocity (mi/hr)	Duration of Fire (hr)	Accident Probability (accident/shipment/10^6 mi) Transport Mode		
			Truck	Rail	Barge
Light	0-30	<1/2			
	0-50	0			
			1.3	0.73	1.7
Medium	0-30	1/2-1			
	30-70	<1/2			
	50-70	0			
			0.3	0.079	0.044
Severe	0 to > 70	> 1			
	30 to > 70	1/2-1			
	> 70	0 to > 1			
			0.008	0.0015	0.0016

TABLE 25: PROBABILITY OF PHYSICAL CONDITIONS IN ACCIDENTS

Physical Condition by Accident Severity	Probabilities by Transport Mode		
	Truck	Rail	Barge
Light Severity Accidents			
Impact Occurs[a]	0.221	0.123	0.9
Puncture Force Occurs[b]	0.008	0.410	-
External Heat Source Nearby[c]	0.014	0.0128	0.0605
Vibration Occurs[d]	0.5	0.5	0.05
Medium Severity Accidents			
Impact Occurs	0.423	0.067	0.08
Puncture Force Occurs	0.066	0.224	-
External Heat Source Nearby	0.0016	0.002	0.0099
Vibration Occurs	0.5	0.5	0.05
Severe Accidents			
Impact Occurs	0.159	0.02	0.02
Puncture Force Occurs	0.022	0.066	
External Heat Source Nearby	0.0002	0.0002	0.0007
Vibration Occurs	0.5	0.5	0.05

[a] Impact probabilities for trucks and railroads are derived from data in Appendix A, Reference 8, for collisions light: 0-32 mph; medium: 32-52 mph; severe: >52 mph.

[b] Puncture probabilities are interpreted as the probability of overturns and derailments given in Appendix A, Reference 8.

[c] External heat source nearby is interpreted as the probability of fires in accidents given in Appendix A, Reference 8.

[d] Vibration probabilities are assigned values used in Reference 15.

The events and conditions which singularly or in combination, can cause a rupture are the inputs to the fault tree. If two or more events are required, they are input to an AND gate. If only one of several events is required, it is input to an OR gate. Conditions that establish a level of force, temperature, etc. required for an event to cause a failure are called inhibit gates. They provide a logical connection between the event and its magnitude.

Each shipping container presents several barriers to the rupturing forces of an accident. For example, from inside to outside spent fuel is contained in a series of envelopes: cladding, cavity walls, shielding material, and outer walls of casket. Simplified schematic diagrams for the types of containers considered in this study are shown in Figures 21, 23, 25, and 27. These containers are here categorized by the radioactive materials they hold.

The calculation of the probability that radioactive material will leak from a container rupture in an accident must take into account the likelihood that each barrier will be breached and also the likelihood that physical events such as those listed above will occur. Such a calculation is made possible by fault tree analysis.

In Figures 22, 24, 26, and 28, fault tree diagrams are presented for each type of container. Probability values for the different elementary events for different severities of accidents for each material container are presented in Tables 26 through 37. The events are keyed by number between the fault tree diagrams and the probability tables.

The release probability $r_{\ell ms}$ is calculated for each container ℓ, transport mode m, and accident severity s by means of a computer program called CONREP (Reference 16) in conjunction with a subroutine called LOGIC, which describes the fault tree. Results of the calculation are given in Table 38. As noted in Tables 26, 29, 32, and 35, the physical inhibit gate probabilities (e. g., probability that impact is great enough to break the container, temperature is great enough, etc.) are assumed to be zero for accident conditions of light severity. Examination of the fault trees in Figures 22, 24, 26, and 28 shows no container failure under these assumptions. Consequently, the study of risks by accident severity may as well be limited to the medium and severe ranges of severity.

The CONREP code evaluates the fault tree probability by making a Monte Carlo selection of chains of elementary events by which the container can fail. The most significant fault tree paths for severe accidents are listed in Table 39.

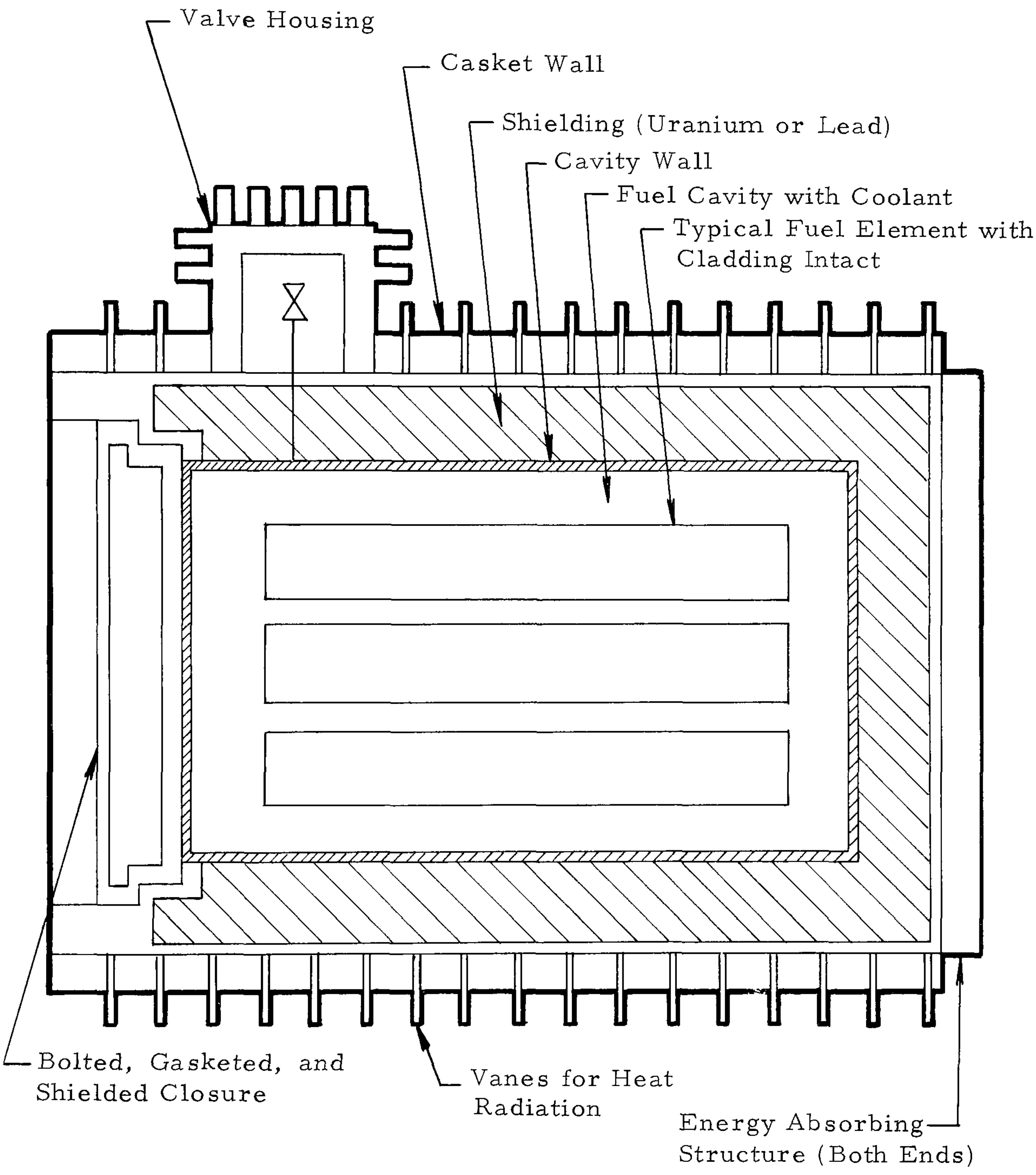


FIGURE 21: SIMPLIFIED SCHEMATIC DIAGRAM OF SPENT FUEL SHIPPING CONTAINER

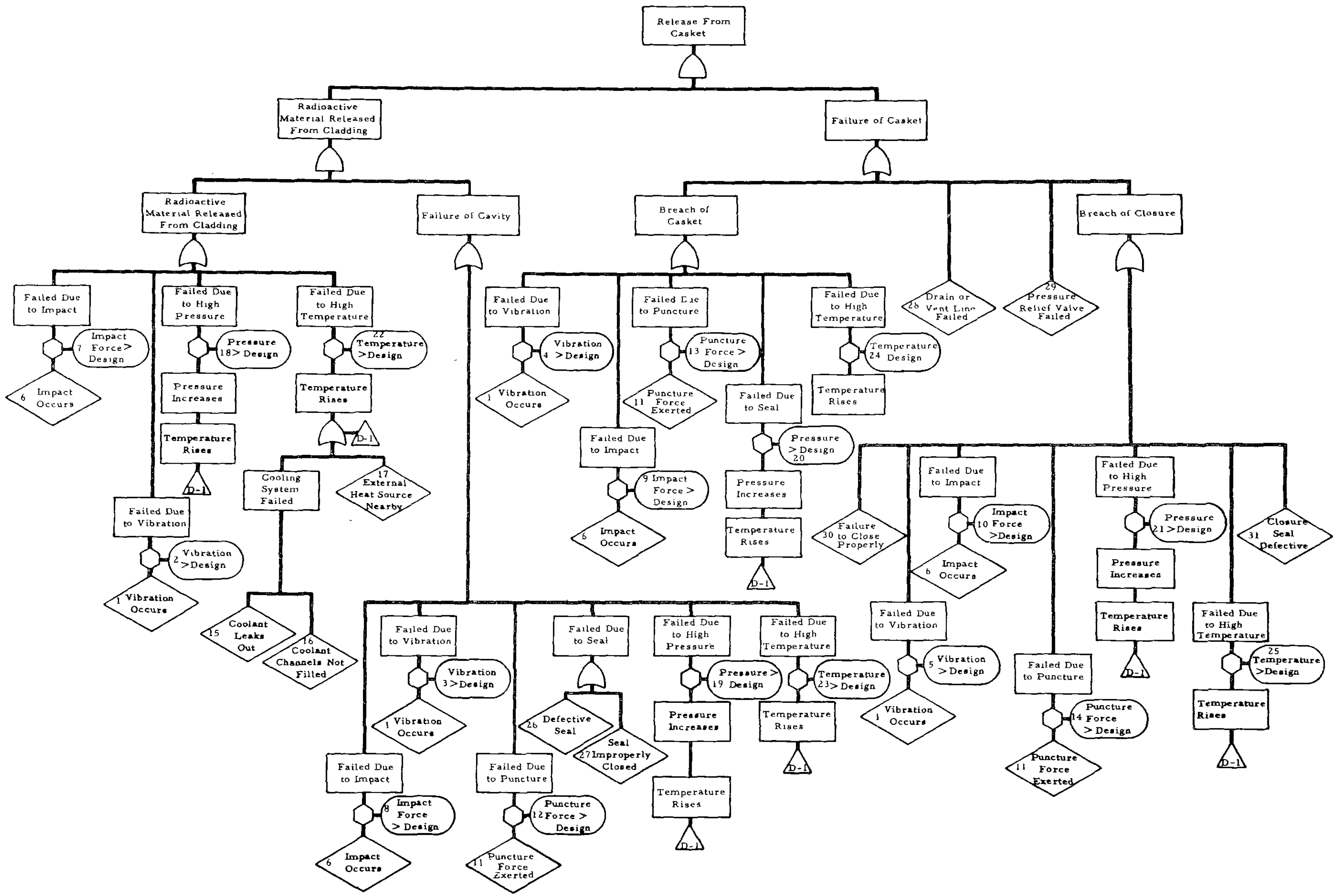


FIGURE 22: FAULT TREE DIAGRAM FOR SPENT FUEL SHIPPING CONTAINER

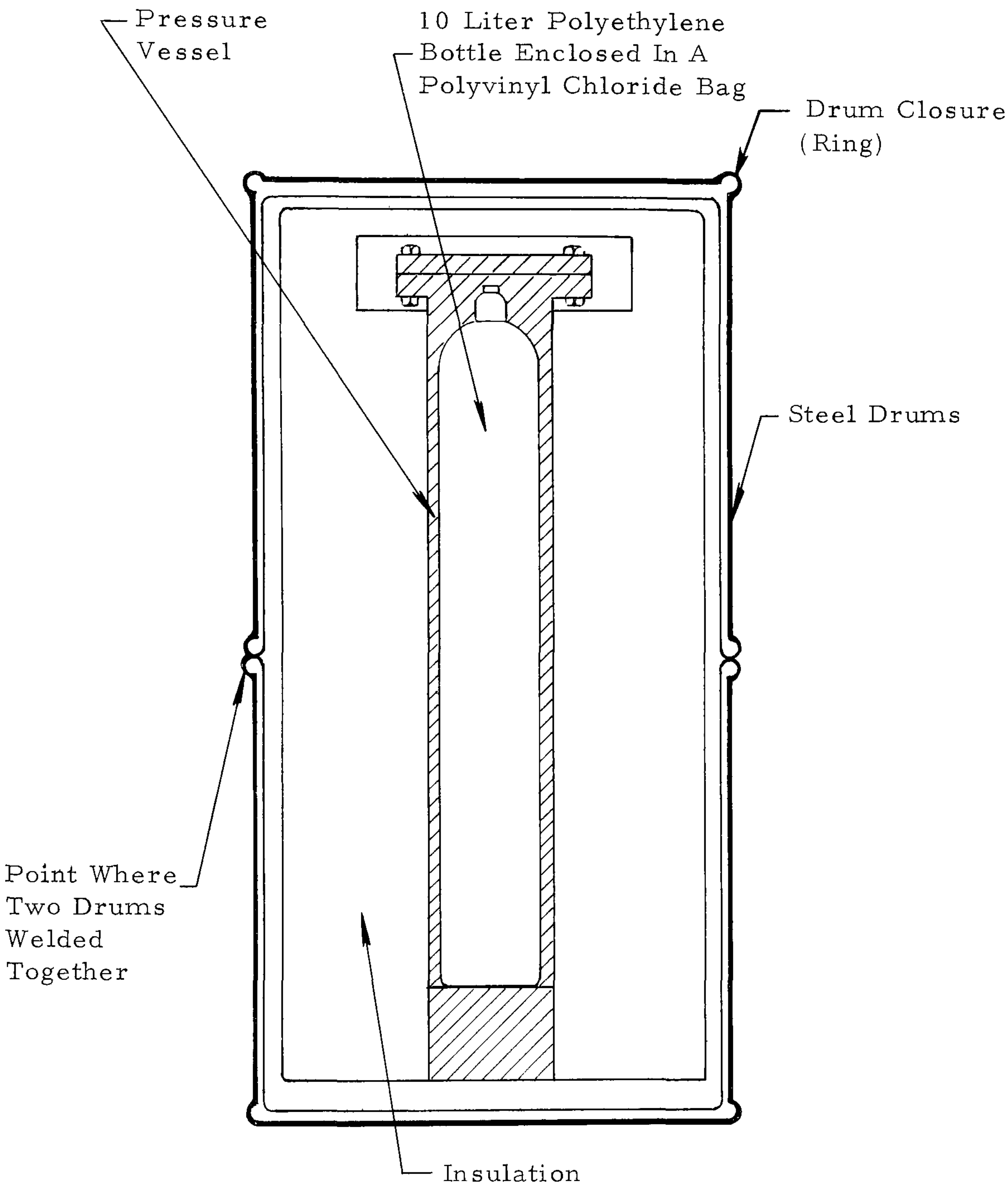


FIGURE 23: SIMPLIFIED SCHEMATIC DIAGRAM OF PLUTONIUM SHIPPING CONTAINER

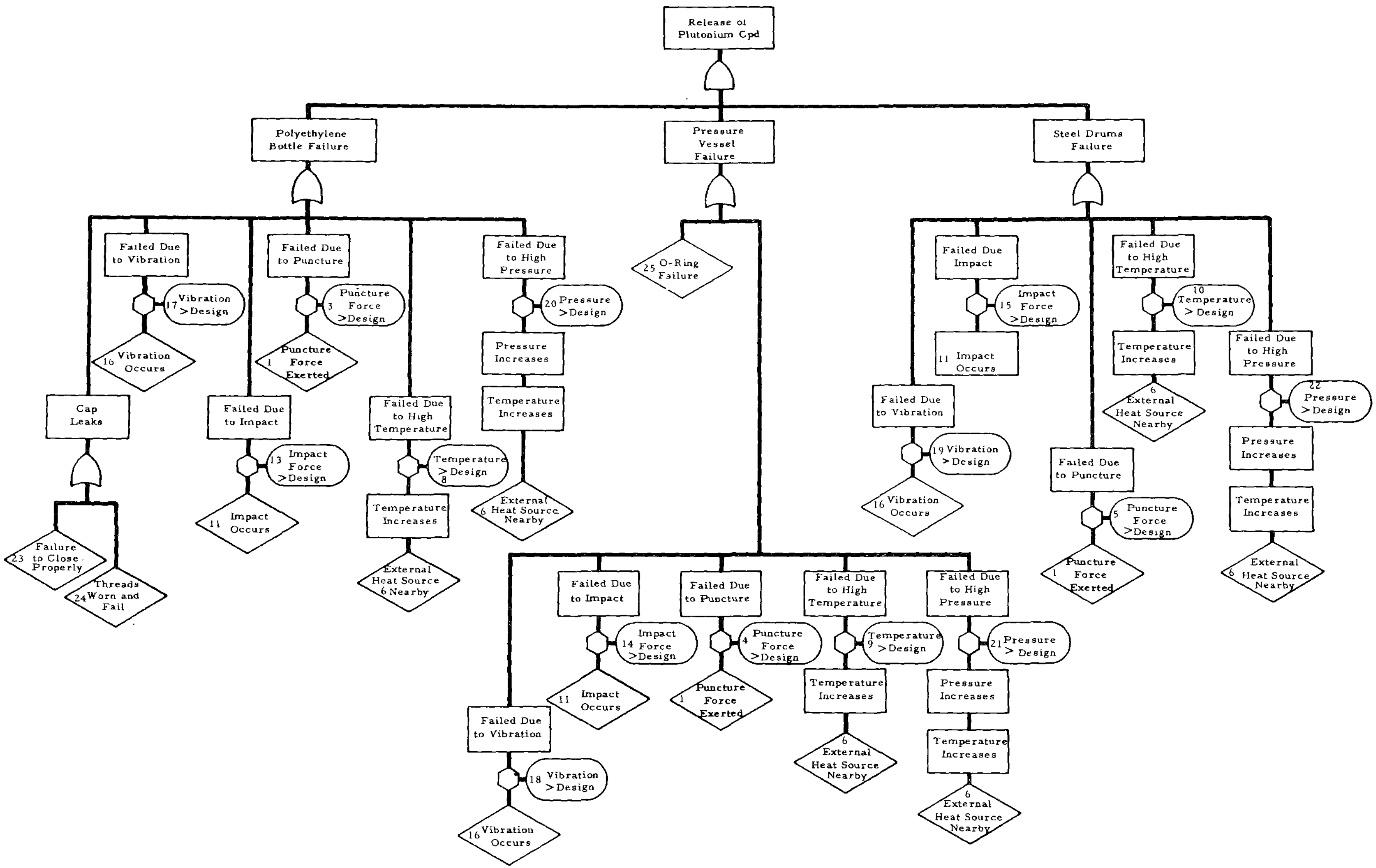


FIGURE 24: FAULT TREE DIAGRAM FOR PLUTONIUM SHIPPING CONTAINER

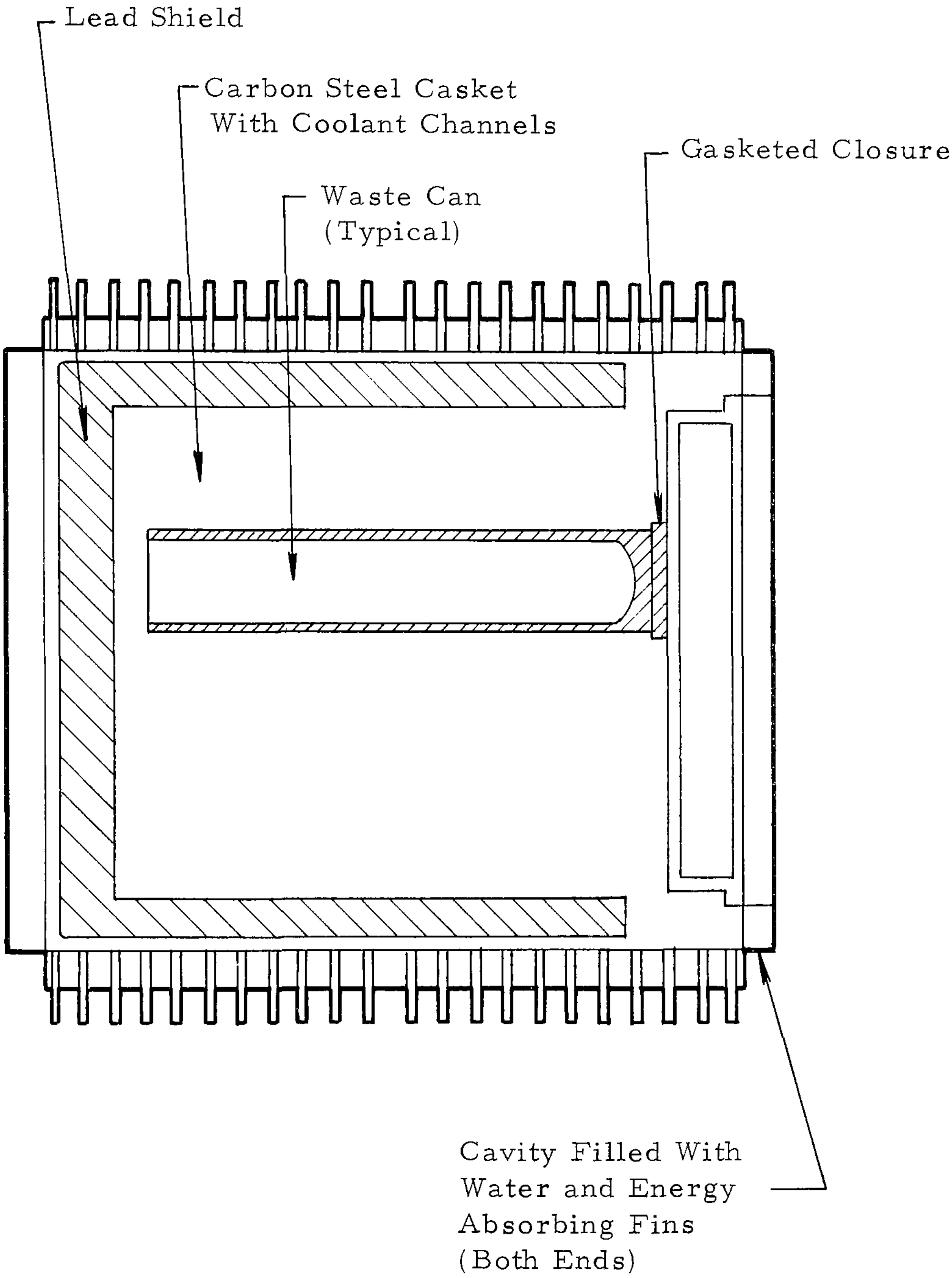


FIGURE 25: SIMPLIFIED SCHEMATIC DIAGRAM OF SHIPPING CONTAINER FOR HIGH LEVEL RADIOACTIVITY SOLIDIFIED WASTE

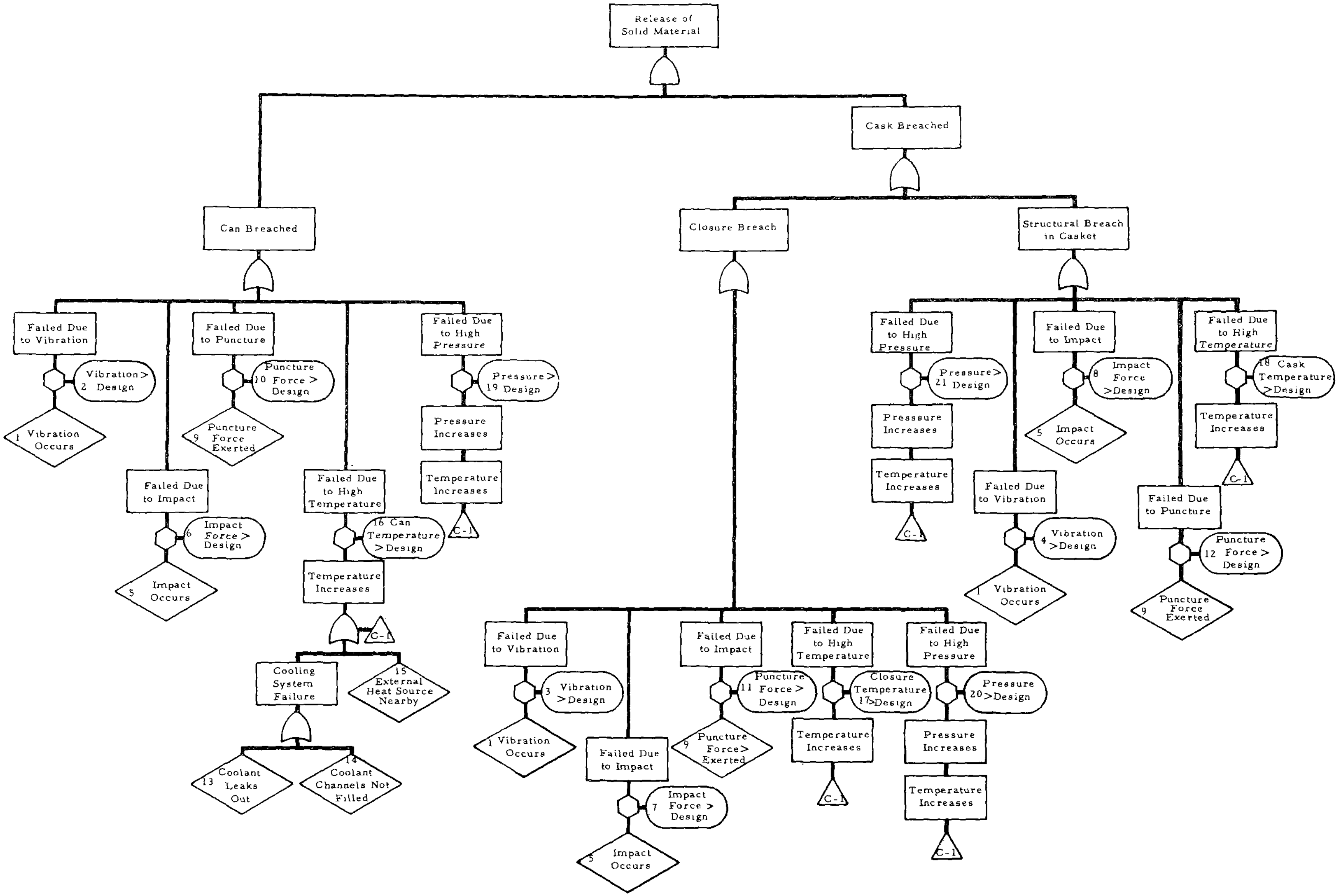


FIGURE 26: FAULT TREE DIAGRAM FOR SHIPPING CONTAINER FOR HIGH LEVEL RADIOACTIVITY SOLIDIFIED WASTE

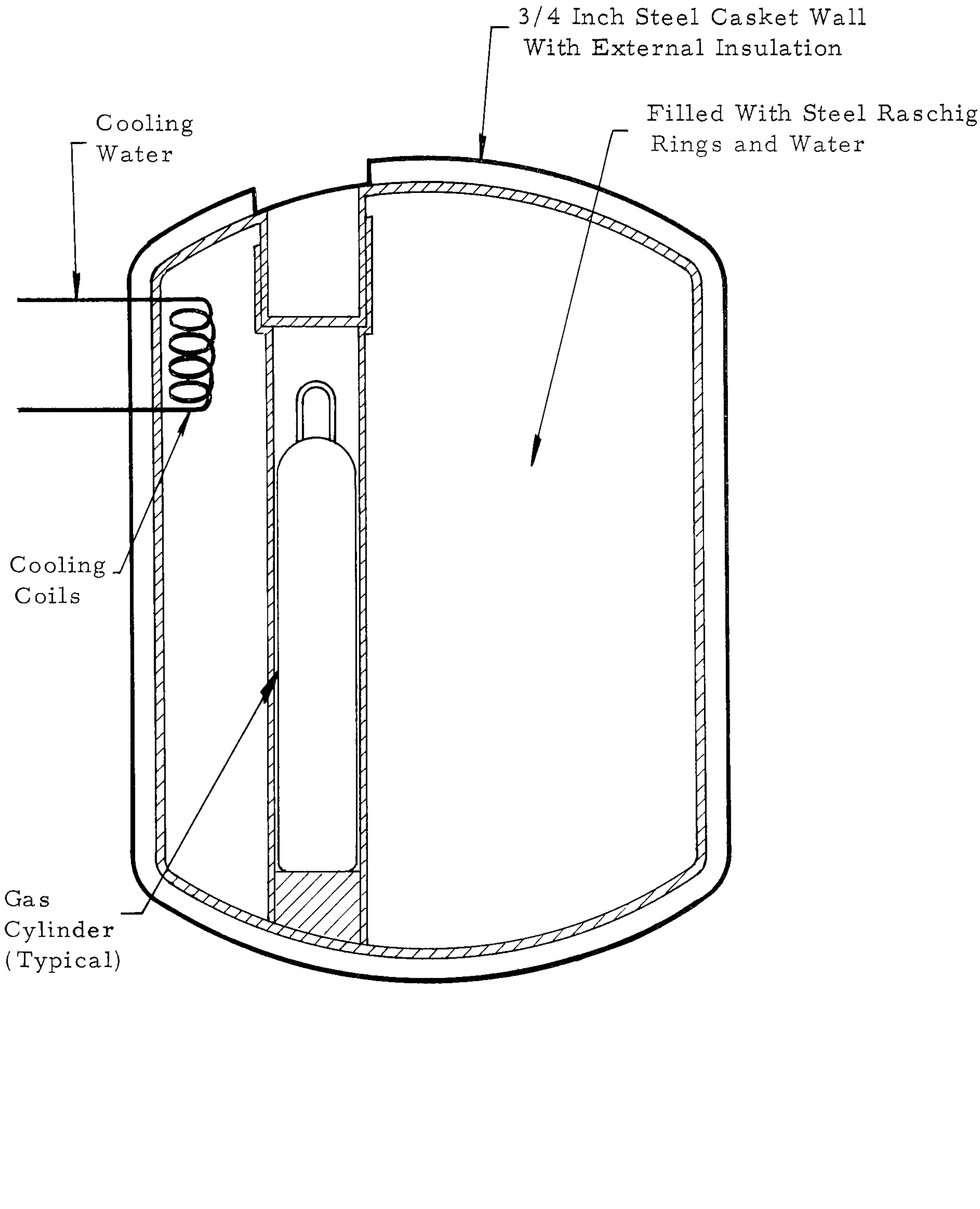


FIGURE 27: SIMPLIFIED SCHEMATIC DIAGRAM OF FISSION PRODUCT (NOBLE) GAS SHIPPING CONTAINER

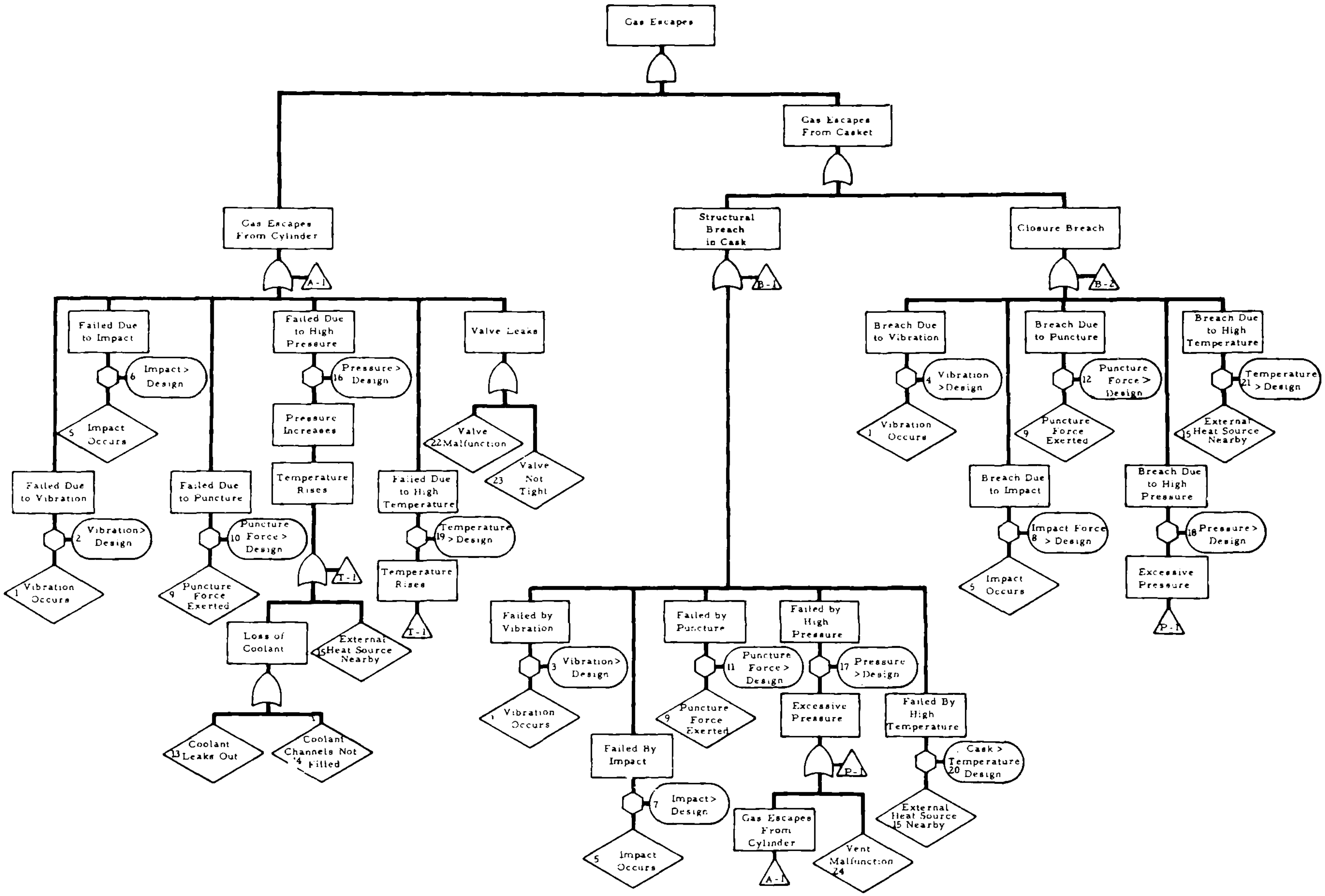


FIGURE 28: FAULT TREE DIAGRAM FOR FISSION PRODUCT (NOBLE) GAS SHIPPING CONTAINER

TABLE 26: FAULT TREE PROBABILITIES FOR SPENT FUEL SHIPPING CONTAINER UNDER ACCIDENT CONDITIONS OF LIGHT SEVERITY[a]

ID Number	Input Event Name	Transport Mode		
		Truck	Rail	Barge
1	Vibration Occurs	0.5	0.5	0.05
2	Vibration > Cladding Design	0	0	0
3	Vibration > Cavity Design	0	0	0
4	Vibration > Casket Design	0	0	0
5	Vibration > Closure Design	0	0	0
6	Impact Occurs	0.221	0.123	0.90
7	Impact > Cladding Design	0	0	0
8	Impact > Cavity Design	0	0	0
9	Impact > Casket Design	0	0	0
10	Impact > Closure Design	0	0	0
11	Puncture Force Occurs	0.008	0.410	--
12	Puncture Force > Cavity Design	0	0	0
13	Puncture Force > Casket Design	0	0	0
14	Puncture Force > Closure Design	0	0	0
15	Coolant Leaks Out[b]	0.5 E-6	0.5 E-6	0.5 E-6
16	Coolant Channels Not Filled	0.3 E-4	0.3 E-4	0.3 E-4
17	External Heat Source Nearby	0.014	0.0128	0.0605
18	Pressure > Cladding Design	0	0	0
19	Pressure > Cavity Design	0	0	0
20	Pressure > Casket Design	0	0	0
21	Pressure > Closure Design	0	0	0
22	Temperature > Cladding Design	0	0	0
23	Temperature > Cavity Design	0	0	0
24	Temperature > Casket Design	0	0	0
25	Temperature > Closure Design	0	0	0
26	Defective Seal	0.5 E-3	0.5 E-3	0.5 E-3
27	Seal Improperly Closed	0.5 E-3	0.5 E-3	0.5 E-3
28	Drain or Vent Line Failure	0.1 E-2	0.1 E-2	0.1 E-2
29	Pressure Relief Valve Failure	0.1 E-2	0.1 E-2	0.1 E-2
30	Casket Closure Fails to Close	0.5 E-3	0.5 E-3	0.5 E-3
31	Casket Closure Seal Defective	0.5 E-3	0.5 E-3	0.5 E-3

[a] For light severity accidents, all inhibit gate probabilities for physical conditions such as impact, puncture, pressure, temperature, and vibration are arbitrarily assigned values of zero.

[b] For light severity accidents, all probabilities related to human error or equipment failure under nonaccident conditions are arbitrarily assigned the same values as for severe accidents.

TABLE 27: FAULT TREE PROBABILITIES FOR SPENT FUEL SHIPPING CONTAINER UNDER ACCIDENT CONDITIONS OF MEDIUM SEVERITY[a]

ID Number	Input Event Name	Transport Mode		
		Truck	Rail	Barge
1	Vibration Occurs	0.5	0.5	0.05
2	Vibration > Cladding Design	0.3 E-7	0.4 E-7	0.1 E-7
3	Vibration > Cavity Design	0.15 E-6	0.2 E-6	0.5 E-7
4	Vibration > Casket Design	0.15 E-6	0.2 E-6	0.5 E-7
5	Vibration > Closure Design	0.75 E-7	0.1 E-6	0.25 E-7
6	Impact Occurs	0.423	0.067	0.08
7	Impact > Cladding Design	0.2 E-3	0.2 E-3	0.2 E-3
8	Impact > Cavity Design	0.1 E-3	0.1 E-3	0.1 E-3
9	Impact > Casket Design	0.1 E-2	0.1 E-2	0.1 E-2
10	Impact > Closure Design	0.1 E-5	0.1 E-5	0.1 E-5
11	Puncture Force Occurs	0.066	0.224	--
12	Puncture Force > Cavity Design	0.1 E-3	0.1 E-3	0.1 E-3
13	Puncture Force > Casket Design	0.1 E-3	0.1 E-3	0.1 E-3
14	Puncture Force > Closure Design	0.1 E-3	0.1 E-3	0.1 E-3
15	Coolant Leaks Out[b]	0.5 E-6	0.5 E-6	0.5 E-6
16	Coolant Channels Not Filled	0.3 E-4	0.3 E-4	0.3 E-4
17	External Heat Source Nearby	0.0016	0.002	0.0099
18	Pressure > Cladding Design	0.3 E-3	0.5 E-2	0.01
19	Pressure > Cavity Design	0.3 E-3	0.5 E-2	0.01
20	Pressure > Casket Design	0.3 E-3	0.5 E-2	0.01
21	Pressure > Closure Design	0.3 E-3	0.5 E-2	0.01
22	Temperature > Cladding Design	0.1 E-5	0.1 E-5	0.1 E-5
23	Temperature > Cavity Design	0.1 E-5	0.1 E-5	0.1 E-5
24	Temperature > Casket Design	0.1 E-4	0.1 E-4	0.1 E-4
25	Temperature > Closure Design	0.1 E-4	0.1 E-4	0.1 E-4
26	Defective Seal	0.5 E-3	0.5 E-3	0.5 E-3
27	Seal Improperly Closed	0.5 E-3	0.5 E-3	0.5 E-3
28	Drain or Vent Line Failure	0.1 E-2	0.1 E-2	0.1 E-2
29	Pressure Relief Valve Failure	0.1 E-2	0.1 E-2	0.1 E-2
30	Casket Closure Fails to Close	0.5 E-3	0.5 E-3	0.5 E-3
31	Casket Closure Seal Defective	0.5 E-3	0.5 E-3	0.5 E-3

[a] For medium severity accidents, all inhibit gate probabilities for physical conditions such as impact, puncture, pressure, temperature, and vibration are arbitrarily assigned values equal to 10 percent of the corresponding values for severe accidents.

[b] See footnote b, Table 26. The same assignment is made for medium severity accidents.

TABLE 28: FAULT TREE PROBABILITIES FOR SPENT FUEL SHIPPING CONTAINER UNDER SEVERE ACCIDENT CONDITIONS*

ID Number	Input Event Name	Transport Mode		
		Truck	Rail	Barge
1	Vibration Occurs	0.5	0.5	0.05
2	Vibration > Cladding Design	0.3 E-6	0.4 E-6	0.1 E-6
3	Vibration > Cavity Design	0.15 E-5	0.2 E-5	0.5 E-6
4	Vibration > Casket Design	0.15 E-5	0.2 E-5	0.5 E-6
5	Vibration > Closure Design	0.75 E-6	0.1 E-5	0.25 E-6
6	Impact Occurs	0.159	0.020	0.02
7	Impact > Cladding Design	0.2 E-2	0.2 E-2	0.2 E-2
8	Impact > Cavity Design	0.1 E-2	0.1 E-2	0.1 E-2
9	Impact > Casket Design	0.1 E-1	0.1 E-1	0.1 E-1
10	Impact > Closure Design	0.1 E-4	0.1 E-4	0.1 E-4
11	Puncture Force Occurs	0.022	0.066	--
12	Puncture Force > Cavity Design	0.1 E-2	0.1 E-2	0.1 E-2
13	Puncture Force > Casket Design	0.1 E-2	0.1 E-2	0.1 E-2
14	Puncture Force > Closure Design	0.1 E-2	0.1 E-2	0.1 E-2
15	Coolant Leaks Out	0.5 E-6	0.5 E-6	0.5 E-6
16	Coolant Channels Not Filled	0.3 E-4	0.3 E-4	0.3 E-4
17	External Heat Source Nearby	0.2 E-3	0.2 E-3	0.7 E-3
18	Pressure > Cladding Design	0.3 E-2	0.05	0.1
19	Pressure > Cavity Design	0.3 E-2	0.05	0.1
20	Pressure > Casket Design	0.3 E-2	0.05	0.1
21	Pressure > Closure Design	0.3 E-2	0.05	0.1
22	Temperature > Cladding Design	0.1 E-4	0.1 E-4	0.1 E-4
23	Temperature > Cavity Design	0.1 E-4	0.1 E-4	0.1 E-4
24	Temperature > Casket Design	0.1 E-3	0.1 E-3	0.1 E-3
25	Temperature > Closure Design	0.1 E-3	0.1 E-3	0.1 E-3
26	Defective Seal	0.5 E-3	0.5 E-3	0.5 E-3
27	Seal Improperly Closed	0.5 E-3	0.5 E-3	0.5 E-3
28	Drain or Vent Line Failure	0.1 E-2	0.1 E-2	0.1 E-2
29	Pressure Relief Valve Failure	0.1 E-2	0.1 E-2	0.1 E-2
30	Casket Closure Fails to Close	0.5 E-3	0.5 E-3	0.5 E-3
31	Casket Closure Seal Defective	0.5 E-3	0.5 E-3	0.5 E-3

* For severe accidents, all inhibit gate probabilities for physical conditions such as impact, puncture, pressure, temperature, and vibration and all probabilities related to human error or equipment failure under nonaccident conditions are assigned values used for similar events in the container analyses of Reference 15.

TABLE 29: FAULT TREE PROBABILITIES FOR PLUTONIUM SHIPPING CONTAINER UNDER ACCIDENT CONDITIONS OF LIGHT SEVERITY[a]

ID Number	Input Event Name	Transport Mode		
		Truck	Rail	Barge
1	Puncture Force Occurs	0.008	0.410	--
2	Puncture Force > Bag Design	1.0	1.0	1.0
3	Puncture Force > Bottle Design	0	0	0
4	Puncture Force > Pressure Vessel Design	0	0	0
5	Puncture Force > Drum Design	0	0	0
6	External Heat Source Nearby	0.014	0.0128	0.0605
7	Temperature > Bag Design	1.0	1.0	1.0
8	Temperature > Bottle Design	0	0	0
9	Temperature > Pressure Vessel Design	0	0	0
10	Temperature > Drum Design	0	0	0
11	Impact Occurs	0.221	0.123	0.90
12	Impact > Bag Design	1.0	1.0	1.0
13	Impact > Bottle Design	0	0	0
14	Impact > Pressure Vessel Design	0	0	0
15	Impact > Drum Design	0	0	0
16	Vibration Occurs	0.5	0.5	0.05
17	Vibration > Bottle Design	0	0	0
18	Vibration > Pressure Vessel Design	0	0	0
19	Vibration > Drum Design	0	0	0
20	Pressure > Bottle Design	0	0	0
21	Pressure > Pressure Vessel Design	0	0	0
22	Pressure > Drum Design	0	0	0
23	Bottle Cap Fails to Close Properly[b]	0.5 E-3	0.5 E-3	0.5 E-3
24	Cap Threads Worn and Fail	0.5 E-3	0.5 E-3	0.5 E-3
25	Pressure Vessel O-Ring Fails	0.5 E-3	0.5 E-3	0.5 E-3

[a] See footnote a, Table 26. Exception for polyvinylchloride bag, which is assumed to be easily ruptured.

[b] See footnote b, Table 26.

TABLE 30: FAULT TREE PROBABILITIES FOR PLUTONIUM SHIPPING CONTAINER UNDER ACCIDENT CONDITIONS OF MEDIUM SEVERITY[a]

ID Number	Input Event Name	Transport Mode		
		Truck	Rail	Barge
1	Puncture Force Occurs	0.066	0.224	--
2	Puncture Force > Bag Design	1.0	1.0	1.0
3	Puncture Force > Bottle Design	0.3 E-4	0.3 E-4	0.3 E-4
4	Puncture Force > Pressure Vessel Design	0.5 E-4	0.5 E-4	0.5 E-4
5	Puncture Force > Drum Design	0.1 E-3	0.1 E-3	0.1 E-3
6	External Heat Source Nearby	0.0016	0.002	0.0099
7	Temperature > Bag Design	1.0	1.0	1.0
8	Temperature > Bottle Design	0.1 E-3	0.1 E-3	0.1 E-3
9	Temperature > Pressure Vessel Design	0.1 E-5	0.1 E-5	0.1 E-5
10	Temperature > Drum Design	0.1 E-4	0.1 E-4	0.1 E-4
11	Impact Occurs	0.423	0.067	0.08
12	Impact > Bag Design	1.0	1.0	1.0
13	Impact > Bottle Design	0.5 E-3	0.1 E-3	0.5 E-3
14	Impact > Pressure Vessel Design	0.1 E-2	0.1 E-2	0.1 E-2
15	Impact > Drum Design	0.03	0.03	0.03
16	Vibration Occurs	0.5	0.5	0.05
17	Vibration > Bottle Design	0.3 E-7	0.4 E-7	0.1 E-7
18	Vibration > Pressure Vessel Design	0.3 E-7	0.4 E-7	0.1 E-7
19	Vibration > Drum Design	0.15 E-6	0.2 E-6	0.5 E-7
20	Pressure > Bottle Design	0.3 E-3	0.5 E-2	0.01
21	Pressure > Pressure Vessel Design	0.3 E-3	0.5 E-2	0.01
22	Pressure > Drum Design	0.3 E-3	0.5 E-2	0.01
23	Bottle Cap Fails to Close Properly[b]	0.5 E-3	0.5 E-3	0.5 E-3
24	Cap Threads Worn and Fail	0.5 E-3	0.5 E-3	0.5 E-3
25	Pressure Vessel O-Ring Fails	0.5 E-3	0.5 E-3	0.5 E-3

[a] See footnote a, Table 27. Exception for polyvinylchloride bag, which is assumed to be easily ruptured.

[b] See footnote b, Table 27.

TABLE 31: FAULT TREE PROBABILITIES FOR PLUTONIUM SHIPPING CONTAINER UNDER SEVERE ACCIDENT CONDITIONS*

ID Number	Input Event Name	Transport Mode		
		Truck	Rail	Barge
1	Puncture Force Occurs	0.022	0.066	--
2	Puncture Force > Bag Design	1.0	1.0	1.0
3	Puncture Force > Bottle Design	0.3 E-3	0.3 E-3	0.3 E-3
4	Puncture Force > Pressure Vessel Design	0.5 E-3	0.5 E-3	0.5 E-3
5	Puncture Force > Drum Design	0.1 E-2	0.1 E-2	0.1 E-2
6	External Heat Source Nearby	0.2 E-3	0.2 E-3	0.7 E-3
7	Temperature > Bag Design	1.0	1.0	1.0
8	Temperature > Bottle Design	0.1 E-2	0.1 E-2	0.1 E-2
9	Temperature > Pressure Vessel Design	0.1 E-4	0.1 E-4	0.1 E-4
10	Temperature > Drum Design	0.1 E-3	0.1 E-3	0.1 E-3
11	Impact Occurs	0.159	0.020	0.02
12	Impact > Bag Design	1.0	1.0	1.0
13	Impact > Bottle Design	0.5 E-2	0.1 E-2	0.5 E-2
14	Impact > Pressure Vessel Design	0.1 E-1	0.1 E-1	0.1 E-1
15	Impact > Drum Design	0.3	0.3	0.3
16	Vibration Occurs	0.5	0.5	0.05
17	Vibration > Bottle Design	0.3 E-6	0.4 E-6	0.1 E-6
18	Vibration > Pressure Vessel Design	0.3 E-6	0.4 E-6	0.1 E-6
19	Vibration > Drum Design	0.15 E-5	0.2 E-5	0.5 E-6
20	Pressure > Bottle Design	0.3 E-2	0.05	0.1
21	Pressure > Pressure Vessel Design	0.3 E-2	0.05	0.1
22	Pressure > Drum Design	0.3 E-2	0.05	0.1
23	Bottle Cap Fails to Close Properly	0.5 E-3	0.5 E-3	0.5 E-3
24	Cap Threads Worn and Fail	0.5 E-3	0.5 E-3	0.5 E-3
25	Pressure Vessel O-Ring Fails	0.5 E-3	0.5 E-3	0.5 E-3

* See footnote, Table 28.

TABLE 32: FAULT TREE PROBABILITIES FOR HIGH LEVEL RADIOACTIVITY SOLIDIFIED WASTE SHIPPING CONTAINER UNDER ACCIDENT CONDITIONS OF LIGHT SEVERITY[a]

ID Number	Input Event Name	Transport Mode		
		Truck	Rail	Barge
1	Vibration Occurs	0.5	0.5	0.05
2	Vibration > Can Design	0	0	0
3	Vibration > Closure Design	0	0	0
4	Vibration > Cask Design	0	0	0
5	Impact Occurs	0.221	0.123	0.90
6	Impact > Can Design	0	0	0
7	Impact > Closure Design	0	0	0
8	Impact > Cask Design	0	0	0
9	Puncture Force Occurs	0.008	0.410	--
10	Puncture Force > Can Design	0	0	0
11	Puncture Force > Closure Design	0	0	0
12	Puncture Force > Cask Design	0	0	0
13	Coolant Leaks Out[b]	0.5 E-6	0.5 E-6	0.5 E-6
14	Coolant Channels Not Filled	0.3 E-4	0.3 E-4	0.3 E-4
15	External Heat Source Nearby	0.014	0.0128	0.0605
16	Temperature > Can Design	0	0	0
17	Temperature > Closure Design	0	0	0
18	Temperature > Cask Design	0	0	0
19	Pressure > Can Design	0	0	0
20	Pressure > Closure Design	0	0	0
21	Pressure > Cask Design	0	0	0

[a] See footnote a, Table 26.

[b] See footnote b, Table 26.

TABLE 33: FAULT TREE PROBABILITIES FOR HIGH LEVEL RADIOACTIVITY SOLIDIFIED WASTE SHIPPING CONTAINER UNDER ACCIDENT CONDITIONS OF MEDIUM SEVERITY[a]

ID Number	Input Event Name	Transport Mode		
		Truck	Rail	Barge
1	Vibration Occurs	0.5	0.5	0.05
2	Vibration > Can Design	0.15 E-6	0.2 E-6	0.5 E-7
3	Vibration > Closure Design	0.75 E-7	0.1 E-6	0.25 E-7
4	Vibration > Cask Design	0.15 E-6	0.2 E-6	0.5 E-7
5	Impact Occurs	0.423	0.067	0.08
6	Impact > Can Design	0.1 E-5	0.1 E-5	0.1 E-5
7	Impact > Closure Design	0.1 E-5	0.1 E-5	0.1 E-5
8	Impact > Cask Design	0.1 E-2	0.1 E-2	0.1 E-2
9	Puncture Force Occurs	0.066	0.224	--
10	Puncture Force > Can Design	0.1 E-3	0.1 E-3	0.1 E-3
11	Puncture Force > Closure Design	0.1 E-3	0.1 E-3	0.1 E-3
12	Puncture Force > Cask Design	0.1 E-3	0.1 E-3	0.1 E-3
13	Coolant Leaks Out[b]	0.5 E-6	0.5 E-6	0.5 E-6
14	Coolant Channels Not Filled	0.3 E-4	0.3 E-4	0.3 E-4
15	External Heat Source Nearby	0.0016	0.002	0.0099
16	Temperature > Can Design	0.1 E-5	0.1 E-5	0.1 E-5
17	Temperature > Closure Design	0.1 E-4	0.1 E-4	0.1 E-4
18	Temperature > Cask Design	0.1 E-4	0.1 E-4	0.1 E-4
19	Pressure > Can Design	0.3 E-3	0.5 E-2	0.01
20	Pressure > Closure Design	0.3 E-3	0.5 E-2	0.01
21	Pressure > Cask Design	0.3 E-3	0.5 E-2	0.01

[a] See footnote a, Table 27.

[b] See footnote b, Table 27.

TABLE 34: FAULT TREE PROBABILITIES FOR HIGH LEVEL RADIOACTIVITY SOLIDIFIED WASTE SHIPPING CONTAINER UNDER SEVERE ACCIDENT CONDITIONS*

ID Number	Input Event Name	Transport Mode		
		Truck	Rail	Barge
1	Vibration Occurs	0.5	0.5	0.05
2	Vibration > Can Design	0.15 E-5	0.2 E-5	0.5 E-6
3	Vibration > Closure Design	0.75 E-6	0.1 E-5	0.25 E-6
4	Vibration > Cask Design	0.15 E-5	0.2 E-5	0.5 E-6
5	Impact Occurs	0.159	0.02	0.02
6	Impact > Can Design	0.1 E-4	0.1 E-4	0.1 E-4
7	Impact > Closure Design	0.1 E-4	0.1 E-4	0.1 E-4
8	Impact > Cask Design	0.1 E-1	0.1 E-1	0.1 E-1
9	Puncture Force Occurs	0.022	0.066	--
10	Puncture Force > Can Design	0.1 E-	0.1 E-	0.1 E-
11	Puncture Force > Closure Design	0.1 E-2	0.1 E-2	0.1 E-2
12	Puncture Force > Cask Design	0.1 E-2	0.1 E-2	0.1 E-2
13	Coolant Leaks Out	0.5 E-6	0.5 E-6	0.5 E-6
14	Coolant Channels Not Filled	0.3 E-4	0.3 E-4	0.3 E-4
15	External Heat Source Nearby	0.2 E-3	0.2 E-3	0.7 E-3
16	Temperature > Can Design	0.1 E-4	0.1 E-4	0.1 E-4
17	Temperature > Closure Design	0.1 E-3	0.1 E-3	0.1 E-3
18	Temperature > Cask Design	0.1 E-3	0.1 E-3	0.1 E-3
19	Pressure > Can Design	0.3 E-2	0.5 E-1	0.1
20	Pressure > Closure Design	0.3 E-2	0.5 E-1	0.1
21	Pressure > Cask Design	0.3 E-2	0.5 E-1	0.1

*See footnote, Table 28.

TABLE 35: FAULT TREE PROBABILITIES FOR FISSION PRODUCT (NOBLE) GAS SHIPPING CONTAINER UNDER ACCIDENT CONDITIONS OF LIGHT SEVERITY[a]

ID Number	Input Event Name	Transport Mode		
		Truck	Rail	Barge
1	Vibration Occurs	0.5	0.5	0.05
2	Vibration > Cylinder Design	0	0	0
3	Vibration > Cask Design	0	0	0
4	Vibration > Closure Design	0	0	0
5	Impact Occurs	0.221	0.123	0.9
6	Impact > Cylinder Design	0	0	0
7	Impact > Cask Design	0	0	0
8	Impact > Closure Design	0	0	0
9	Puncture Force Occurs	0.008	0.410	--
10	Puncture Force > Cylinder Design	0	0	0
11	Puncture Force > Cask Design	0	0	0
12	Puncture Force > Closure Design	0	0	0
13	Coolant Leaks Out[b]	0.5 E-6	0.5 E-6	0.5 E-6
14	Coolant Channels Not Filled	0.3 E-4	0.3 E-4	0.3 E-4
15	External Heat Source Nearby	0.014	0.0128	0.0605
16	Pressure > Cylinder Design	0	0	0
17	Pressure > Cask Design	0	0	0
18	Pressure > Closure Design	0	0	0
19	Temperature > Cylinder Design	0	0	0
20	Temperature > Cask Design	0	0	0
21	Temperature > Closure Design	0	0	0
22	Cylinder Valve Malfunction	0.1 E-2	0.1 E-2	0.1 E-2
23	Cylinder Valve Not Tightened	0.7 E-3	0.7 E-3	0.7 E-3
24	Cask Vent Malfunction	0.1 E-2	0.1 E-2	0.1 E-2

[a] See footnote a, Table 26.
[b] See footnote b, Table 26.

TABLE 36: FAULT TREE PROBABILITIES FOR FISSION PRODUCT (NOBLE) GAS SHIPPING CONTAINER UNDER ACCIDENT CONDITIONS OF MEDIUM SEVERITY[a]

ID Number	Input Event Name	Transport Mode		
		Truck	Rail	Barge
1	Vibration Occurs	0.5	0.5	0.05
2	Vibration > Cylinder Design	0.3 E-7	0.4 E-7	0.1 E-7
3	Vibration > Cask Design	0.15 E-6	0.2 E-6	0.5 E-7
4	Vibration > Closure Design	0.75 E-7	0.1 E-6	0.25 E-7
5	Impact Occurs	0.423	0.067	0.08
6	Impact > Cylinder Design	0.1 E-3	0.1 E-3	0.1 E-3
7	Impact > Cask Design	0.5 E-2	0.5 E-2	0.5 E-2
8	Impact > Closure Design	0.1 E-5	0.1 E-5	0.1 E-5
9	Puncture Force Occurs	0.066	0.224	--
10	Puncture Force > Cylinder Design	0.1 E-3	0.1 E-3	0.1 E-3
11	Puncture Force > Cask Design	0.1 E-3	0.1 E-3	0.1 E-3
12	Puncture Force > Closure Design	0.1 E-3	0.1 E-3	0.1 E-3
13	Coolant Leaks Out[b]	0.5 E-6	0.5 E-6	0.5 E-6
14	Coolant Channels Not Filled	0.3 E-4	0.3 E-4	0.3 E-4
15	External Heat Source Nearby	0.0016	0.002	0.0099
16	Pressure > Cylinder Design	0.3 E-3	0.5 E-2	0.01
17	Pressure > Cask Design	0.3 E-3	0.5 E-2	0.01
18	Pressure > Closure Design	0.3 E-3	0.5 E-2	0.01
19	Temperature > Cylinder Design	0.1 E-5	0.1 E-5	0.1 E-5
20	Temperature > Cask Design	0.1 E-4	0.1 E-4	0.1 E-4
21	Temperature > Closure Design	0.1 E-4	0.1 E-4	0.1 E-4
22	Cylinder Valve Malfunction	0.1 E-2	0.1 E-2	0.1 E-2
23	Cylinder Valve Not Tightened	0.7 E-3	0.7 E-3	0.7 E-3
24	Cask Vent Malfunction	0.1 E-2	0.1 E-2	0.1 E-2

[a] See footnote a, Table 27.
[b] See footnote b, Table 27.

TABLE 37: FAULT TREE PROBABILITIES FOR FISSION PRODUCT (NOBLE) GAS SHIPPING CONTAINER UNDER SEVERE ACCIDENT CONDITIONS*

ID Number	Input Event Name	Transport Mode		
		Truck	Rail	Barge
1	Vibration Occurs	0.5	0.5	0.05
2	Vibration > Cylinder Design	0.3 E-6	0.4 E-6	0.1 E-6
3	Vibration > Cask Design	0.15 E-5	0.2 E-5	0.5 E-6
4	Vibration > Closure Design	0.75 E-6	0.1 E-5	0.25 E-6
5	Impact Occurs	0.159	0.02	0.02
6	Impact > Cylinder Design	0.1 E-2	0.1 E-2	0.1 E-2
7	Impact > Cask Design	0.05	0.05	0.05
8	Impact > Closure Design	0.1 E-4	0.1 E-4	0.1 E-4
9	Puncture Force Occurs	0.022	0.066	--
10	Puncture Force > Cylinder Design	0.1 E-2	0.1 E-2	0.1 E-2
11	Puncture Force > Cask Design	0.1 E-2	0.1 E-2	0.1 E-2
12	Puncture Force > Closure Design	0.1 E-2	0.1 E-2	0.1 E-2
13	Coolant Leaks Out	0.5 E-6	0.5 E-6	0.5 E-6
14	Coolant Channels Not Filled	0.3 E-4	0.3 E-4	0.3 E-4
15	External Heat Source Nearby	0.2 E-3	0.2 E-3	0.7 E-3
16	Pressure > Cylinder Design	0.3 E-2	0.05	0.1
17	Pressure > Cask Design	0.3 E-2	0.05	0.1
18	Pressure > Closure Design	0.3 E-2	0.05	0.1
19	Temperature > Cylinder Design	0.1 E-4	0.1 E-4	0.1 E-4
20	Temperature > Cask Design	0.1 E-3	0.1 E-3	0.1 E-3
21	Temperature > Closure Design	0.1 E-3	0.1 E-3	0.1 E-3
22	Cylinder Valve Malfunction	0.1 E-2	0.1 E-2	0.1 E-2
23	Cylinder Valve Not Tightened	0.7 E-3	0.7 E-3	0.7 E-3
24	Cask Vent Malfunction	0.1 E-2	0.1 E-2	0.1 E-2

*See footnote, Table 28.

TABLE 38: RELEASE PROBABILITIES FOR SHIPPING CONTAINERS INVOLVED IN ACCIDENTS

Material	Accident Severity	Transport Mode		
		Truck	Rail	Barge
Spent Fuel	Light	0	0	0
	Medium	0.15E-9	0.16E-9	0.13E-7
	Severe	0.19E-8	0.33E-7	0.15E-5
Plutonium	Light	0	0	0
	Medium	0.30E-7	0.25E-8	0.22E-7
	Severe	0.30E-5	0.16E-6	0.11E-5
High Level Solid Waste	Light	0	0	0
	Medium	0.50E-8	0.11E-6	0.20E-5
	Severe	0.23E-7	0.13E-5	0.15E-4
Noble Gas	Light	0	0	0
	Medium	0.26E-6	0.44E-6	0.22E-5
	Severe	0.93E-5	0.11E-4	0.20E-4

TABLE 39: SIGNIFICANT FAILURE MODES AND PROBABILITIES FOR SHIPPING CONTAINERS SUBJECT TO SEVERE ACCIDENTS

Material Container	Transport Mode	ID Number	Event Description	Event Probability	Probability of Completing Chain	Release Probability
Spent Fuel	Truck	6	Impact Occurs	0.159		
		7	Impact > Clad	0.002		
		9	Impact > Casket	0.01		
		27	Improper Seal	0.0005	0.16 E-8	
		6	Impact Occurs	0.159		
		7	Impact > Clad	0.002		
		26	Defective Seal	0.0005		
		28	Vent Line Failure	0.001	0.16 E-9	0.19 E-8
Spent Fuel	Rail	17	Heat Nearby	0.0002		
		18	Pressure > Clad	0.05		
		19	Pressure > Cavity	0.05		
		21	Pressure > Closure	0.05	0.25 E-7	
		16	Coolant Channels Not Filled	0.00003		
		18	Pressure > Clad	0.05		
		19	Pressure > Cavity	0.05		
		20	Pressure > Casket	0.05	0.38 E-8	
		16	Coolant Channels Not Filled	0.00003		
		18	Pressure > Clad	0.05		
		19	Pressure > Cavity	0.05		
		21	Pressure > Closure	0.05	0.38 E-8	0.33 E-7

TABLE 39 (continued)

Material Container	Transport Mode	ID Number	Event Description	Event Probability	Probability of Completing Chain	Release Probability
Spent Fuel	Barge	17	Heat Nearby	0.0007		
		18	Pressure > Clad	0.1		
		19	Pressure > Cavity	0.1		
		21	Pressure > Closure	0.1	0.7 E-6	
		17	Heat Nearby	0.0007		
		18	Pressure > Clad	0.05		
		19	Pressure > Cavity	0.05		
		20	Pressure > Casket	0.05	0.7 E-6	0.15 E-5
Plutonium	Truck	11	Impact Occurs	0.159		
		12	Impact > Bag	1.0		
		13	Impact > Bottle	0.005		
		14	Impact > Vessel	0.01		
		15	Impact > Drum	0.3	0.24 E-5	
		11	Impact Occurs	0.159		
		12	Impact > Bag	1.0		
		14	Impact > Vessel	0.005		
		15	Impact > Drum	0.3		
		23	Failed Bottle Cap	0.0005	0.24 E-6	
		11	Impact Occurs	0.159		
		12	Impact > Bag	1.0		
		14	Impact > Vessel	0.005		
		15	Impact > Drum	0.3		
		24	Failed Cap Threads	0.005	0.24 E-6	0.30 E-5

TABLE 39 (continued)

Material Container	Transport Mode	ID Number	Event Description	Event Probability	Probability of Completing Chain	Release Probability
Plutonium	Rail	11	Impact Occurs	0.020		
		12	Impact > Bag	1.0		
		13	Impact > Bottle	0.001		
		14	Impact > Vessel	0.01		
		15	Impact > Drum	0.3	0.6 E-7	
		11	Impact Occurs	0.020		
		12	Impact > Bag	1.0		
		14	Impact > Vessel	0.01		
		15	Impact > Drum	0.3		
		23	Failed Bottle Cap	0.0005	0.3 E-7	
		11	Impact Occurs	0.02		
		12	Impact > Bag	1.0		
		14	Impact > Vessel	0.01		
		15	Impact > Drum	0.3		
		24	Failed Cap Threads	0.0005	0.3 E-7	
		6	Heat Nearby	0.0002		
		7	Temperature > Bag	1.0		
		20	Pressure > Bottle	0.05		
		21	Pressure > Vessel	0.05		
		22	Pressure > Drum	0.05	0.25 E-7	0.16 E-6
Plutonium	Barge	6	Heat Nearby	0.0007		
		7	Temperature > Bag	1.0		
		20	Pressure > Bottle	0.1		
		21	Pressure > Vessel	0.1		
		22	Pressure > Drum	0.1	0.7 E-6	

TABLE 39 (continued)

Material Container	Transport Mode	ID Number	Event Description	Event Probability	Probability of Completing Chain	Release Probability
Plutonium	Barge (Cont'd)	11	Impact Occurs	0.02		
		12	Impact > Bag	1.0		
		13	Impact > Bottle	0.005		
		14	Impact > Vessel	0.01		
		15	Impact > Drum	0.3	0.3 E-6	0.11 E-5
High Level Solid Waste	Truck	5	Impact Occurs	0.159		
		6	Impact > Can	0.00001		
		8	Impact > Cask	0.01	0.16 E-7	
		15	Heat Nearby	0.0002		
		19	Pressure > Can	0.003		
		21	Pressure > Cask	0.003	0.18 E-8	
		15	Heat Nearby	0.0002		
		19	Pressure > Can	0.003		
		20	Pressure > Closure	0.003	0.18 E-8	
		1	Vibration Occurs	0.5		
		2	Vibration > Can	0.0000015		
		5	Impact Occurs	0.159		
		8	Impact > Cask	0.01	0.12 E-8	0.23 E-7

TABLE 39 (continued)

Material Container	Transport Mode	ID Number	Event Description	Event Probability	Probability of Completing Chain	Release Probability
High Level Solid Waste	Rail	15	Heat Nearby	0.0002		
		19	Pressure > Can	0.05		
		21	Pressure > Cask	0.05	0.5 E-6	
		15	Heat Nearby	0.0002		
		19	Pressure > Can	0.05		
		20	Pressure > Closure	0.05	0.5 E-6	0.13 E-5
High Level Solid Waste	Barge	15	Heat Nearby	0.0007		
		19	Pressure > Can	0.1		
		20	Pressure > Closure	0.1	0.7 E-5	
		15	Heat Nearby	0.0007		
		19	Pressure > Can	0.1		
		21	Pressure > Cask	0.1	0.7 E-5	0.15 E-4
Noble Gas	Truck	5	Impact Occurs	0.159		
		6	Impact > Cylinder	0.001		
		7	Impact > Cask	0.05	0.8 E-5	
		5	Impact Occurs	0.159		
		6	Impact > Cylinder	0.001		
		17	Pressure > Cask	0.003	0.48 E-6	
		5	Impact Occurs	0.159		
		6	Impact > Cylinder	0.001		
		18	Pressure > Closure	0.003	0.48 E-6	

TABLE 39 (continued)

Material Container	Transport Mode	ID Number	Event Description	Event Probability	Probability Completing Chain	Release Probability
Noble Gas	Truck (Cont'd)	5	Impact Occurs	0.159		
		7	Impact > Cask	0.05		
		9	Puncture Occurs	0.022		
		10	Puncture > Cylinder	0.001	0.17 E-6	0.93 E-5
Noble Gas	Rail	9	Puncture Occurs	0.066		
		10	Puncture > Cylinder	0.001		
		18	Pressure > Closure	0.05	0.33 E-5	
		9	Puncture Occurs	0.066		
		10	Puncture > Cylinder	0.001		
		17	Pressure > Cask	0.05	0.33 E-5	
		5	Impact Occurs	0.02		
		6	Impact > Cylinder	0.001		
		17	Pressure > Cask	0.05	0.1 E-5	
		5	Impact Occurs	0.02		
		6	Impact > Cylinder	0.001		
		7	Impact > Cask	0.05	0.1 E-5	
		5	Impact Occurs	0.02		
		6	Impact > Cylinder	0.001		
		18	Pressure > Closure	0.05	0.1 E-5	0.11 E-4

TABLE 39 (continued)

Material Container	Transport Mode	ID Number	Event Description	Event Probability	Probability of Completing Chain	Release Probability
Noble Gas	Barge	15	Heat Nearby	0.0007		
		16	Pressure > Cylinder	0.1		
		18	Pressure > Closure	0.1	0.7 E-5	
		15	Heat Nearby	0.0007		
		16	Pressure > Cylinder	0.1		
		17	Pressure > Cask	0.1	0.7 E-5	
		5	Impact Occurs	0.02		
		6	Impact > Cylinder	0.001		
		18	Pressure > Closure	0.1	0.2 E-5	
		5	Impact Occurs	0.02		
		6	Impact > Cylinder	0.001		
		17	Pressure > Cask	0.1	0.2 E-5	
		5	Impact Occurs	0.02		
		6	Impact > Cylinder	0.001		
		7	Impact > Cask	0.05	0.1 E-5	0.20 E-4

FRACTION OF CARGO LIKELY TO BE RELEASED IN AN ACCIDENT

Considering maximum credible severity of accidents, one might assume the following scenarios:

1. Spent Fuel: Loss of coolant in spent fuel cask; fuel rods broken or perforated so that all the noble gas contained in the fuel rod plenum escapes.

2. Plutonium: Shipped in the form of a solid, part of the contents spill out of the ruptured cask.

3. High Level Solid Waste: Part of the glassy matrix is shattered into fine particles upon impact and escapes through the opened cask.

4. Noble Gas: Shipped in pressurized cylinders, all the gas is released when both the cylinders and cask break.

The ratio of fission gas radiation to total radiation of fission products and fissile material in an LWR fuel element is about 11×10^3 Ci/4.5×10^6 Ci, or about 2×10^{-3}. The ratio varies to .001 for LWR-Pu and LMFBR fuels and .0128 for HTGR fuel. The fraction .001 was chosen as the severe release fraction for spent fuel.

Plutonium is expected to be shipped in solidified form, probably as pellets of PuO_2. A shipment of plutonium is thus quite similar to a shipment of solid waste. The severe accident release fraction for plutonium is arbitrarily set to 0.001.

Solidified waste release fractions are difficult to estimate, but since more nuclides will probably be involved in a release of solid waste than in a release of spent fuel, the severe release fraction is arbitrarily set at 5 times the spent fuel value.

Gaseous fission products are assumed in this study to be transported in pressurized cylinders, although technology may be found in the future to allow shipping of gases in solid matrices. The severe release fraction for noble gases is thus assumed to be unity.

Release fractions for light and medium severity releases are estimated as fractions of the severe release fractions. The results are tabulated in Table 40.

TABLE 40: RELEASE FRACTIONS DURING ACCIDENTS

Material	Accident Severity		
	Light	Medium	Severe
Spent Fuel	1×10^{-9}	1×10^{-6}	1×10^{-3}
Recycled Plutonium	1×10^{-9}	1×10^{-6}	1×10^{-3}
Solid Waste	1×10^{-9}	1×10^{-6}	5×10^{3}
Noble Gas	1×10^{-2}	5×10^{-1}	1

RADIATION DOSES FROM ACCIDENT RELEASES (RADIATION DISPERSION MODEL)

The dose D absorbed by biota surrounding the site of an accidental release decreases with increasing distance from the release site. In particular, the dose is considered as a function of the area around the accident. A certain meteorological condition, which is assumed to describe the capability of the atmosphere to disperse the released radiation or radioactive material, is modeled by the empirical linear logarithmic relation:

$$\ell n D_{Q_{\ell jms}}(A_i) = -0.93001 \; \ell n A_i + (\ell n Q_{\ell jms} K_\ell - 13.895),$$

where

A = the area surrounding the accident in which the dose equals or exceeds D

K_ℓ = dose coefficient for material ℓ, in $(\text{rem} \cdot m^3)/(\text{Ci} \cdot \text{sec})$

i = an index distinguishing concentric circular isopleths bounding areas which absorb different amounts of radiation

$Q_{\ell jms}$ = the source in curies (Ci) from an accident of severity s involving material ℓ in year j in transport mode m.

The above equation is an approximation to data given in Appendix B of Reference 8 for the Pasquill weather stability class D. The dose is given in rems.

EXPOSURE TO RADIATION

The exposure of human beings to radiation risk is quantified by the product of the dose and the number of people near the accident scene who may reasonably be expected to absorb the radiation. For convenience, knowledge of the population density distribution near the accident is used to determine the number of human absorbers likely to be present. Consequently, the exposure to risk is written

$$X_{\ell jmski} = D_{\ell jms}(A_i) \, A_i p_{jki}$$

where

X = the exposure to risk (population dose)

p = the population density.

If the population density is one person per unit area, then the exposure to risk of that person is the product of dose and area. Alternatively, the area-dose product may be interpreted as the exposure to risk of the environment. The human-dose product may then be found from the area-dose product by multiplying by a nonunity population density.

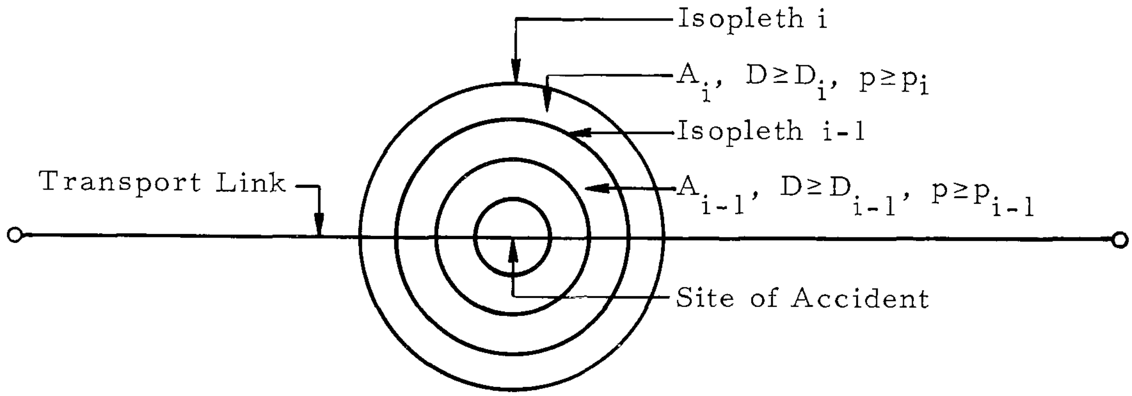
The probable numbers of people in the vicinity of an accident are based on census data. Using the national average values for population density presented in Table 3, the distribution in terms of multiples of the population density is derived from some assumptions. First, the population density is assumed to be independent of isopleth area A_i. Secondly, the fraction of a transport link expected to lie in rural or urban areas is assumed to be given by the 1980 projection of population density distribution within 50 miles of a reactor (Reference 8, Appendix B). A graphical representation of the areal and linear population distributions is given in Figure 29.

Under these assumptions, the level of risk to exposure may be calculated from a simplified formula:

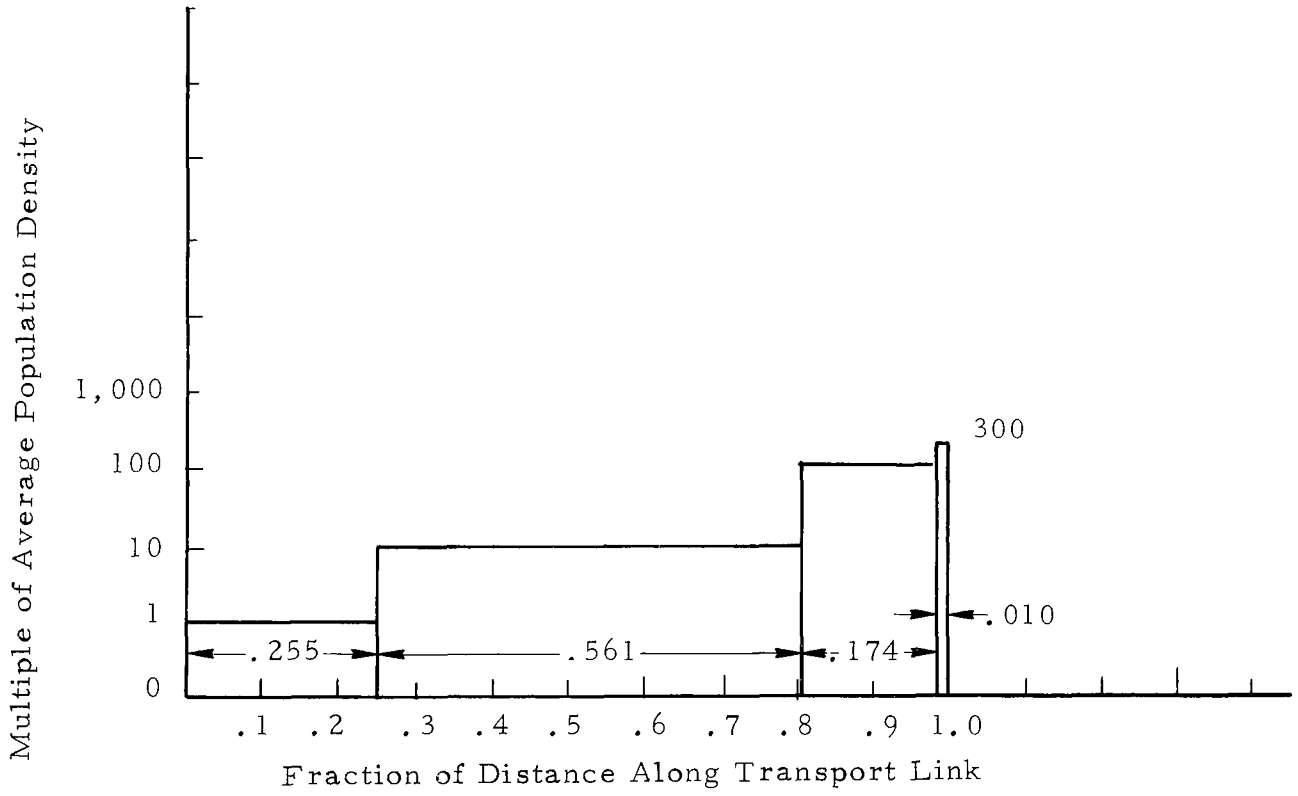
$$
\begin{aligned}
X_{\ell jms} &= \sum_k \sum_i D_{\ell jms}(A_i)\, A_i\, p_{jki} \\
&= \sum_k p_{jk} \sum_i D_{\ell jms}(A_i)\, A_i \\
&= (0.255 \times 1 + 0.561 \times 10 + 0.174 \times 100 + 0.01 \times 300) \\
&\quad\; p_j \sum_i D_{\ell jms}(A_i)\, A_i \\
&\cong 26.3\, p_j \sum_i D_{\ell jms}(A_i)\, A_i
\end{aligned}
$$

CONSEQUENCES OF RADIATION ABSORPTION FROM ACCIDENT RELEASES (HEALTH EFFECTS MODEL)

A quantitative and qualitative description of the effects on human health of absorbed radiation is still a subject of research. Available data includes the response of small animals, of diseased persons, and of persons exposed to high levels of radiation, such as the atom bombs exploded in World War II. The human health response to low levels of radiation, such as are being discussed in this report, is complicated by the requirements of large irradiated populations to study; by the long time delay between radiation exposure and appearance of neoplasms; by difficulty in distinguishing radiation imposed cancers from cancers produced from other causes or from background radiation; and because cancer susceptibility is a widely varying function of age, sex, genetic constitution, diet, personal habits, socioeconomic factors, and other variables (Reference 24).



a. Definition of Isopleth Areas.



b. Population Distribution Along Transport Link.

FIGURE 29: GRAPHICAL REPRESENTATION OF DOSE AND POPULATION DISTRIBUTIONS AT THE SCENE OF AN ACCIDENT

For low levels of radiation, the absolute hazards (difference between hazards of irradiated and nonirradiated populations) can be estimated from linear relationships between health effects and absorbed dose. The EPA Office of Radiation Programs is currently using a straight line with slope of 200 excess cases/10^6 exposed persons/year/rem to estimate the number of fatalities and nonlethal cancers resulting from chronic whole body exposure to low levels of ionizing radiation. Their straight line describing the effects from plutonium irradiation has one-fourth this slope. Plutonium emits alpha particles, which are readily stopped by clothing or skin and therefore poses no external hazard. Additionally, the health hazard from ingested plutonium is slight. However, the hazard from inhaled plutonium is quite serious. These guidelines are used in this report to estimate the number of nonlethal cancers.

For high levels of radiation, such as might be absorbed by persons near a transport accident release, the number of lethal cases is estimated by the $LD_{50/60}$ measure. Recent studies indicate that $LD_{50/60}$ (dose resulting in 50 percent demise of the absorbing population within 60 days) lies between 243 and 300 rads (Reference 23). The number of fatalities is determined in this report by dividing half the expected number of man-rems by the larger value for $LD_{50/60}$, assuming an RBE factor of unity.

HAZARD VECTOR FIELD

The assessment of hazard from transportation accidents related to the nuclear power industry is characterized by the following five quantities which are conceptually considered as the components of a vector:

1. Amount (Ci) of radiation likely to be released from transport accidents.

2. Exposure to risk of environment (area-dose or acre-rems).

3. Exposure to risk of humans (population-dose, or man-rems).

4. Expected number of fatalities resulting from population-dose.

5. Expected number of nonlethal cancers resulting from population-dose.

The various components are calculated from formulae already given. The calculations and symbols are summed up in Table 41.

TABLE 41: SUMMARY OF HAZARDS ANALYSIS MODEL

Hazard Vector Component	Description	Formula
$Q^{*}_{\ell jmks}$	Likely number of curies (Ci) released in year j from transport accident of severity s involving material ℓ and mode m and occurring in route link segment k.	$Q^{*}_{\ell jmks} = Q_{\ell jm} \, P(A\|S)_{\ell jkms} \, r_{\ell ms} \, f_{\ell s}$
$X^{(1)}_{\ell jms}$	Exposure to risk of environment (radiation absorbed by single human or equivalent in environment, whence the superscript (1), measured in area-dose quantities (acre-rems).	$X^{(1)}_{\ell jms} = \sum_i D_{\ell jms}(A_i) \, A_i$
$X_{\ell jms}$	Exposure to risk of human population, measured in population-dose quantities (man-rems).	$X_{\ell jms} = \sum_i D_{\ell jms}(A_i) \, A_i \, p_i$
$F_{\ell jms}$	Expected number of fatalities resulting from population-dose.	$F_{\ell jms} = 0.5 \, X_{\ell jms} / LD_{50/60}$
$C_{\ell jms}$	Expected number of nonlethal cancers resulting from population-dose.	$C_{\ell jms} = X_{\ell jms}$ man-rem x 200 nonlethal cancers/10^6 man-rem/year

TABLE 41 (continued)

Hazard Vector Subfactors	Description	Formula
$Q_{\ell jm}$	Likely number of curies (Ci) transported of material ℓ in year j by mode m.	$Q_{\ell jm} = q_{\ell} S_{\ell j} b_m$
q_{ℓ}	Number of curies in material ℓ loaded in a single shipment.	
$S_{\ell j}$	Number of shipments of material ℓ made in year j.	
b_m	Fraction of number of shipments hauled by mode m.	
$P(A\|S)_{\ell jkms}$	Probability that a shipment of material ℓ by mode m in year j will encounter an accident of severity s in link segment k.	$P(A\|S)_{\ell jkms} = d_{\ell jk} a_{ms}$
$d_{\ell jk}$	Distance traveled by shipment of material ℓ in year j on link segment k.	
a_{ms}	Probability of transport mode m encountering an accident of severity s in a unit of distance traveled.	

TABLE 41 (continued)

Hazard Vector Subfactors	Description	Formula
$r_{\ell ms}$	Probability that an accident of severity s involving transport mode m will result in a rupture of the shipping container for material ℓ.	Monte Carlo simulation of shipping container fault tree.
$f_{\ell s}$	Fraction of a cargo of material ℓ released to the environment in an accident of severity s.	
$D_{\ell jms}(A_i)$	Dose of radiation absorbed by a person in area A_i by means of dispersion of radiation or radio-active material from a transport accident site.	$D_{\ell jmsk}(A_i) = Q^*_{\ell jmks} K_\ell e^{-13.895} A_i^{-0.93001}$ ℓ — K_ℓ(rem·m^3/Ci/sec) Spent Fuel — 7.30 E+2 — (Reference 8) Plutonium — 3.81 E+5 — (Reference 22) Solid Waste — 7.30 E+2 — (Reference 8) Noble Gas — 5.30 E-2 — (Reference 8,10)
A_i	Area bounded by concentric (with accident site) circular isopleth i over which the radiation dose is $D_{\ell jmsk}(A_i)$ or greater.	

TABLE 41 (continued)

Hazard Vector Subfactors	Description	Formula
p_i	Population density in isopleth area A_i.	
$LD_{50/60}$	Lethal dose, usually measured in rad, which, if absorbed by each member of the exposed population, will result in 50 percent fatality to the population within a time period of 60 days of the accident dose.	

<u>Indices</u>

ℓ Material of shipment cargo; type of shipping container.

j Year in which shipments are performed.

m Transport mode.

k Segment of transport link.

s Severity of accident.

i Isopleth area.

SECTION VII

CASE EVALUATIONS OF ACCIDENTAL HAZARDS

Several computer calculations have been made to study the effect of varying several of the parameters in the transportation model. Hazard vectors were computed for the following sets of case variables:

1. Annual hazards for every fifth year from 1970-2020.

2. Single shipment hazards based on year 1990 as representative.

3. Hazards pertaining to each type of material shipping container.

4. Hazards pertaining to several mixes of transport modes.

5. Hazards pertaining to each accident severity.

6. Hazards associated with nuclear shipments in high, low, and chosen estimates.

For convenience, the shipping data for each of the four materials - spent fuel, recycled plutonium, high level radioactive solidified waste, and noble gas - for the chosen projection are collected in Tables 42 through 45. Data for accident probabilities, release probabilities, release fractions, and population densities are repeated in Tables 46 through 49. Computer printouts of the hazard vectors for medium and severe accidents, for an assumed population distribution, and for an assumed mix of transport modes then follow.

In the fault trees pertaining to shipping containers under accident conditions of light severity, the inhibit gate probabilities for various physical conditions breaking the containers were set to zero. As a result, no failure mode is described by these fault trees. Consequently, the release probabilities in light severity accidents are effectively assumed to be zero, and the hazard becomes zero. No further discussion of light accidents is admitted under these premises.

Hazard vectors for a transport mix of 20 percent trucks, 75 percent railroads, and 5 percent barges are presented in Tables 50 through 57 for the chosen estimate of shipping data. A population density of 26.3 times the average population density for a given year is used to allow

TABLE 42: ANNUAL SHIPPING DATA FOR SPENT FUE

YEAR	AMOUNT SHIPPED	RADIOACTIVITY (10**9 CURIES)	NUMBER OF SHIPMENTS	SHIPPING DISTANCE (MILES)	SHIPPING UNITS (10**6 UNIT MILES)
1970	15.00	.070	5	700	.002
1975	567.00	2.840	191	600	.115
1980	2050.00	10.250	934	500	.457
1985	4474.00	22.370	1612	450	.725
1990	7798.00	39.000	3297	400	1.319
1995	12314.00	61.570	7463	400	2.985
2000	16869.00	84.340	10224	400	4.090
2005	21622.00	108.110	12100	400	4.840
2010	27000.00	135.000	16360	400	6.544
2015	32500.00	162.500	19697	400	7.879
2020	38500.00	192.500	23334	400	9.334

TABLE 43: ANNUAL SHIPPING DATA FOR PLUTONIUM

YEAR	AMOUNT SHIPPED	RADIOACTIVITY (10**9 CURIES)	NUMBER OF SHIPMENTS	SHIPPING DISTANCE (MILES)	SHIPPING UNITS (10**6 UNIT MILES)
1974	0.00	0.000	0	0	0.000
1975	0.00	0.000	0	0	0.000
1980	801.20	.504	10680	500	5.340
1985	542.70	.341	7234	450	3.255
1990	43.50	.016	580	400	.232
1995	238.50	.087	3179	400	1.272
2000	586.10	.213	7813	400	3.125
2005	1085.10	.395	14464	400	5.786
2010	1575.00	.573	20995	400	8.398
2015	2100.00	.765	27993	400	11.197
2020	2625.00	.956	34991	400	13.996

TABLE 44: ANNUAL SHIPPING DATA FOR SOLID RADIOACTIVE WASTE

YEAR	AMOUNT SHIPPED	RADIOACTIVITY (10**9 CURIES)	NUMBER OF SHIPMENTS	SHIPPING DISTANCE (MILES)	SHIPPING UNITS (10**6 UNIT MILES)
1970	0.00	0.000	0	0	0.000
1975	0.00	0.000	0	0	0.000
1980	.05	.005	1	2500	.002
1985	1.70	.178	23	2500	.057
1990	4.83	.651	65	2200	.143
1995	10.52	1.506	140	2200	.309
2000	19.36	2.742	257	2200	.565
2005	31.60	4.496	420	2200	.924
2010	45.94	6.364	610	2000	1.220
2015	64.19	8.309	852	2000	1.704
2020	82.40	10.250	1094	2000	2.188

TABLE 45: ANNUAL SHIPPING DATA FOR NOBLE GAS

YEAR	AMOUNT SHIPPED	RADIOACTIVITY (10**9 CURIES)	NUMBER OF SHIPMENTS	SHIPPING DISTANCE (MILES)	SHIPPING UNITS (10**6 UNIT MILES)
1970	0.00	0.000	0	0	0.000
1975	0.00	0.000	0	0	0.000
1980	175.00	.032	30	2500	.075
1985	350.00	.063	59	2500	.147
1990	590.00	.106	99	2200	.218
1995	800.00	.144	134	2200	.295
2000	1020.00	.184	170	2200	.374
2005	1210.00	.218	202	2200	.444
2010	1400.00	.252	234	2000	.468
2015	1580.00	.284	264	2000	.528
2020	1730.00	.311	289	2000	.578

TABLE 46: ACCIDENT PROBABILITIES PER MILLION VEHICLE MILES

ACCIDENT TYPE	TRANSPORTATION METHOD		
	TRUCK	RAIL	BARGE
LIGHT	1.3000E+00	7.3000E-01	1.7000E+00
MEDIUM	3.0000E-01	7.9000E-02	4.4000E-02
SEVERE	8.0000E-03	1.5000E-03	1.6000E-03

TABLE 47: RELEASE PROBABILITIES FOR GIVEN ACCIDENTS

MATERIAL TYPE	ACCIDENT TYPE	TRANSPORTATION METHOD TRUCK	RAIL	BARGE
NOBLE GAS	LIGHT	0.	0.	0.
	MEDIUM	2.6000E-07	4.4000E-07	2.2000E-06
	SEVERE	9.3000E-06	1.1000E-05	2.0000E-05
SOLID RADIOACTIVE WASTE	LIGHT	0.	0.	0.
	MEDIUM	5.0000E-09	1.1000E-07	2.0000E-06
	SEVERE	2.3000E-08	1.3000E-06	1.6000E-05
SPENT FUEL	LIGHT	0.	0.	0.
	MEDIUM	1.5000E-10	1.6000E-10	1.3000E-08
	SEVERE	1.9000E-09	3.3000E-08	1.5000E-06
PLUTONIUM	LIGHT	0.	0.	0.
	MEDIUM	3.0000E-08	2.5000E-09	2.2000E-08
	SEVERE	3.0000E-06	1.6000E-07	1.1000E-06

TABLE 48: RELEASE FRACTIONS DURING ACCIDENTS

MATERIAL TYPE	ACCIDENT TYPE LIGHT	ACCIDENT TYPE MEDIUM	ACCIDENT TYPE SEVERE
NOBLE GAS	1.0000E-02	5.0000E-01	1.0000E+00
SOLID RADIOACTIVE WASTE	1.0000E-09	1.0000E-06	5.0000E-03
SPENT FUEL	1.0000E-09	1.0000E-06	1.0000E-03
PLUTONIUM	1.0000E-09	1.0000E-06	1.0000E-03

TABLE 49: AVERAGE POPULATION DENSITY FACTORS

YEAR	DENSITY (PEOPLE PER SQUARE MILE)
1970	67.2
1975	72.1
1980	76.9
1985	82.5
1990	88.6
1995	92.4
2000	96.0
2005	102.0
2010	108.0
2015	114.0
2020	120.0

TABLE 50: ANNUAL HAZARD VECTORS FOR MEDIUM SEVERITY SPENT FUEL ACCIDENTS

POPULATION DENSITY : 26.3 TIMES AVERAGE DENSITY

TRANSPORT MIX : 20 PCT TRUCKS, 75 PCT RAILROADS, 5 PCT BARGES

MATERIAL TYPE : SPENT FUEL

ACCIDENT SEVERITY : MEDIUM

YEAR	CURIES	EXPECTED CURIES RELEASED	EXPECTED ACRE REMS	EXPECTED MAN REMS	EXPECTED FATALITIES	EXPECTED NUMBER NONLETHAL CANCERS
1970	7.0000E+07	4.7608E-12	1.7023E-11	4.7010E-11	7.8349E-14	2.3505E-15
1975	2.8400E+09	1.6556E-10	5.9199E-10	1.7540E-09	2.9233E-12	8.7699E-14
1980	1.0250E+10	4.9794E-10	1.7805E-09	5.6265E-09	9.3776E-12	2.8133E-13
1985	2.2370E+10	9.7806E-10	3.4972E-09	1.1900E-08	1.9833E-11	5.9498E-13
1990	3.9000E+10	1.5157E-09	5.4196E-09	1.9732E-08	3.2887E-11	9.8662E-13
1995	6.1570E+10	2.3929E-09	8.5561E-09	3.2488E-08	5.4147E-11	1.6244E-12
2000	8.4340E+10	3.2778E-09	1.1720E-08	4.6237E-08	7.7061E-11	2.3118E-12
2005	1.0811E+11	4.2016E-09	1.5024E-08	6.2972E-08	1.0495E-10	3.1486E-12
2010	1.3500E+11	5.2466E-09	1.8760E-08	8.3261E-08	1.3877E-10	4.1630E-12
2015	1.6250E+11	6.3154E-09	2.2582E-08	1.0579E-07	1.7631E-10	5.2894E-12
2020	1.9250E+11	7.4813E-09	2.6751E-08	1.3191E-07	2.1986E-10	6.5957E-12
REP. PER SHIPMENT QUANTITIES	1.1829E+07	4.5972E-13	1.6438E-12	5.9850E-12	9.9749E-15	2.9925E-16

TABLE 51: ANNUAL HAZARD VECTORS FOR SEVERE SPENT FUEL ACCIDENTS

POPULATION DENSITY : 26.3 TIMES AVERAGE DENSITY

TRANSPORT MIX : 20 PCT TRUCKS, 75 PCT RAILROADS, 5 PCT BARGES

MATERIAL TYPE : SPENT FUEL

ACCIDENT SEVERITY : SEVERE

YEAR	CURIES	EXPECTED CURIES RELEASED	EXPECTED ACRE REMS	EXPECTED MAN REMS	EXPECTED FATALITIES	EXPECTED NUMBER NONLETHAL CANCERS
1970	7.0000E+07	1.3762E-08	4.9210E-08	1.3589E-07	2.2649E-10	6.7946E-12
1975	2.8400E+09	4.7859E-07	1.7113E-06	5.1703E-06	8.4506E-09	2.5352E-10
1980	1.0250E+10	1.4394E-06	5.1469E-06	1.6265E-05	2.7108E-08	8.1325E-10
1985	2.2370E+10	2.8273E-06	1.0110E-05	3.4399E-05	5.7331E-08	1.7199E-09
1990	3.9000E+10	4.3815E-06	1.5667E-05	5.7041E-05	9.5069E-08	2.8521E-09
1995	6.1570E+10	6.9171E-06	2.4733E-05	9.3914E-05	1.5652E-07	4.6957E-09
2000	8.4340E+10	9.4752E-06	3.3880E-05	1.3366E-04	2.2276E-07	6.6829E-09
2005	1.0811E+11	1.2146E-05	4.3429E-05	1.9204E-04	3.0339E-07	9.1018E-09
2010	1.3500E+11	1.5167E-05	5.4231E-05	2.4065E-04	4.0114E-07	1.2034E-08
2015	1.6250E+11	1.8256E-05	6.5278E-05	3.0581E-04	5.0968E-07	1.5290E-08
2020	1.9250E+11	2.1627E-05	7.7330E-05	3.8133E-04	6.3555E-07	1.9067E-08
REP. PER SHIPMENT QUANTITIES	1.1829E+07	1.3289E-09	4.7518E-09	1.7301E-08	2.8835E-11	8.6505E-13

TABLE 52: ANNUAL HAZARD VECTORS FOR MEDIUM SEVERITY PLUTONIUM ACCIDENTS

POPULATION DENSITY : 26.3 TIMES AVERAGE DENSITY

TRANSPORT MIX : 20 PCT TRUCKS, 75 PCT RAILROADS, 5 PCT BARGES

MATERIAL TYPE : PLUTONIUM

ACCIDENT SEVERITY : MEDIUM

YEAR	CURIES	EXPECTED CURIES RELEASED	EXPECTED ACRE REMS	EXPECTED MAN REMS	EXPECTED FATALITIES	EXPECTED NUMBER NONLETHAL CANCERS
1970	0.	0.	0.	0.	0.	0.
1975	0.	0.	0.	0.	0.	0.
1980	5.0400E+08	2.7468E-10	5.1263E-07	1.6200E-06	2.6999E-09	8.0998E-11
1985	3.4100E+08	1.6726E-10	3.1215E-07	1.0621E-06	1.7702E-09	5.3106E-11
1990	1.6000E+07	6.9761E-12	1.3019E-08	4.7401E-08	7.9002E-11	2.3701E-12
1995	8.7000E+07	3.7932E-11	7.0791E-08	2.6880E-07	4.4800E-10	1.3440E-11
2000	2.1300E+08	9.2869E-11	1.7332E-07	6.8373E-07	1.1396E-09	3.4187E-11
2005	3.9500E+08	1.7222E-10	3.2141E-07	1.3472E-06	2.2453E-09	6.7360E-11
2010	5.7300E+08	2.4983E-10	4.6624E-07	2.0693E-06	3.4488E-09	1.0346E-10
2015	7.6500E+08	3.3354E-10	6.2247E-07	2.9161E-06	4.8602E-09	1.4580E-10
2020	9.5600E+08	4.1682E-10	7.7789E-07	3.8360E-06	6.3933E-09	1.9180E-10
REP. PER SHIPMENT QUANTITIES	2.7586E+04	1.2028E-14	2.2447E-11	8.1726E-11	1.3621E-13	4.0863E-15

TABLE 53: ANNUAL HAZARD VECTORS FOR SEVERE PLUTONIUM ACCIDENTS

POPULATION DENSITY : 26.3 TIMES AVERAGE DENSITY

TRANSPORT MIX : 20 PCT TRUCKS, 75 PCT RAILROADS, 5 PCT BARGES

MATERIAL TYPE : PLUTONIUM

ACCIDENT SEVERITY : SEVERE

YEAR	CURIES	EXPECTED CURIES RELEASED	EXPECTED ACRE REMS	EXPECTED MAN REMS	EXPECTED FATALITIES	EXPECTED NUMBER NONLETHAL CANCERS
1970	0.	0.	0.	0.	0.	0.
1975	0.	0.	0.	0.	0.	0.
1980	5.0400E+08	5.4782E-07	1.0224E-03	3.2308E-03	5.3846E-06	1.6154E-07
1985	3.4100E+08	3.3358E-07	6.2254E-04	2.1182E-03	3.5304E-06	1.0591E-07
1990	1.6000E+07	1.3913E-08	2.5965E-05	9.4535E-05	1.5756E-07	4.7267E-09
1995	8.7000E+07	7.5651E-08	1.4118E-04	5.3608E-04	8.9347E-07	2.6804E-08
2000	2.1300E+08	1.8521E-07	3.4565E-04	1.3636E-03	2.2727E-06	6.8180E-08
2005	3.9500E+08	3.4347E-07	6.4100E-04	2.6868E-03	4.4780E-06	1.3434E-07
2010	5.7300E+08	4.9825E-07	9.2986E-04	4.1268E-03	6.8780E-06	2.0634E-07
2015	7.6500E+08	6.6521E-07	1.2414E-03	5.8157E-03	9.6929E-06	2.9079E-07
2020	9.5600E+08	8.3129E-07	1.5514E-03	7.6503E-03	1.2750E-05	3.8251E-07
REP. PER SHIPMENT QUANTITIES	2.7586E+04	2.3988E-11	4.4767E-08	1.6299E-07	2.7165E-10	8.1495E-12

TABLE 54: ANNUAL HAZARD VECTORS FOR MEDIUM SEVERITY SOLID RADIOACTIVE WASTE ACCIDENTS

POPULATION DENSITY : 26.3 TIMES AVERAGE DENSITY

TRANSPORT MIX : 20 PCT TRUCKS, 75 PCT RAILROADS, 5 PCT BARGES

MATERIAL TYPE : SOLID RADIOACTIVE WASTE

ACCIDENT SEVERITY : MEDIUM

YEAR	CURIES	EXPECTED CURIES RELEASED	EXPECTED ACRE REMS	EXPECTED MAN REMS	EXPECTED FATALITIES	EXPECTED NUMBER NONLETHAL CANCERS
1970	0.	0.	0.	0.	0.	0.
1975	0.	0.	0.	0.	0.	0.
1980	5.0000E+06	2.7858E-10	9.9610E-10	3.1478E-09	5.2463E-12	1.5739E-13
1985	1.7800E+08	9.9173E-09	3.5461E-08	1.2066E-07	2.0110E-10	6.0329E-12
1990	6.5100E+08	3.1918E-08	1.1413E-07	4.1553E-07	6.9255E-10	2.0777E-11
1995	1.5060E+09	7.3838E-08	2.6402E-07	1.0025E-06	1.6708E-09	5.0125E-11
2000	2.7420E+09	1.3444E-07	4.8071E-07	1.8964E-06	3.1607E-09	9.4820E-11
2005	4.4960E+09	2.2044E-07	7.8821E-07	3.3038E-06	5.5064E-09	1.6519E-10
2010	6.3640E+09	2.8366E-07	1.0143E-06	4.5014E-06	7.5024E-09	2.2507E-10
2015	8.3090E+09	3.7035E-07	1.3243E-06	6.2037E-06	1.0340E-08	3.1019E-10
2020	1.0250E+10	4.5686E-07	1.6336E-06	8.0557E-06	1.3426E-08	4.0278E-10
REP. PER SHIPMENT QUANTITIES	1.0015E+07	4.9105E-10	1.7558E-09	6.3928E-09	1.0655E-11	3.1964E-13

TABLE 55: ANNUAL HAZARD VECTORS FOR SEVERE SOLID RADIOACTIVE WASTE ACCIDENTS

POPULATION DENSITY : 26.3 TIMES AVERAGE DENSITY

TRANSPORT MIX : 20 PCT TRUCKS, 75 PCT RAILROADS, 5 PCT BARGES

MATERIAL TYPE : SOLID RADIOACTIVE WASTE

ACCIDENT SEVERITY : SEVERE

YEAR	CURIES	EXPECTED CURIES RELEASED	EXPECTED ACRE REMS	EXPECTED MAN REMS	EXPECTED FATALITIES	EXPECTED NUMBER NONLETHAL CANCERS
1970	0.	0.	0.	0.	0.	0.
1975	0.	0.	0.	0.	0.	0.
1980	5.0000E+06	3.0322E-07	1.0842E-06	3.4263E-06	5.7104E-09	1.7131E-10
1985	1.7800E+08	1.0795E-05	3.8598E-05	1.3133E-04	2.1889E-07	6.5666E-09
1990	6.5100E+08	3.4742E-05	1.2423E-04	4.5229E-04	7.5382E-07	2.2615E-08
1995	1.5060E+09	8.0370E-05	2.8738E-04	1.0912E-03	1.8187E-06	5.4560E-08
2000	2.7420E+09	1.4633E-04	5.2324E-04	2.0642E-03	3.4403E-06	1.0321E-07
2005	4.4960E+09	2.3994E-04	8.5794E-04	3.5961E-03	5.9935E-06	1.7981E-07
2010	6.3640E+09	3.0875E-04	1.1040E-03	4.8997E-03	8.1661E-06	2.4498E-07
2015	8.3090E+09	4.0311E-04	1.4414E-03	6.7525E-03	1.1254E-05	3.3763E-07
2020	1.0250E+10	4.9728E-04	1.7781E-03	8.7684E-03	1.4614E-05	4.3842E-07
REP. PER SHIPMENT QUANTITIES	1.0015E+07	5.3449E-07	1.9112E-06	6.9584E-06	1.1597E-08	3.4792E-10

TABLE 56: ANNUAL HAZARD VECTORS FOR MEDIUM SEVERITY NOBLE GAS ACCIDENTS

POPULATION DENSITY : 26.3 TIMES AVERAGE DENSITY

TRANSPORT MIX : 20 PCT TRUCKS, 75 PCT RAILROADS, 5 PCT BARGES

MATERIAL TYPE : NOBLE GAS

ACCIDENT SEVERITY : MEDIUM

YEAR	CURIES	EXPECTED CURIES RELEASED	EXPECTED ACRE REMS	EXPECTED MAN REMS	EXPECTED FATALITIES	EXPECTED NUMBER NONLETHAL CANCERS
1970	0.	0.	0.	0.	0.	0.
1975	0.	0.	0.	0.	0.	0.
1980	3.1500E+07	2.3528E-03	6.1075E-07	1.9300E-06	3.2167E-09	9.6501E-11
1985	6.3000E+07	4.7056E-03	1.2215E-06	4.1562E-06	6.9270E-09	2.0781E-10
1990	1.0620E+08	6.9804E-03	1.8120E-06	6.5973E-06	1.0996E-08	3.2987E-10
1995	1.4400E+08	9.4649E-03	2.4569E-06	9.3292E-06	1.5549E-08	4.6646E-10
2000	1.8360E+08	1.2068E-02	3.1326E-06	1.2358E-05	2.0597E-08	6.1791E-10
2005	2.1780E+08	1.4316E-02	3.7161E-06	1.5576E-05	2.5961E-08	7.7882E-10
2010	2.5200E+08	1.5058E-02	3.9088E-06	1.7348E-05	2.8913E-08	8.6738E-10
2015	2.8440E+08	1.6994E-02	4.4113E-06	2.0666E-05	3.4443E-08	1.0333E-09
2020	3.1140E+08	1.8607E-02	4.8301E-06	2.3819E-05	3.9698E-08	1.1909E-09
REP. PER SHIPMENT QUANTITIES	1.0727E+06	7.0509E-05	1.8303E-08	6.6640E-08	1.1107E-10	3.3320E-12

TABLE 57: ANNUAL HAZARD VECTORS FOR SEVERE NOBLE GAS ACCIDENTS

POPULATION DENSITY : 26.3 TIMES AVERAGE DENSITY

TRANSPORT MIX : 20 PCT TRUCKS, 75 PCT RAILROADS, 5 PCT BARGES

MATERIAL TYPE : NOBLE GAS

ACCIDENT SEVERITY : SEVERE

YEAR	CURIES	EXPECTED CURIES RELEASED	EXPECTED ACRE REMS	EXPECTED MAN REMS	EXPECTED FATALITIES	EXPECTED NUMBER NONLETHAL CANCERS
1970	0.	0.	0.	0.	0.	0.
1975	0.	0.	0.	0.	0.	0.
1980	3.1500E+07	2.4541E-03	6.3705E-07	2.0132E-06	3.3553E-09	1.0066E-10
1985	6.3000E+07	4.9083E-03	1.2741E-06	4.3352E-06	7.2254E-09	2.1676E-10
1990	1.0620E+08	7.2811E-03	1.8900E-06	6.8615E-06	1.1469E-08	3.4407E-10
1995	1.4400E+08	9.8726E-03	2.5628E-06	9.7310E-06	1.6218E-08	4.8655E-10
2000	1.8360E+08	1.2588E-02	3.2675E-06	1.2890E-05	2.1484E-08	6.4452E-10
2005	2.1780E+08	1.4932E-02	3.8762E-06	1.6247E-05	2.7079E-08	8.1237E-10
2010	2.5200E+08	1.5706E-02	4.0771E-06	1.8095E-05	3.0158E-08	9.0474E-10
2015	2.8440E+08	1.7726E-02	4.6013E-06	2.1556E-05	3.5926E-08	1.0779E-09
2020	3.1140E+08	1.9409E-02	5.0382E-06	2.4845E-05	4.1408E-08	1.2422E-09
REP. PER SHIPMENT QUANTITIES	1.0727E+06	7.3546E-05	1.9091E-08	6.9510E-08	1.1585E-10	3.4755E-12

for a variation in population distribution along a typical transport link. Reasoning behind this factor was given in Section VI.

The components of the hazard vectors were calculated from formulas discussed in Section VI. The estimates of fatalities were determined from the LD $_{50/60}$ estimate of 300 rads. Assuming a radiological biology equivalence factor of unity, the number of fatalities (half the population in 60 days) is obtained by dividing the number of man-rems by 600. For estimates of nonlethal effects, the EPA guide of 200 nonlethal cancers per 1,000,000 man-rems per year was used.

ANALYSIS OF TRANSPORTATION HAZARDS BY ACCIDENT SEVERITY

Graphical comparisons of expected man-rems for different accident severities are given in Figures 30 to 37. In Figures 30 and 31, the results for spent fuel are plotted. All the spent fuel is assumed to be shipped by trucks in Figure 30 and is assumed to be shipped by rail in Figure 31. Similar comparisons are made in Figures 32 and 33 for recycled plutonium, in Figures 34 and 35 for high level radioactive solid waste, and in Figures 36 and 37 for noble gas.

In the case of spent fuel, the medium severity curve for truck transport is 10 times greater than that for rail transport. The severe curve for rails is about 3 times higher than the severe curve for trucks. The difference between the medium and severe curves for trucks is about a factor of 300, with the greater exposure to risk being represented by the severe accidents. The annual severe truck exposure varies from 7×10^{-9} man-rems in 1970 to 2×10^{-5} man-rems in 2020.

In the case of plutonium, both curves for rails are about 0.01 as high as the curves for trucks. About a factor of 10^{-3} separates the severe and medium curves for each mode. The annual severe truck exposure decreases from 3×10^{-2} man-rems in 1980 to 1×10^{-3} man-rems in 1990, but then increases to about 0.8 man-rems in 2020.

In the case of solid waste, the severe curve for truck transport is 10 times greater than that for rail transport. The medium curves differ by about a factor of 4, with the truck curve lower. The severe truck curve is about 600 times higher than the medium truck curve. The annual severe truck exposure varies from 1×10^{-7} man-rems in 1980 to 3×10^{-4} man-rems in 2020.

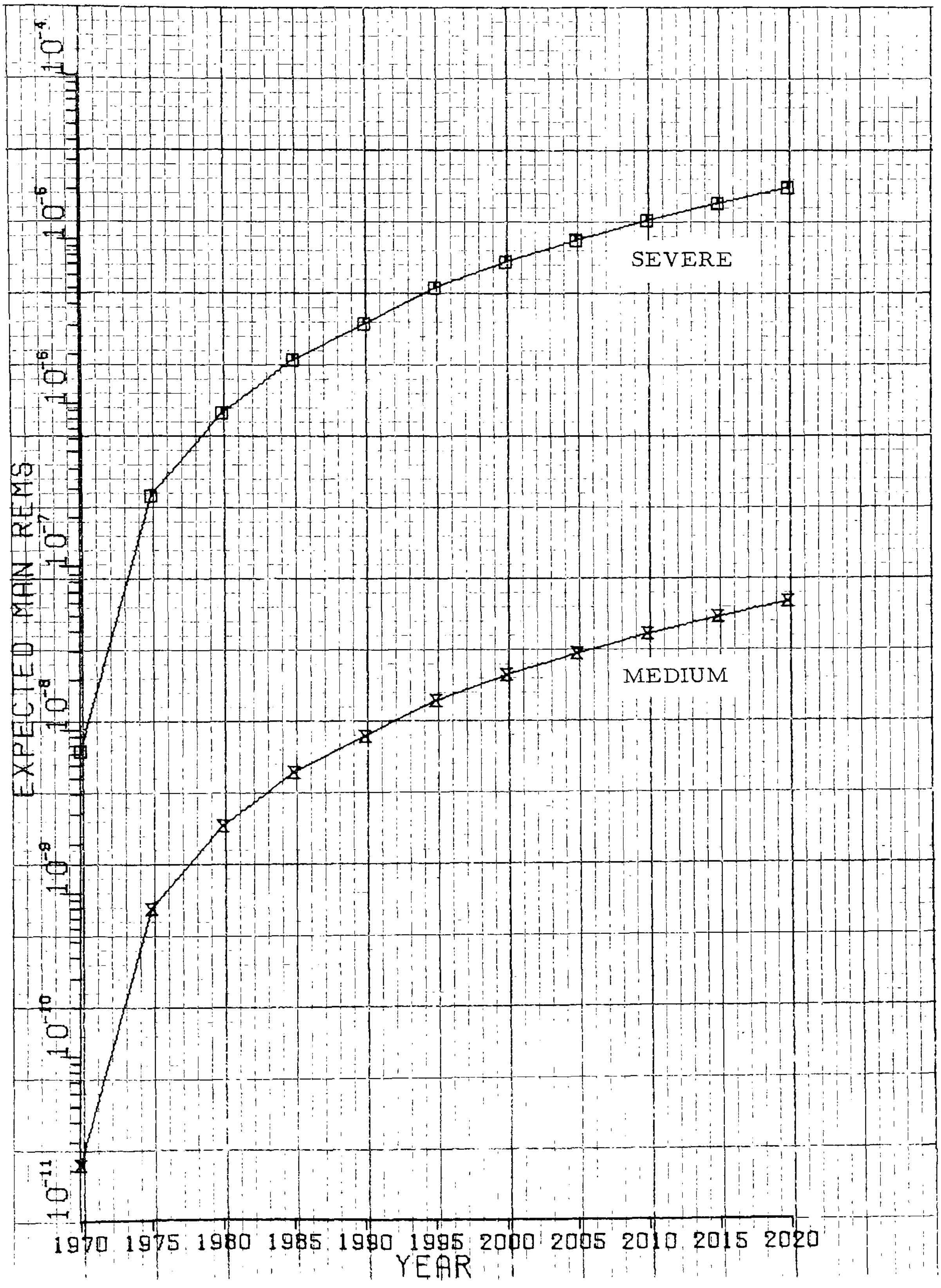


FIGURE 30: COMPARISON OF RISK TO EXPOSURE FOR DIFFERENT ACCIDENT SEVERITIES IN 100 PERCENT TRUCK TRANSPORTATION OF SPENT FUEL

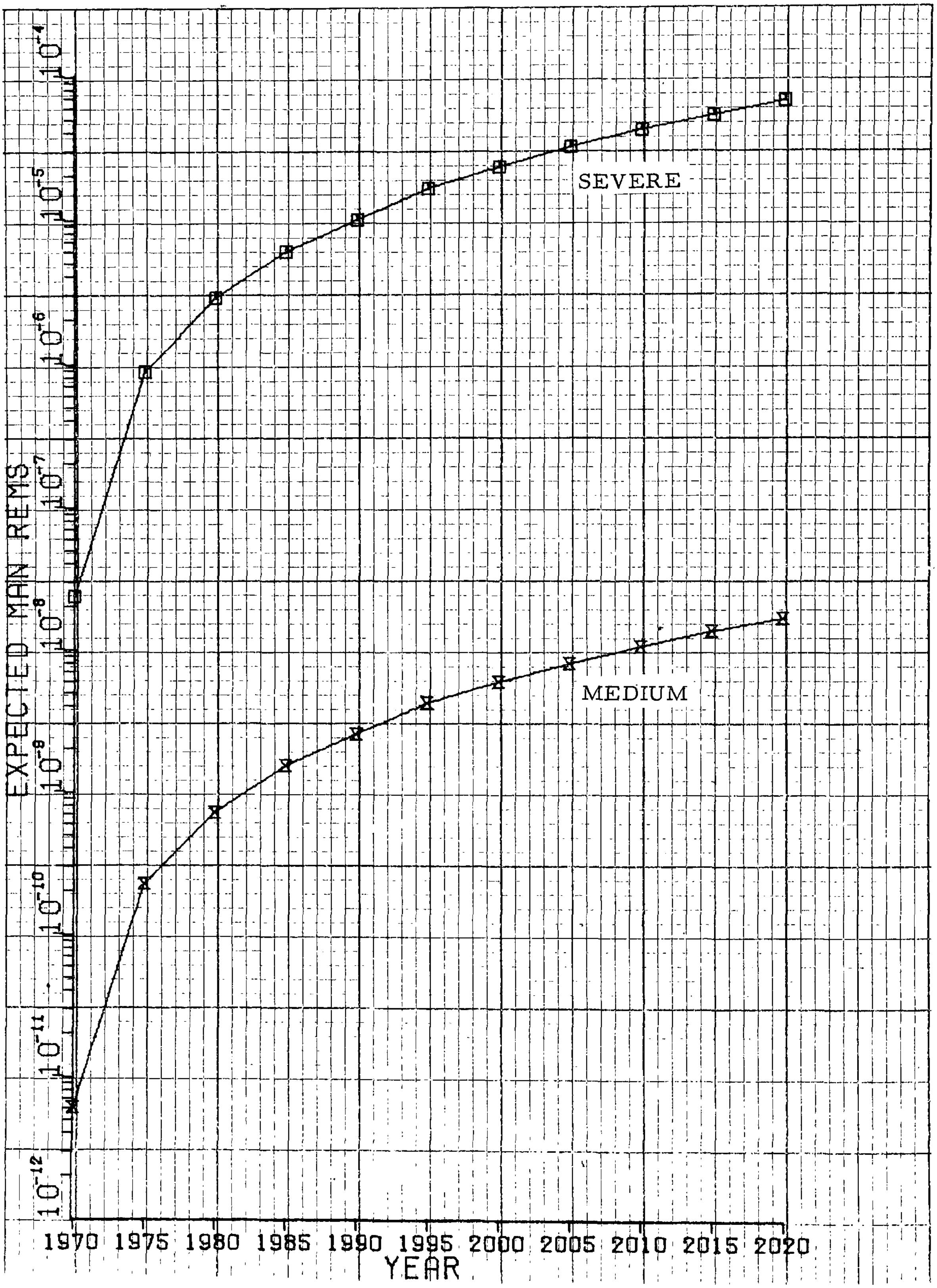


FIGURE 31: COMPARISON OF RISK TO EXPOSURE FOR DIFFERENT ACCIDENT SEVERITIES IN 100 PERCENT RAIL TRANSPORTATION OF SPENT FUEL

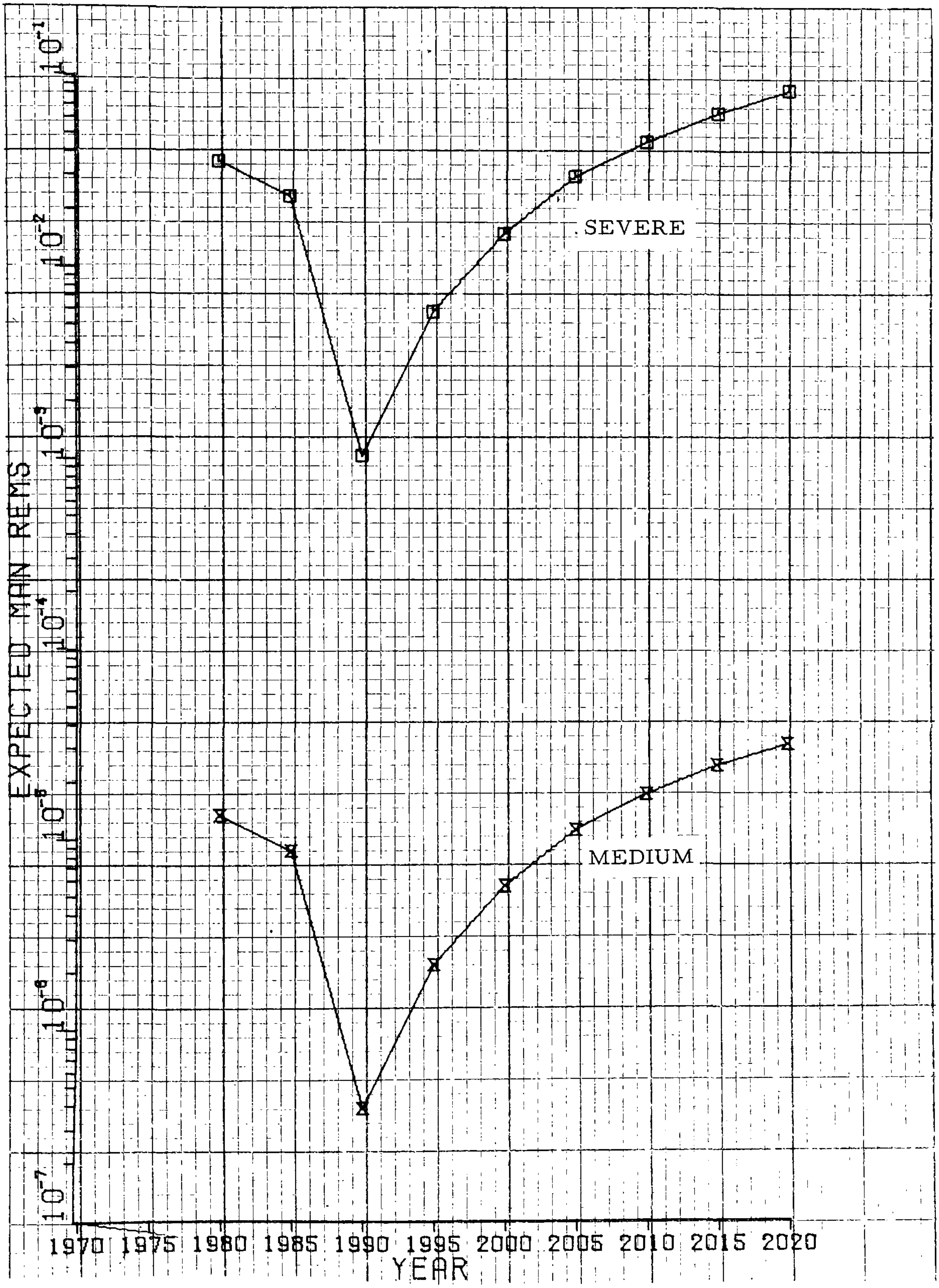


FIGURE 32: COMPARISON OF RISK TO EXPOSURE FOR DIFFERENT ACCIDENT SEVERITIES IN 100 PERCENT TRUCK TRANSPORTATION OF RECYCLED PLUTONIUM

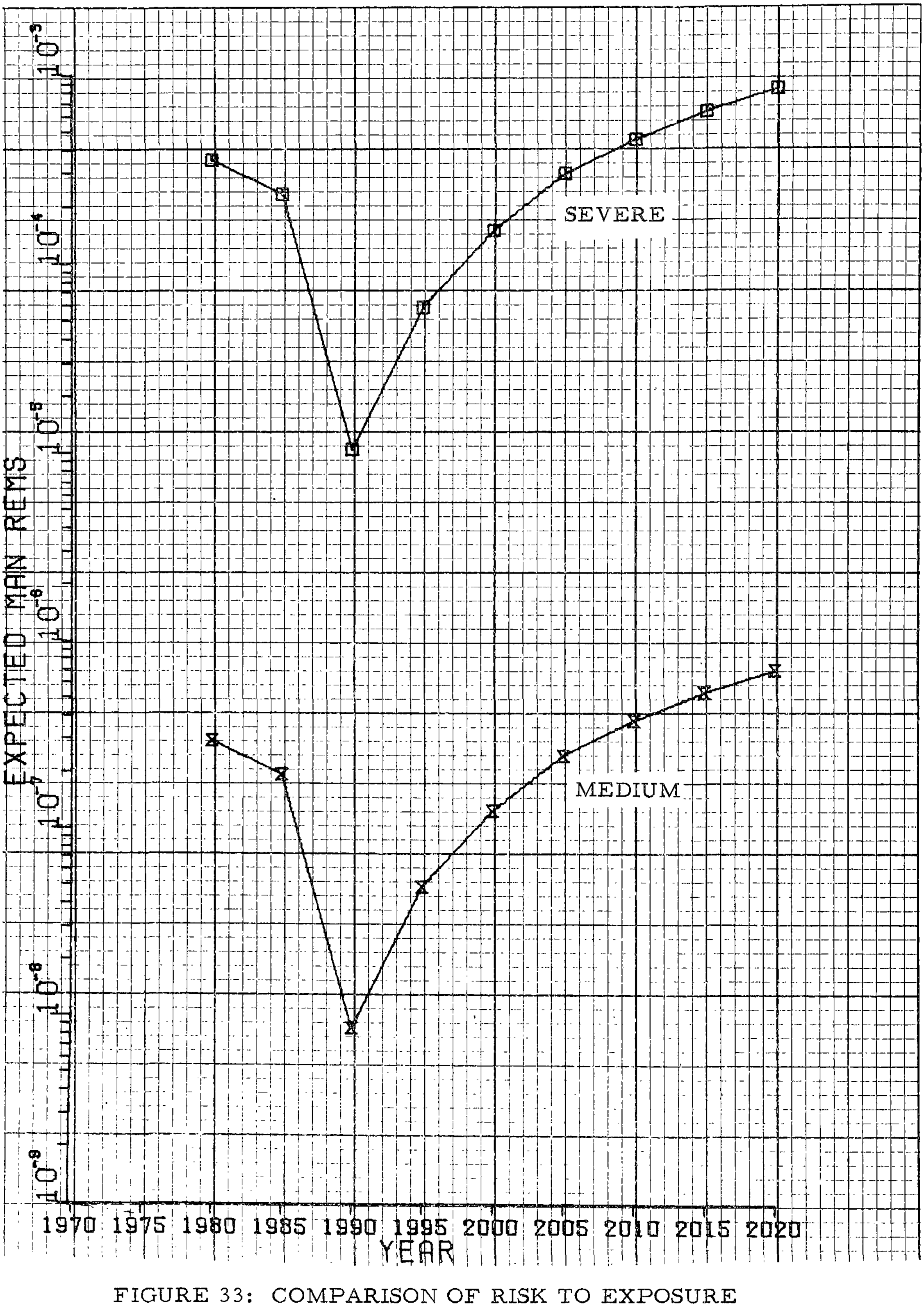


FIGURE 33: COMPARISON OF RISK TO EXPOSURE FOR DIFFERENT ACCIDENT SEVERITIES IN 100 PERCENT RAIL TRANSPORTATION OF RECYCLED PLUTONIUM

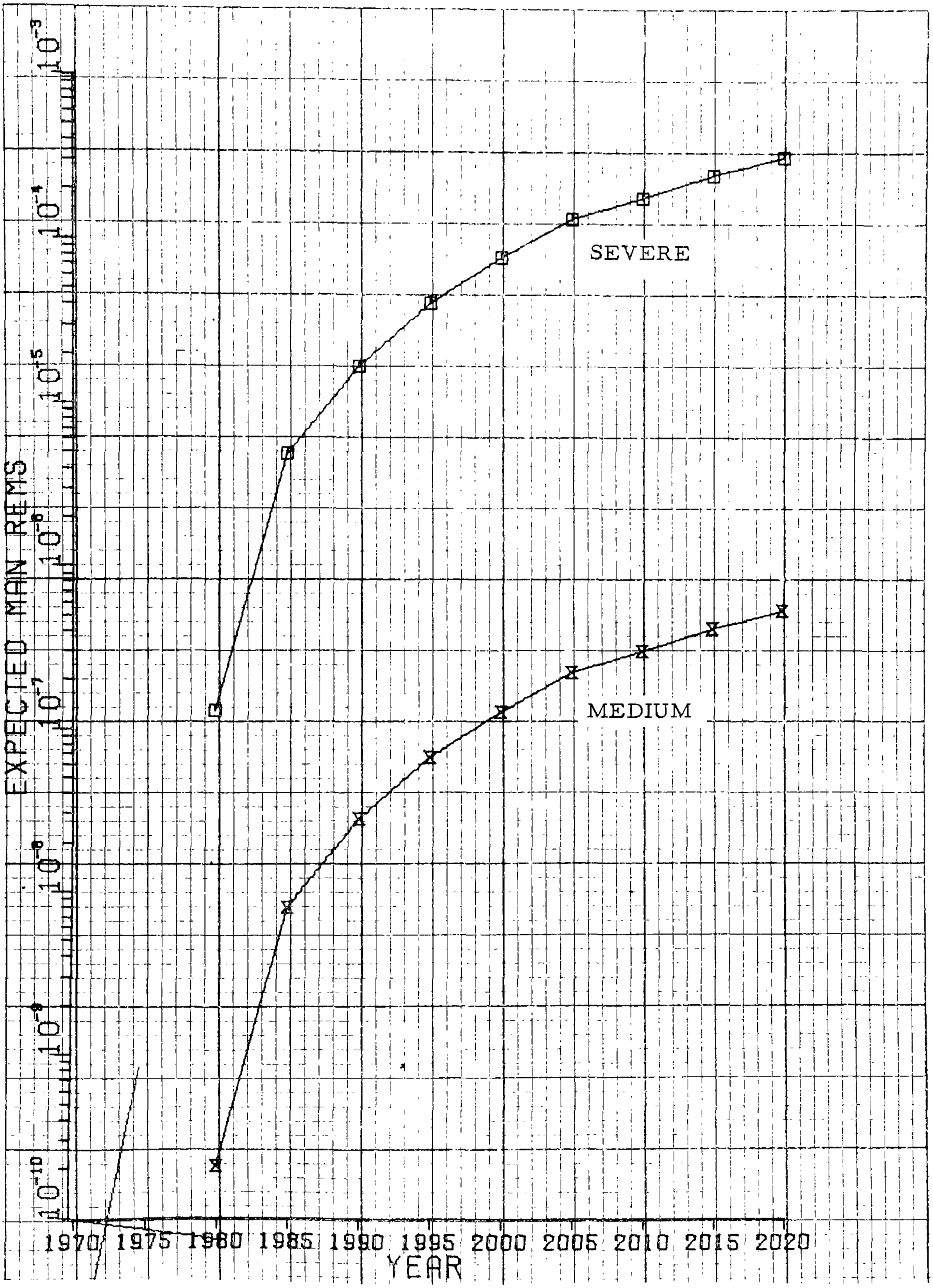


FIGURE 34: COMPARISON OF RISK TO EXPOSURE FOR DIFFERENT ACCIDENT SEVERITIES IN 100 PERCENT TRUCK TRANSPORTATION OF HIGH LEVEL RADIOACTIVE SOLID WASTE

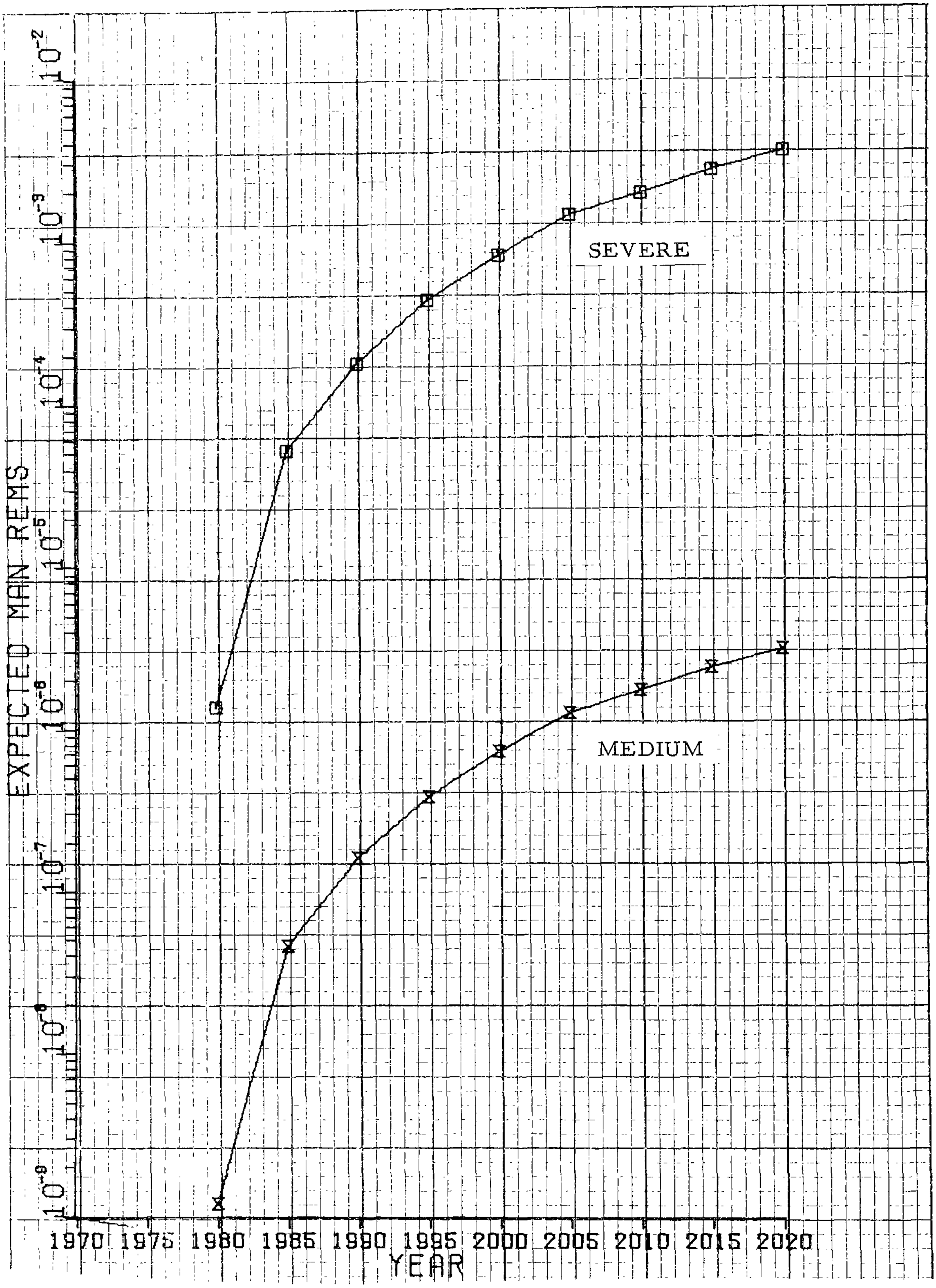


FIGURE 35: COMPARISON OF RISK TO EXPOSURE FOR DIFFERENT ACCIDENT SEVERITIES IN 100 PERCENT RAIL TRANSPORTATION OF HIGH LEVEL RADIOACTIVE SOLID WASTE

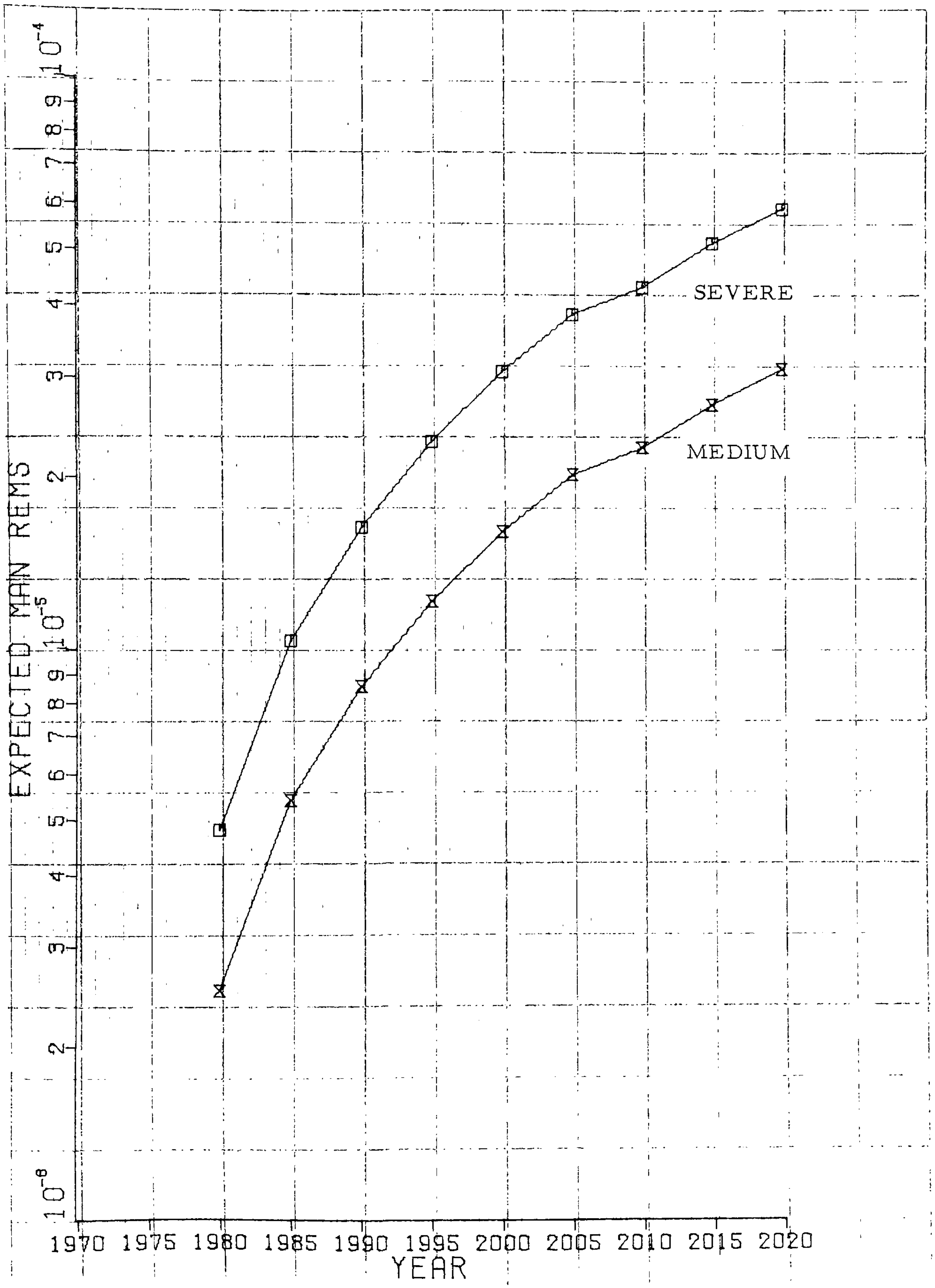


FIGURE 36: COMPARISON OF RISK TO EXPOSURE FOR DIFFERENT ACCIDENT SEVERITIES IN 100 PERCENT TRUCK TRANSPORTATION OF NOBLE GAS

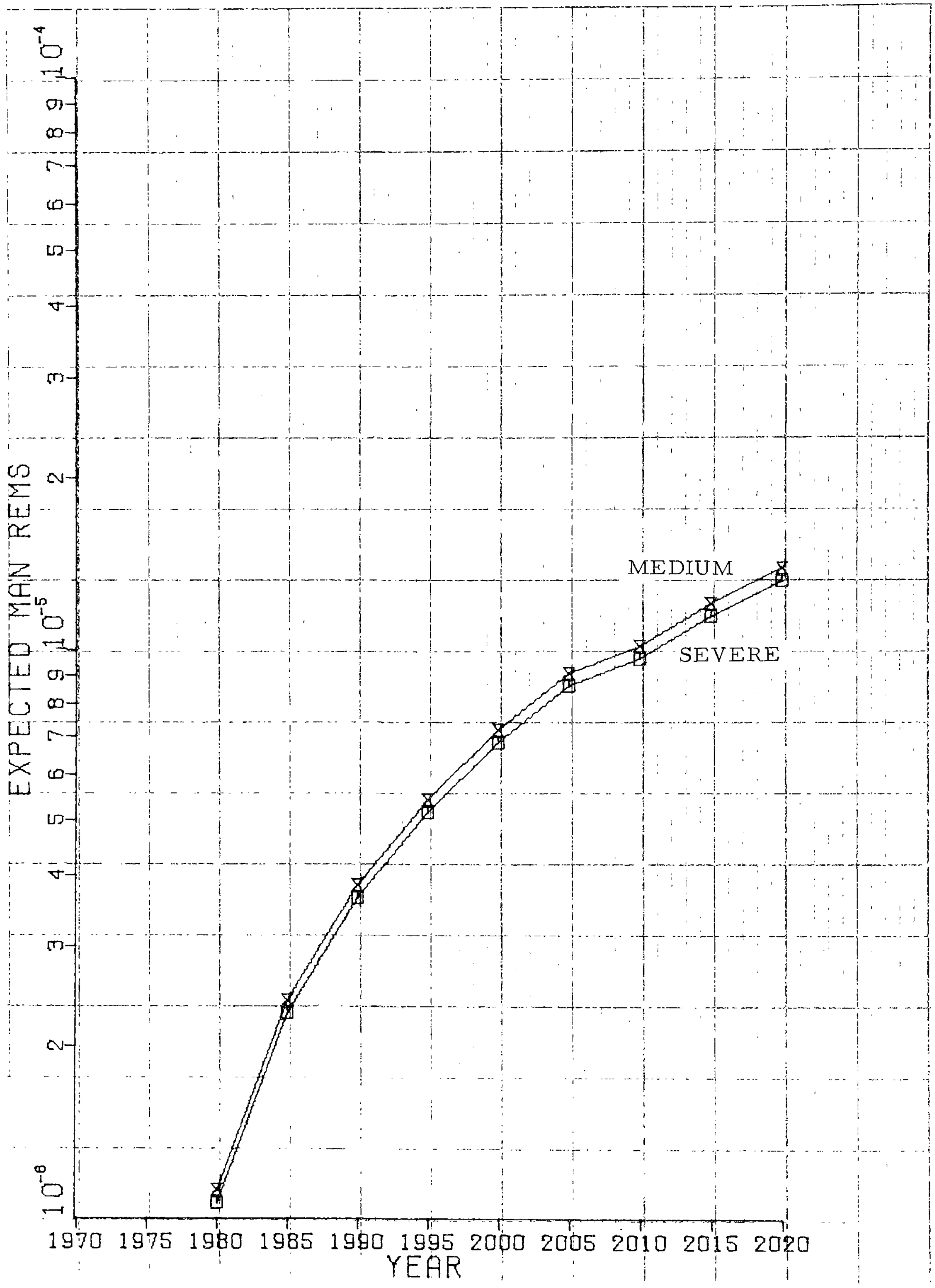


FIGURE 37: COMPARISON OF RISK TO EXPOSURE FOR DIFFERENT ACCIDENT SEVERITIES IN 100 PERCENT RAIL TRANSPORTATION OF NOBLE GAS

In the case of noble gas, both the rail curves are nearly coincident, and both the truck curves are higher than the rail curves. The medium truck curve is about twice as high and the severe truck curve is about 4 times as high. The annual truck severe exposure varies from 5×10^{-6} man-rems in 1980 to 6×10^{-5} man-rems in 2020.

ANALYSIS OF TRANSPORTATION HAZARDS BY CARGO

Graphical comparisons of material container performance characteristics are shown in Figures 38 through 41. The ordinate in each graph is the expected number of man-rems absorbed from releases resulting from severe accidents. In Figure 38, only trucks are assumed to be used; and in Figure 39, only rails are assumed to be used. In Figure 40, a mix of 20 percent trucks, 75 percent rails, and 5 percent barges is assumed; and in Figure 41, a mix of 25 percent trucks, 70 percent rails, and 5 percent barges is assumed.

In the case of all truck transportation, the risk to exposure during the period 1985 to 2020 from the different materials descends in the order: plutonium, solid waste, noble gas, and spent fuel. In 2020, plutonium is expected to give about 0.08 man-rems, solid waste about 3×10^{-4} man-rems, noble gas about 6×10^{-5} man-rems, and spent fuel about 2×10^{-5} man-rems. The ratio between spent fuel and solid waste and the ratio between spent fuel and noble gas can be explained by the ratios in the release fractions given in Table 48, except for a factor of 3.

In the case of all rail transportation, the risk to exposure during the period 1990 to 2020 from the different materials descends in the order: solid waste, plutonium, spent fuel, and noble gas. In 2020, solid waste is expected to give about 3×10^{-3} man-rems, plutonium about 9×10^{-4} man-rems, spent fuel about 7×10^{-5} man-rems, and noble gas about 1×10^{-5} man-rems.

In the case of the transport mix, 20 percent trucks, 75 percent rails, and 5 percent barges, the risk to exposure during the period 1988 to 2020 from the different materials descends in the order: solid waste, plutonium, spent fuel, and noble gas. This order is the same as for all truck transportation; but in this scenario, the plutonium curve lies closer to the solid waste variation. In 2020, the expected number of man-rems are: 9×10^{-3} for solid waste, 7×10^{-3} for plutonium, 4×10^{-4} for spent fuel, and 2×10^{-5} for noble gas.

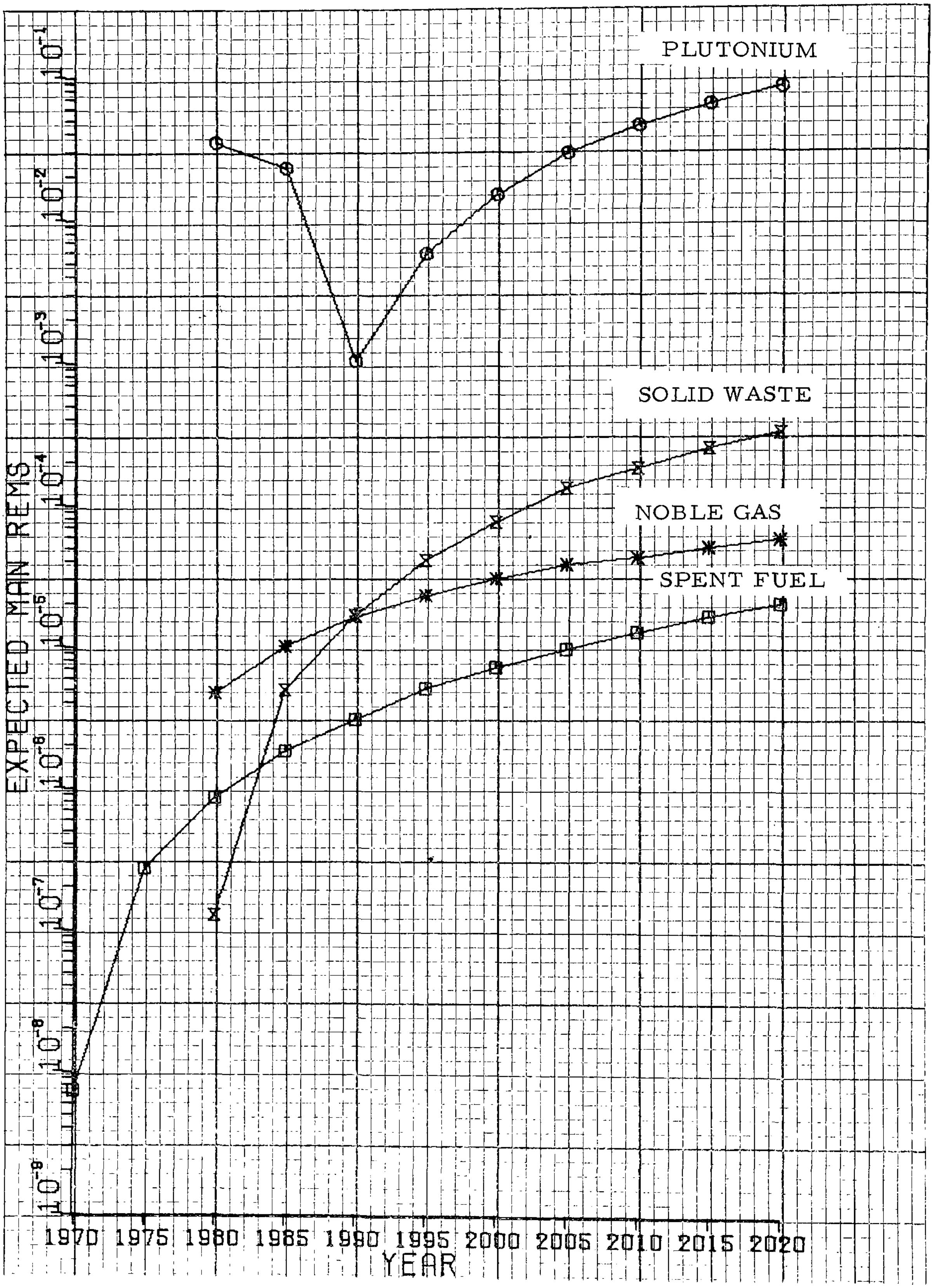


FIGURE 38: COMPARISON OF RISK TO EXPOSURE FOR SEVERE ACCIDENTS TO DIFFERENT MATERIALS. TRANSPORTATION IS BY TRUCKS ONLY.

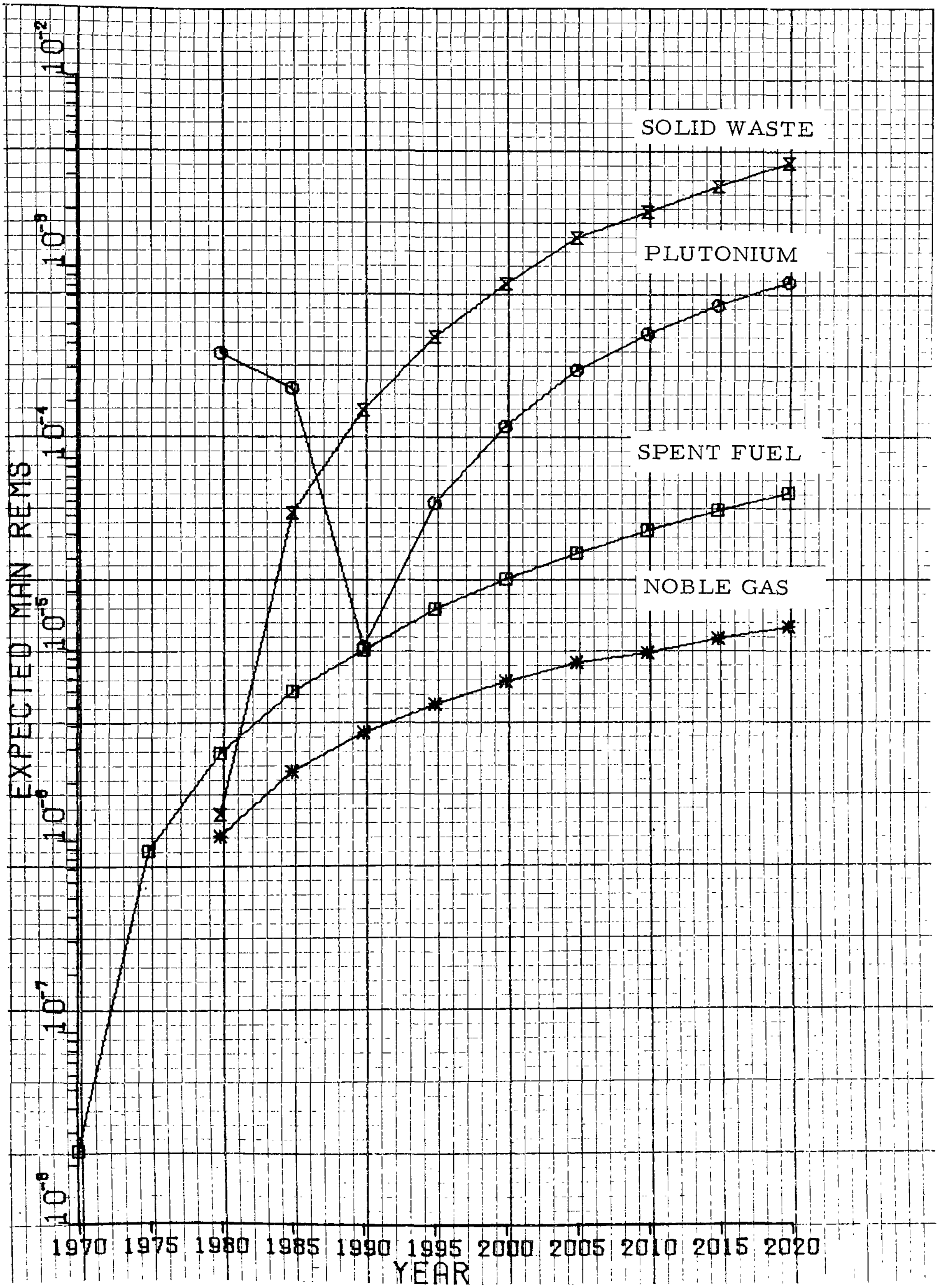


FIGURE 39: COMPARISON OF RISK TO EXPOSURE FOR SEVERE ACCIDENTS TO DIFFERENT MATERIALS. TRANSPORTATION IS BY RAILS ONLY.

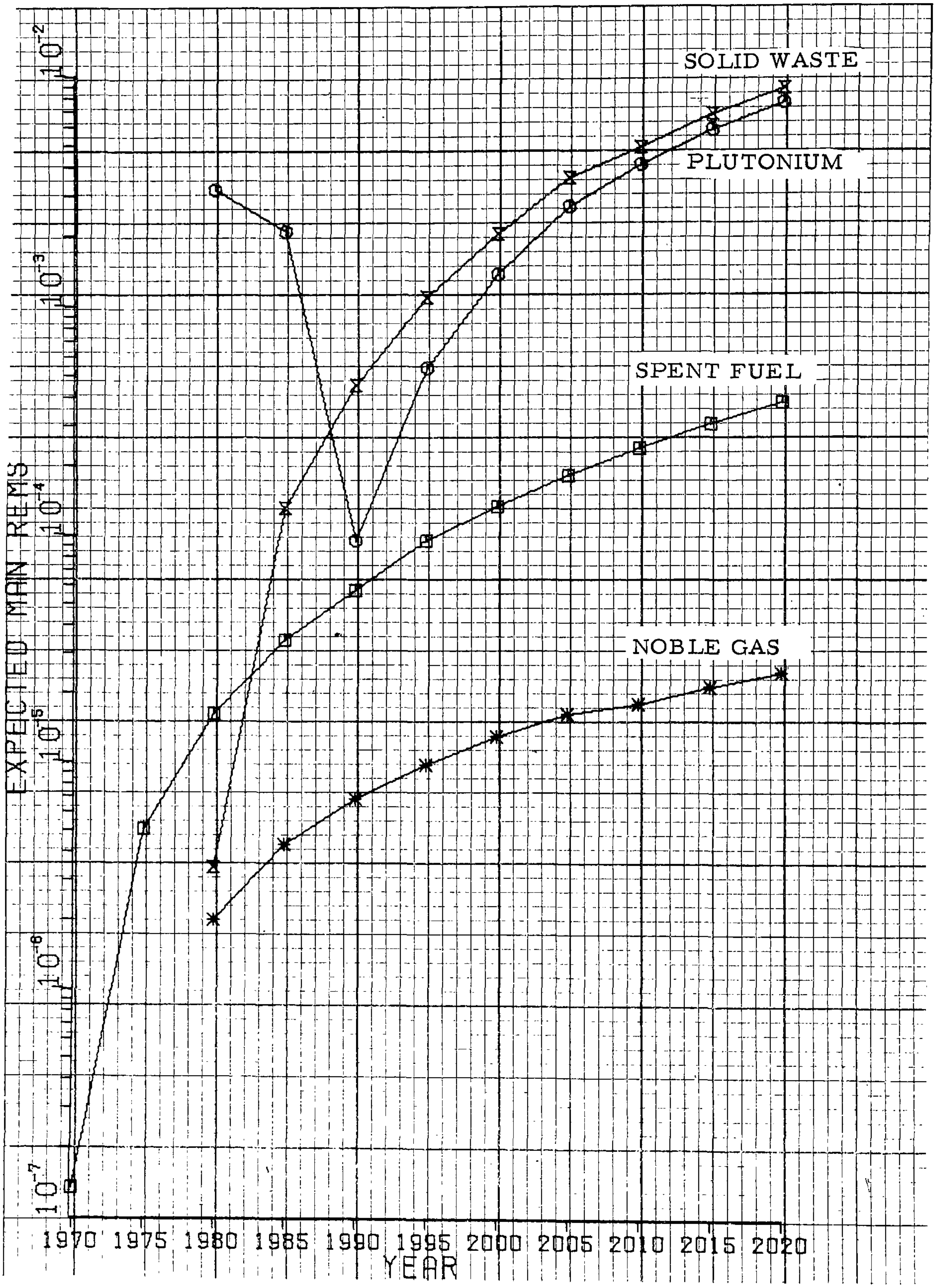


FIGURE 40: COMPARISON OF RISK TO EXPOSURE FOR SEVERE ACCIDENTS TO DIFFERENT MATERIALS. TRANSPORTATION IS BY 20 PERCENT TRUCKS, 75 PERCENT RAILS, AND 5 PERCENT BARGES.

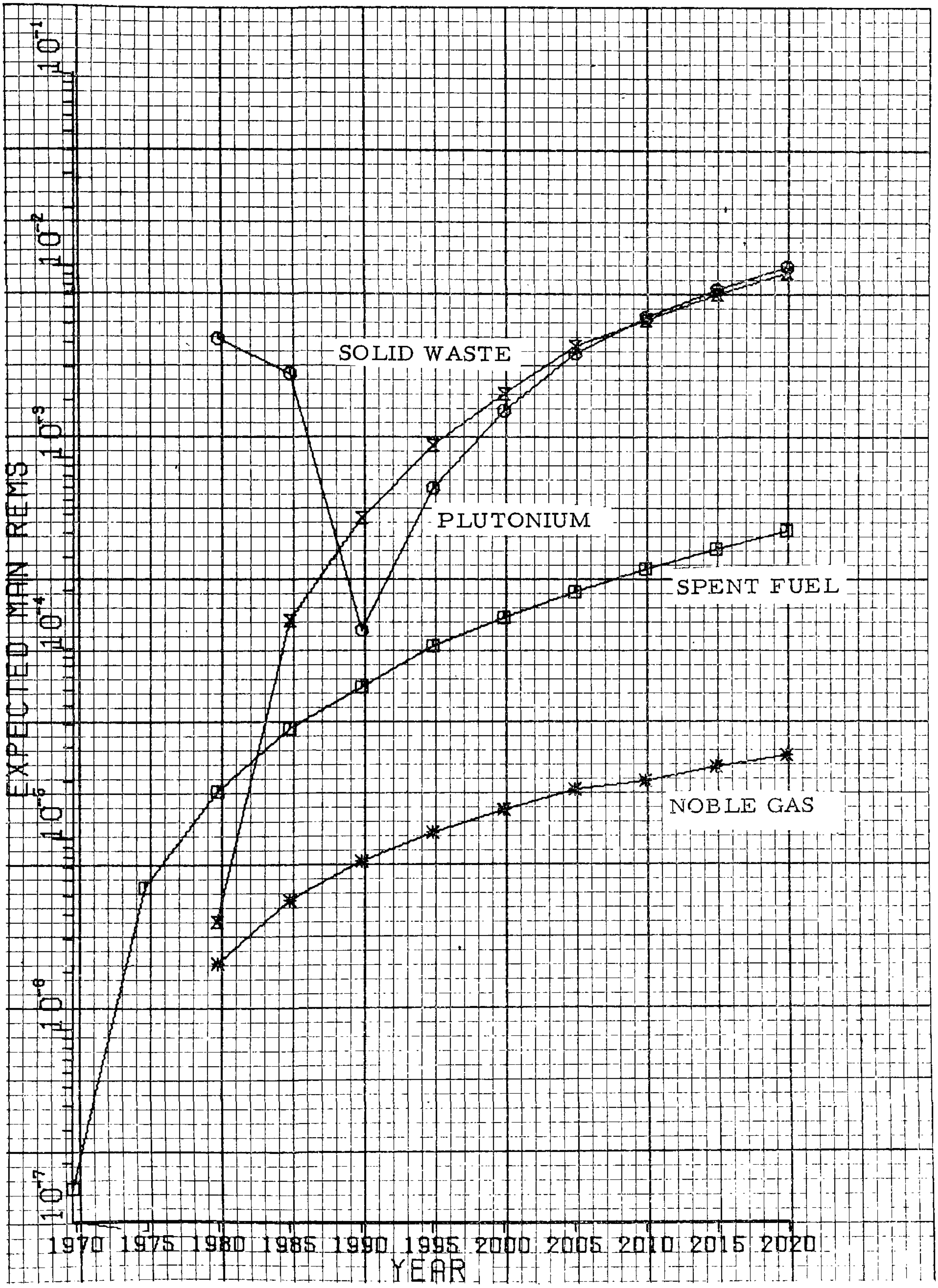


FIGURE 41: COMPARISON OF RISK TO EXPOSURE FOR SEVERE ACCIDENTS TO DIFFERENT MATERIALS. TRANSPORTATION IS BY 25 PERCENT TRUCKS, 70 PERCENT RAILS, AND 5 PERCENT BARGES.

By altering the portions of trucks and rails in the transport mix to 25 percent trucks and 70 percent rails, not much happens to the cargo comparison. The number of man-rems expected in 2020 changes to: 9×10^{-3} for solid waste, 1×10^{-2} for plutonium, 4×10^{-4} for spent fuel, and 2×10^{-5} for noble gas. Evidently the mix which depends less on trucks is preferable.

EFFECT OF VARYING TRANSPORT MIX

To facilitate the comparison of hazards for transport systems employing different portions of trucks, rails, and barges, graphs showing this comparison are given in Figures 42 through 45. Each graph compares the exposure to risk from severe accidents for the use of all trucks, all rails, a mix of 20 percent trucks, 75 percent rails, and 5 percent barges, and a mix of 25 percent trucks, 70 percent rails, and 5 percent barges.

In the case of spent fuel shipments, the greatest exposure to risk comes from the two mixes of transport modes. The expected number of man-rems from the 20-75-5 mix is only slightly less than from the 25-70-5 mix. The risk to exposure using only rails is about 5 times smaller than the mix risks and the risk to exposure using only trucks is about 3 times smaller than the rail risk. From this comparison, one can conclude that truck transportation is preferable for spent fuel.

In the case of plutonium shipments, the greatest exposure to risk is derived from the use of all trucks. The safest scenario is with all rail transport. Quantitatively, the expected annual number of man-rems in 2020 is about 0.08 for all trucks, 0.01 for the 25-70-5 mix, 0.008 for the 20-75-5 mix, and 0.0008 for all rails.

In the case of shipments of high level radioactive solid waste, the greatest risk to exposure is provided by the use of the transport mixes, with the 20-75-5 curve only slightly displaced below the 25-70-5 curve. The risk from all rails is about one-third as large as with the mixes, and the risk from all trucks is about 10 times smaller than the rail risk. The expected annual number of man-rems from the 25-70-5 mix varies from 4×10^{-6} in 1980 to 9×10^{-3} in 2020.

In the case of noble gas shipments, the greatest exposure to risk is derived from the use of all trucks, and the least exposure is from the use of all rails. The expected annual number of man-rems in 2020 is

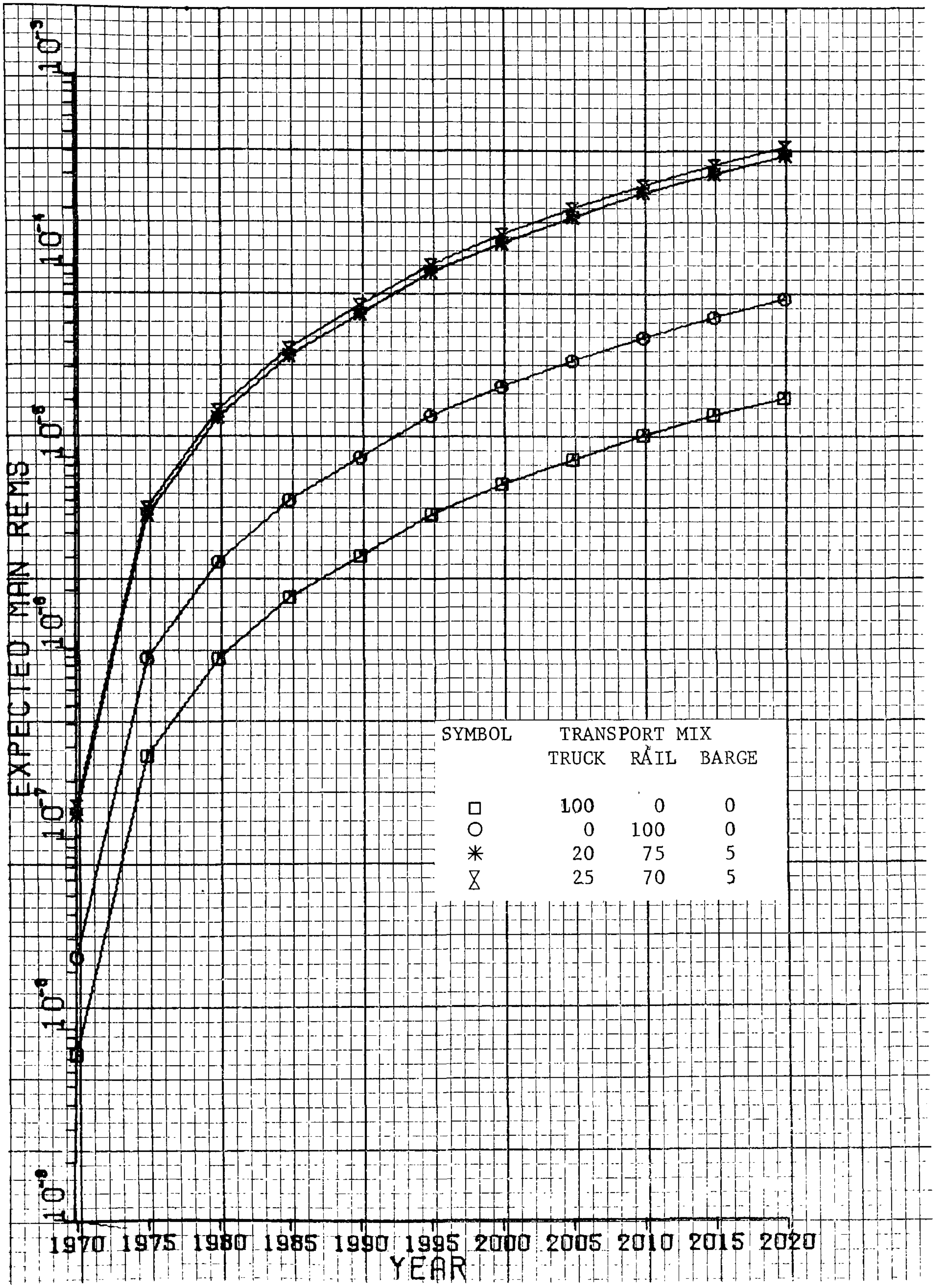


FIGURE 42: COMPARISON OF EXPOSURE TO RISK OF SEVERE ACCIDENTS TO SPENT FUEL SHIPMENTS IN DIFFERENT TRANSPORT MIXES

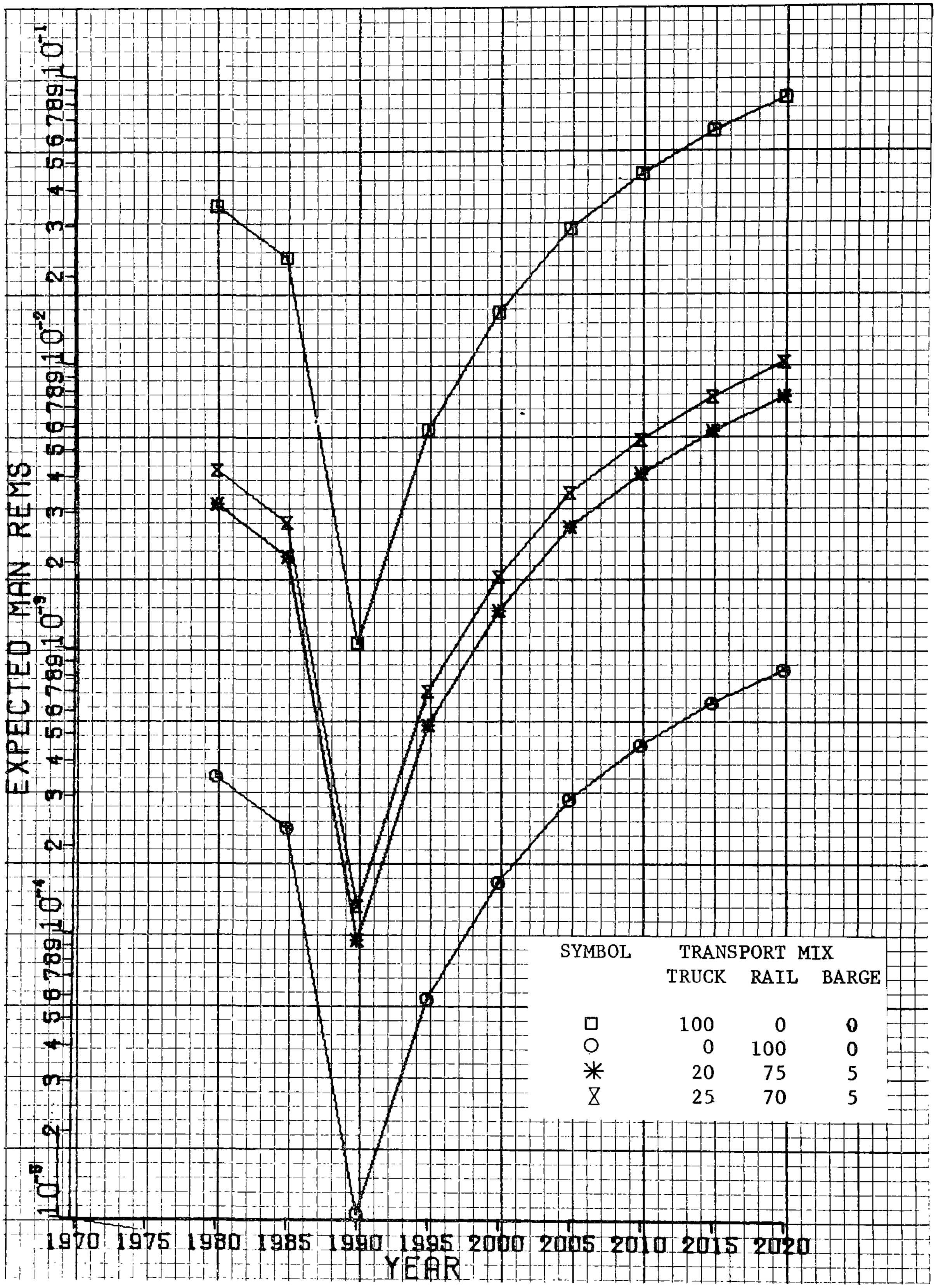


FIGURE 43: COMPARISON OF EXPOSURE TO RISK OF SEVERE ACCIDENTS TO RECYCLED PLUTONIUM SHIPMENTS IN DIFFERENT TRANSPORT MIXES

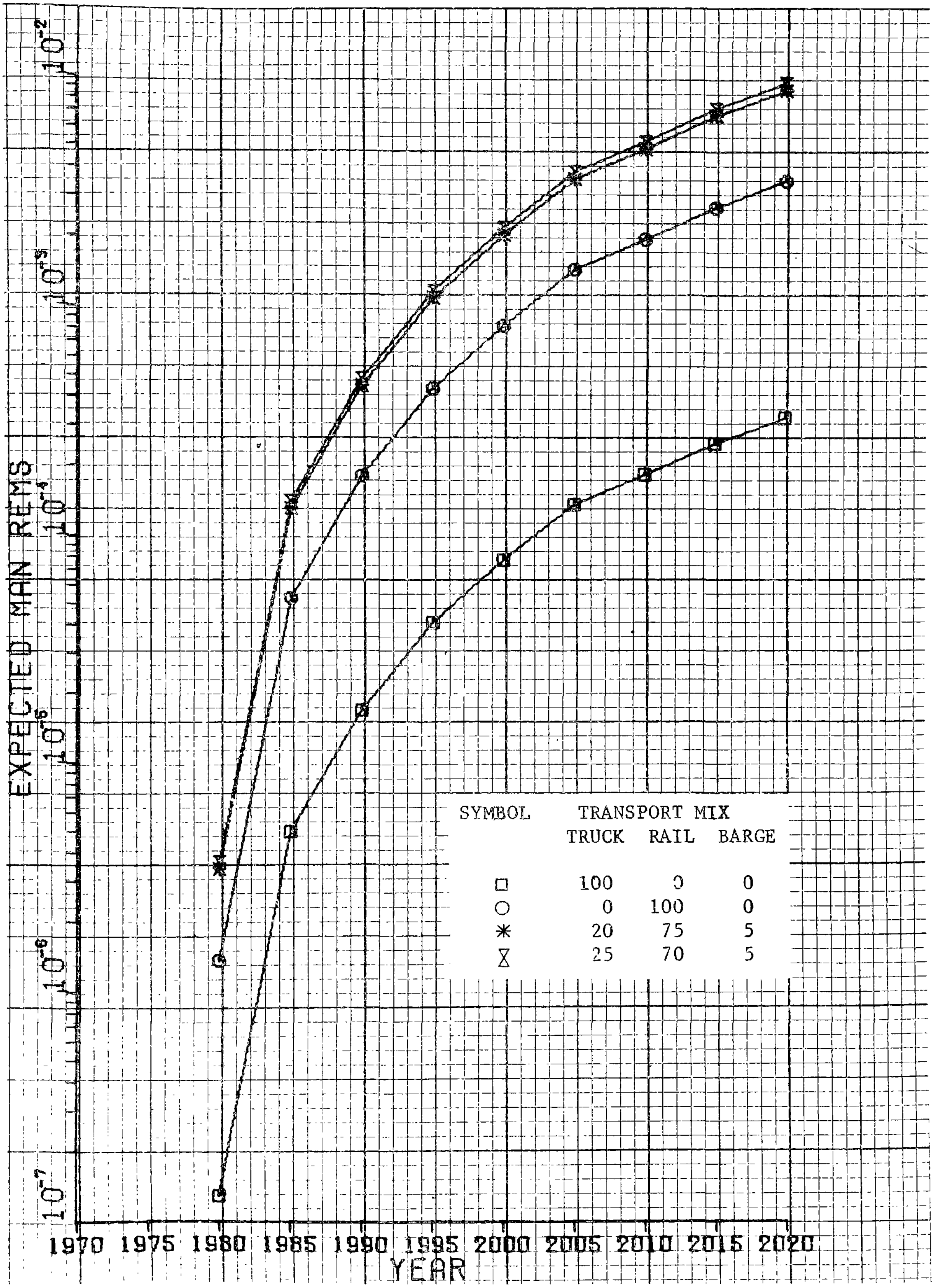


FIGURE 44: COMPARISON OF EXPOSURE TO RISK OF SEVERE ACCIDENTS TO HIGH LEVEL RADIOACTIVE SOLID WASTE SHIPMENTS IN DIFFERENT TRANSPORT MIXES

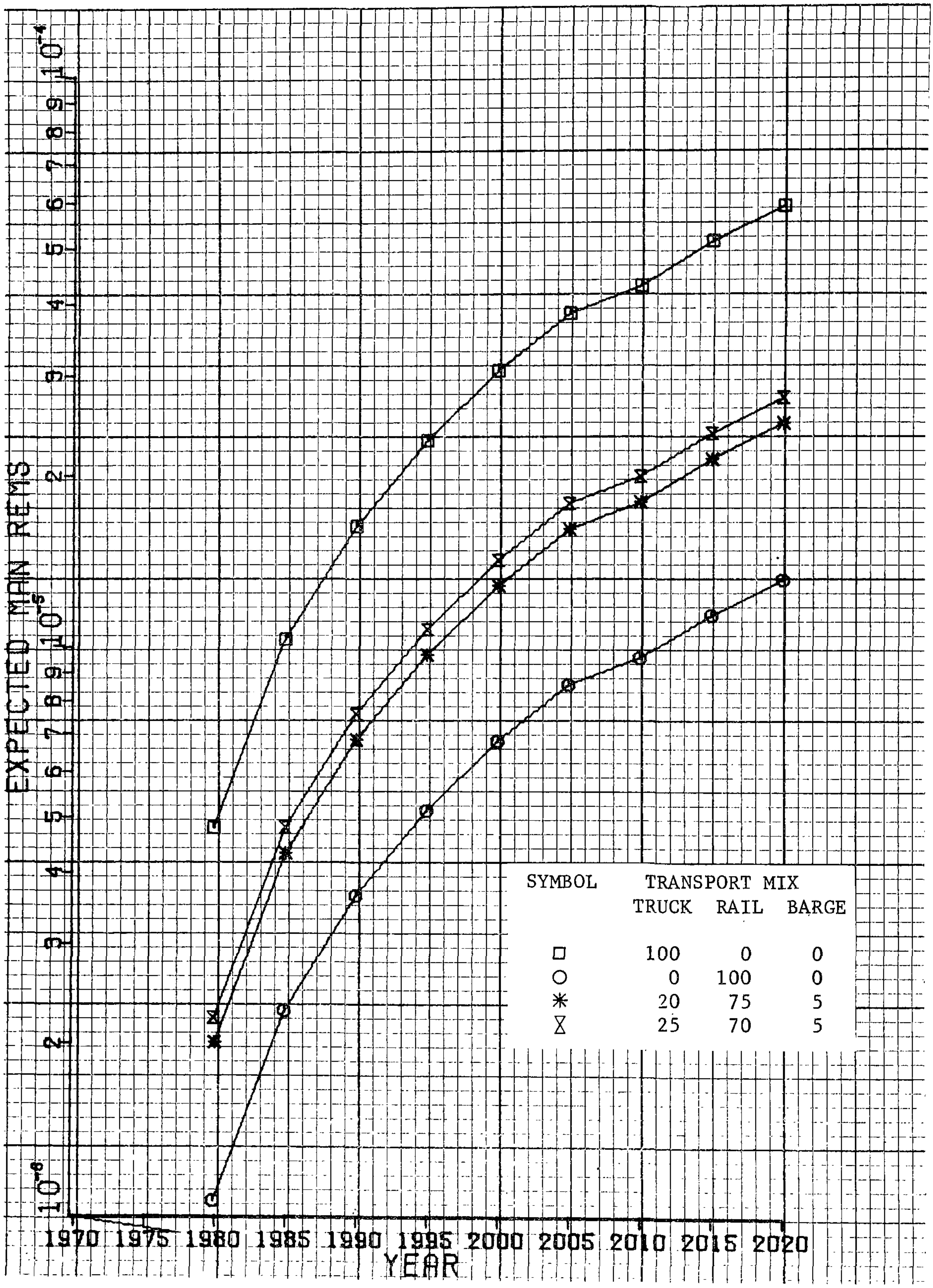


FIGURE 45: COMPARISON OF EXPOSURE TO RISK OF SEVERE ACCIDENTS TO NOBLE GAS SHIPMENTS IN DIFFERENT TRANSPORT MIXES

$6x10^{-5}$ for all trucks, $3x10^{-5}$ for the 25-70-5 mix, $2x10^{-5}$ for the 20-75-5 mix, and $1x10^{-5}$ for all rails.

Given the validity of the fault trees and release fractions, one would conclude from this analysis that all truck transportation is preferable, from a safety point of view, for shipments of spent fuel and solid waste, and all rail transportation is preferable for shipments of plutonium and noble gas.

ANALYSIS OF ACCIDENTS BY SEVERITY AND DISPERSION MEDIA

An accident summary for each of the materials for total usage of trucks and rails is presented in each of Tables 58 through 65. In Tables 58 and 59, the expected annual number of accidents and the expected number of releases in air or water are tabulated for spent fuel shipments. In Table 58, only trucks are assumed for transport, and in Table 59, only rails are assumed for transport. Similar analyses are given in Tables 60 and 61 for recycled plutonium, in Tables 62 and 63 for high level radioactive solid waste, and in Tables 64 and 65 for noble gas.

The basis for this kind of analysis is simply the product of the number of shipment-miles and the accident probability for the given accident severity and transport mode. The basis for the water-air dispersion medium analysis rests with observations of previous nuclear transportation accidents (Reference 21).

The numbers of accidents given in these tables can be construed as accident rates, with 1 year as the basic unit of time. Looking at Table 58 for spent fuel, the 1980 numbers, for example, are meaningless if literally interpreted as the number of accidents expected to occur in the whole year, since these numbers are proper fractions and the number of accidents can only be integral. The numbers should be taken to mean the annual accident rate; i.e., the expected number of light accidents (0.6071) should be interpreted to mean that one light accident is expected to occur in the reciprocal (1/.6701 = 1.49) number of years.

In the case when only trucks are used for transport, Table 58 indicates that in 2020 spent fuel shipments are expected to encounter 12.13 light accidents per year, 2.8 medium accidents per year, and 0.075 severe accidents per year. One expects that at that time an accident serious enough (i.e., the severe category) to possibly cause a rupture of the spent fuel cask will occur sometime in an interval of 13.4 years.

TABLE 58: ANALYSIS OF TRUCK ACCIDENTS INVOLVING SPENT FUEL BY SEVERITY AND DISPERSION MEDIUM

TRANSPORT MIX : 100 PCT TRUCKS, 0 PCT RAILROADS, 0 PCT BARGES

MATERIAL TYPE : SPENT FUEL

EXPECTED ACCIDENTS SUMMARY

YEAR	NO OF SHIPMENTS	EXPECTED NUMBER OF ACCIDENTS LIGHT	MEDIUM	SEVERE	TOTAL	EXPECTED NUMBER OF RELEASE INCIDENTS AIR	WATER	TOTAL
1970	5	4.5500E-03	1.0500E-03	2.8000E-05	5.6280E-03	1.3594E-14	6.7968E-15	2.1070E-13
1975	191	1.4898E-01	3.4380E-02	9.1680E-04	1.8429E-01	4.4509E-13	2.2255E-13	6.8989E-12
1980	934	6.0710E-01	1.4010E-01	3.7360E-03	7.5094E-01	1.8138E-12	9.0688E-13	2.8113E-11
1985	1612	9.4302E-01	2.1762E-01	5.8032E-03	1.1664E+00	2.8174E-12	1.4087E-12	4.3569E-11
1990	3297	1.7144E+00	3.9564E-01	1.0550E-02	2.1206E+00	5.1220E-12	2.5610E-12	7.9392E-11
1995	7463	3.8808E+00	8.9556E-01	2.3882E-02	4.8002E+00	1.1594E-11	5.7971E-12	1.7971E-10
2000	10224	5.3165E+00	1.2269E+00	3.2717E-02	6.5761E+00	1.5883E-11	7.9417E-12	2.4619E-10
2005	12100	6.2920E+00	1.4520E+00	3.8720E-02	7.7827E+00	1.8798E-11	9.3990E-12	2.9137E-10
2010	16360	8.5072E+00	1.9632E+00	5.2352E-02	1.0523E+01	2.5416E-11	1.2708E-11	3.9395E-10
2015	19697	1.0242E+01	2.3636E+00	6.3030E-02	1.2669E+01	3.0600E-11	1.5300E-11	4.7430E-10
2020	23334	1.2134E+01	2.8001E+00	7.4669E-02	1.5008E+01	3.6250E-11	1.8125E-11	5.6188E-10

TABLE 59: ANALYSIS OF RAIL ACCIDENTS INVOLVING SPENT FUEL BY SEVERITY AND DISPERSION MEDIUM

TRANSPORT MIX : 0 PCT TRUCKS, 100 PCT RAILROADS, 0 PCT BARGES

MATERIAL TYPE : SPENT FUEL

EXPECTED ACCIDENTS SUMMARY

YEAR	NO OF	EXPECTED NUMBER OF ACCIDENTS				EXPECTED NUMBER OF RELEASE INCIDENTS		
	SHIPMENTS	LIGHT	MEDIUM	SEVERE	TOTAL	AIR	WATER	TOTAL
1970	5	2.5550E-03	2.7650E-04	5.2500E-06	2.8367E-03	1.4032E-14	7.0158E-15	2.1749E-13
1975	191	8.3658E-02	9.0534E-03	1.7190E-04	9.2883E-02	4.5944E-13	2.2972E-13	7.1212E-12
1980	934	3.4091E-01	3.6893E-02	7.0050E-04	3.7850E-01	1.8722E-12	9.3611E-13	2.9019E-11
1985	1612	5.2954E-01	5.7307E-02	1.0861E-03	5.8794E-01	2.9082E-12	1.4541E-12	4.5076E-11
1990	3297	9.6272E-01	1.0419E-01	1.9762E-03	1.0689E+00	5.2871E-12	2.6436E-12	8.1950E-11
1995	7463	2.1792E+00	2.3583E-01	4.4778E-03	2.4195E+00	1.1968E-11	5.9839E-12	1.8550E-10
2000	10224	2.9854E+00	3.2308E-01	6.1344E-03	3.3146E+00	1.6395E-11	8.1977E-12	2.5413E-10
2005	12100	3.5332E+00	3.8236E-01	7.2600E-03	3.9228E+00	1.9404E-11	9.7019E-12	3.0076E-10
2010	16360	4.7771E+00	5.1698E-01	9.8160E-03	5.3039E+00	2.6235E-11	1.3118E-11	4.0664E-10
2015	19697	5.7515E+00	6.2243E-01	1.1818E-02	6.3859E+00	3.1586E-11	1.5793E-11	4.8959E-10
2020	23334	6.8135E+00	7.3735E-01	1.4000E-02	7.5649E+00	3.7419E-11	1.8709E-11	5.7999E-10

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TABLE 60: ANALYSIS OF TRUCK ACCIDENTS INVOLVING PLUTONIUM BY SEVERITY AND DISPERSION MEDIUM

TRANSPORT MIX : 100 PCT TRUCKS, 0 PCT RAILROADS, 0 PCT BARGES

MATERIAL TYPE : PLUTONIUM

EXPECTED ACCIDENTS SUMMARY

YEAR	NO OF SHIPMENTS	EXPECTED NUMBER OF ACCIDENTS LIGHT	MEDIUM	SEVERE	TOTAL	EXPECTED NUMBER OF RELEASE INCIDENTS AIR	WATER	TOTAL
1970	0	0.	0.	0.	0.	0.	0.	0.
1975	0	0.	0.	0.	0.	0.	0.	0.
1980	10680	6.9420E+00	1.6020E+00	4.2720E-02	8.5867E+00	1.1369E-08	5.6845E-09	1.7622E-07
1985	7234	4.2319E+00	9.7659E-01	2.0042E-02	5.2345E+00	6.9306E-09	3.4653E-09	1.0742E-07
1990	580	3.0160E-01	6.9600E-02	1.8560E-03	3.7306E-01	4.9394E-10	2.4697E-10	7.6560E-09
1995	3179	1.6531E+00	3.8148E-01	1.0173E-02	2.0447E+00	2.7073E-09	1.3536E-09	4.1963E-08
2000	7813	4.0628E+00	9.3756E-01	2.5002E-02	5.0253E+00	6.6537E-09	3.3268E-09	1.0313E-07
2005	14464	7.5213E+00	1.7357E+00	4.6285E-02	9.3032E+00	1.2318E-08	6.1589E-09	1.9092E-07
2010	20995	1.0917E+01	2.5194E+00	6.7184E-02	1.3504E+01	1.7880E-08	8.9398E-09	2.7713E-07
2015	27993	1.4556E+01	3.3592E+00	8.9578E-02	1.8005E+01	2.3839E-08	1.1920E-08	3.6951E-07
2020	34991	1.8195E+01	4.1989E+00	1.1197E-01	2.2506E+01	2.9799E-08	1.4899E-08	4.6188E-07

TABLE 61: ANALYSIS OF RAIL ACCIDENTS INVOLVING PLUTONIUM BY SEVERITY AND DISPERSION MEDIUM

TRANSPORT MIX : 0 PCT TRUCKS, 100 PCT RAILROADS, 0 PCT BARGES

MATERIAL TYPE : PLUTONIUM

EXPECTED ACCIDENTS SUMMARY

YEAR	NO OF	EXPECTED NUMBER OF ACCIDENTS				EXPECTED NUMBER OF RELEASE INCIDENTS		
	SHIPMENTS	LIGHT	MEDIUM	SEVERE	TOTAL	AIR	WATER	TOTAL
1970	0	0.	0.	0.	0.	0.	0.	0.
1975	0	0.	0.	0.	0.	0.	0.	0.
1980	10680	3.8982E+00	4.2186E-01	8.0100E-03	4.3281E+00	1.5073E-10	7.5363E-11	2.3362E-09
1985	7234	2.3764E+00	2.5717E-01	4.8829E-03	2.6384E+00	9.1883E-11	4.5942E-11	1.4242E-09
1990	580	1.6936E-01	1.8328E-02	3.4800E-04	1.8804E-01	6.5484E-12	3.2742E-12	1.0150E-10
1995	3179	9.2827E-01	1.0046E-01	1.9074E-03	1.0306E+00	3.5892E-11	1.7946E-11	5.5632E-10
2000	7813	2.2814E+00	2.4689E-01	4.6878E-03	2.5330E+00	8.8211E-11	4.4106E-11	1.3673E-09
2005	14464	4.2235E+00	4.5706E-01	8.6784E-03	4.6892E+00	1.6330E-10	8.1652E-11	2.5312E-09
2010	20995	6.1305E+00	6.6344E-01	1.2597E-02	6.8066E+00	2.3704E-10	1.1852E-10	3.6741E-09
2015	27993	8.1740E+00	8.8458E-01	1.6796E-02	9.0753E+00	3.1605E-10	1.5802E-10	4.8988E-09
2020	34991	1.0217E+01	1.1057E+00	2.0995E-02	1.1344E+01	3.9506E-10	1.9753E-10	6.1234E-09

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TABLE 62: ANALYSIS OF TRUCK ACCIDENTS INVOLVING SOLID RADIOACTIVE WASTE BY SEVERITY AND DISPERSION MEDIUM

TRANSPORT MIX : 100 PCT TRUCKS, 0 PCT RAILROADS, 0 PCT BARGES

MATERIAL TYPE : SOLID RADIOACTIVE WASTE

EXPECTED ACCIDENTS SUMMARY

YEAR	NO OF SHIPMENTS	EXPECTED NUMBER OF ACCIDENTS				EXPECTED NUMBER OF RELEASE INCIDENTS		
		LIGHT	MEDIUM	SEVERE	TOTAL	AIR	WATER	TOTAL
1970	0	0.	0.	0.	0.	0.	0.	0.
1975	0	0.	0.	0.	0.	0.	0.	0.
1980	1	3.2500E-03	7.5000E-04	2.0000E-05	4.0200E-03	2.7161E-13	1.3581E-13	4.2100E-12
1985	23	7.4750E-02	1.7250E-02	4.6000E-04	9.2460E-02	6.2471E-12	3.1235E-12	9.6830E-11
1990	65	1.8590E-01	4.2900E-02	1.1440E-03	2.2994E-01	1.5536E-11	7.7681E-12	2.4081E-10
1995	140	4.0040E-01	9.2400E-02	2.4640E-03	4.9526E-01	3.3463E-11	1.6731E-11	5.1867E-10
2000	257	7.3502E-01	1.6962E-01	4.5232E-03	9.0916E-01	6.1428E-11	3.0714E-11	9.5213E-10
2005	420	1.2012E+00	2.7720E-01	7.3920E-03	1.4858E+00	1.0039E-10	5.0194E-11	1.5560E-09
2010	610	1.5860E+00	3.6600E-01	9.7600E-03	1.9618E+00	1.3255E-10	6.6274E-11	2.0545E-09
2015	852	2.2152E+00	5.1120E-01	1.3632E-02	2.7400E+00	1.8513E-10	9.2566E-11	2.8695E-09
2020	1094	2.8444E+00	6.5640E-01	1.7504E-02	3.5183E+00	2.3772E-10	1.1886E-10	3.6846E-09

TABLE 63: ANALYSIS OF RAIL ACCIDENTS INVOLVING SOLID RADIOACTIVE WASTE BY SEVERITY AND DISPERSION MEDIUM

TRANSPORT MIX : 0 PCT TRUCKS, 100 PCT RAILROADS, 0 PCT BARGES

MATERIAL TYPE : SOLID RADIOACTIVE WASTE

EXPECTED ACCIDENTS SUMMARY

YEAR	NO OF SHIPMENTS	EXPECTED NUMBER OF ACCIDENTS LIGHT	MEDIUM	SEVERE	TOTAL	EXPECTED NUMBER OF RELEASE INCIDENTS AIR	WATER	TOTAL
1970	0	0.	0.	0.	0.	0.	0.	0.
1975	0	0.	0.	0.	0.	0.	0.	0.
1980	1	1.8250E-03	1.9750E-04	3.7500E-06	2.0262E-03	1.7161E-12	8.5806E-13	2.6500E-11
1985	23	4.1975E-02	4.5425E-03	8.6250E-05	4.6604E-02	3.9471E-11	1.9735E-11	6.1190E-10
1990	65	1.0439E-01	1.1297E-02	2.1450E-04	1.1590E-01	9.8163E-11	4.9081E-11	1.5215E-09
1995	140	2.2484E-01	2.4332E-02	4.6200E-04	2.4963E-01	2.1143E-10	1.0571E-10	3.2771E-09
2000	257	4.1274E-01	4.4667E-02	8.4810E-04	4.5826E-01	3.8812E-10	1.9406E-10	6.0159E-09
2005	420	6.7452E-01	7.2996E-02	1.3860E-03	7.4890E-01	6.3428E-10	3.1714E-10	9.8314E-09
2010	610	8.9060E-01	9.6380E-02	1.8300E-03	9.8881E-01	8.3747E-10	4.1874E-10	1.2981E-08
2015	852	1.2439E+00	1.3462E-01	2.5560E-03	1.3811E+00	1.1697E-09	5.8486E-10	1.8131E-08
2020	1094	1.5972E+00	1.7285E-01	3.2820E-03	1.7734E+00	1.5020E-09	7.5098E-10	2.3280E-08

TABLE 64: ANALYSIS OF TRUCK ACCIDENTS INVOLVING NOBLE GAS BY SEVERITY AND DISPERSION MEDIUM

TRANSPORT MIX : 100 PCT TRUCKS, 0 PCT RAILROADS, 0 PCT BARGES

MATERIAL TYPE : NOBLE GAS

EXPECTED ACCIDENTS SUMMARY

YEAR	NO OF	EXPECTED NUMBER OF ACCIDENTS				EXPECTED NUMBER OF RELEASE INCIDENTS		
	SHIPMENTS	LIGHT	MEDIUM	SEVERE	TOTAL	AIR	WATER	TOTAL
1970	0	0.	0.	0.	0.	0.	0.	0.
1975	0	0.	0.	0.	0.	0.	0.	0.
1980	30	9.7500E-02	2.2500E-02	6.0000E-04	1.2060E-01	7.3742E-10	3.6871E-10	1.1430E-08
1985	59	1.9175E-01	4.4250E-02	1.1800E-03	2.3718E-01	1.4503E-09	7.2513E-10	2.2479E-08
1990	99	2.8314E-01	6.5340E-02	1.7424E-03	3.5022E-01	2.1415E-09	1.0707E-09	3.3193E-08
1995	134	3.8324E-01	8.8440E-02	2.3584E-03	4.7404E-01	2.8985E-09	1.4493E-09	4.4928E-08
2000	170	4.8620E-01	1.1220E-01	2.9920E-03	6.0139E-01	3.6773E-09	1.8386E-09	5.6998E-08
2005	202	5.7772E-01	1.3332E-01	3.5552E-03	7.1460E-01	4.3695E-09	2.1847E-09	6.7727E-08
2010	234	6.0840E-01	1.4040E-01	3.7440E-03	7.5254E-01	4.6015E-09	2.3007E-09	7.1323E-08
2015	264	6.8640E-01	1.5840E-01	4.2240E-03	8.4902E-01	5.1914E-09	2.5957E-09	8.0467E-08
2020	289	7.5140E-01	1.7340E-01	4.6240E-03	9.2942E-01	5.6830E-09	2.8415E-09	8.8087E-08

TABLE 65: ANALYSIS OF RAIL ACCIDENTS INVOLVING NOBLE GAS BY SEVERITY AND DISPERSION MEDIUM

TRANSPORT MIX : 0 PCT TRUCKS, 100 PCT RAILROADS, 0 PCT BARGES

MATERIAL TYPE : NOBLE GAS

EXPECTED ACCIDENTS SUMMARY

YEAR	NO OF SHIPMENTS	EXPECTED NUMBER OF ACCIDENTS				EXPECTED NUMBER OF RELEASE INCIDENTS		
		LIGHT	MEDIUM	SEVERE	TOTAL	AIR	WATER	TOTAL
1970	0	0.	0.	0.	0.	0.	0.	0.
1975	0	0.	0.	0.	0.	0.	0.	0.
1980	30	5.4750E-02	5.9250E-03	1.1250E-04	6.0787E-02	2.4803E-10	1.2402E-10	3.8445E-09
1985	59	1.0767E-01	1.1652E-02	2.2125E-04	1.1955E-01	4.8780E-10	2.4390E-10	7.5508E-09
1990	99	1.5899E-01	1.7206E-02	3.2670E-04	1.7653E-01	7.2029E-10	3.6014E-10	1.1164E-08
1995	134	2.1520E-01	2.3289E-02	4.4220E-04	2.3894E-01	9.7493E-10	4.8747E-10	1.5111E-08
2000	170	2.7302E-01	2.9546E-02	5.6100E-04	3.0313E-01	1.2369E-09	6.1843E-10	1.9171E-08
2005	202	3.2441E-01	3.5108E-02	6.6660E-04	3.6019E-01	1.4697E-09	7.3484E-10	2.2780E-08
2010	234	3.4164E-01	3.6972E-02	7.0200E-04	3.7931E-01	1.5477E-09	7.7386E-10	2.3990E-08
2015	264	3.8544E-01	4.1712E-02	7.9200E-04	4.2794E-01	1.7461E-09	8.7307E-10	2.7065E-08
2020	289	4.2194E-01	4.5662E-02	8.6700E-04	4.6847E-01	1.9115E-09	9.5575E-10	2.9628E-08

The other tables indicate that for all truck transportation in 2020, plutonium shipments are expected to encounter 0.112 severe accidents per year, solid waste 0.0175, and noble gas 0.0046. These numbers with all rail transportation in 2020 are 0.014 severe accidents per year with spent fuel, 0.021 for plutonium, 0.0033 for solid waste, and 0.00087 for noble gas. From this criterion, one would say that all rail transportation of all the materials is safer than all truck transportation, and that the materials rank in safety as follows: plutonium is least safe, spent fuel is next safe, solid waste is safer yet, and noble gas is most safe.

The number of accidents resulting in releases dispersing through air and through water is a very small number in all cases. The largest number of truck accidents resulting in release in air should occur with plutonium (3×10^{-8} releases per year) in 2020. The largest number of rail accidents resulting in release in air should occur with either solid waste or noble gas (2×10^{-9} releases per year) in 2020. The largest number of truck accidents resulting in releases in water is expected to be with plutonium (2×10^{-8} releases per year) in 2020. Finally, the largest number of rail accidents expected to result in water releases should happen to noble gas (1×10^{-8} releases per year).

EFFECT OF CHANGING RELEASE PROBABILITIES

A hypothesis was formulated that the fault tree probabilities pertaining to the occurrence of impact, puncture, and heat were not a function of accident severity. Some of the inhibit gate probabilities were also assumed to be different than the values given in Tables 26 through 37. The new release probabilities for severe accidents were calculated from the fault tree. The release probabilities for light and medium severity accidents were then obtained from the severe accident release probabilities by arbitrary ratios. The resultant release probabilities are compared in Table 66 with the release probabilities obtained in Section VI. The new release probabilities are significantly higher than those from Section VI, and thus the new numbers describe shipping containers that are considerably inferior to the Section VI containers. A comparison of curies released from both qualities of containers will give a measure of importance of the tightness of the containers compared to, say, the frequency of accidents.

In Tables 67 through 70, calculations of partial hazard vectors calculated with the new release probabilities for severe accidents and for a 20-75-5 transport mix are compared with similar partial hazard vectors calculated with the release probabilities obtained from Section VI.

TABLE 66: COMPARISON OF RELEASE PROBABILITIES

Material	Accident Severity	Transport Mode: Truck, Superior Container	Transport Mode: Truck, Inferior Container	Transport Mode: Rail, Superior Container	Transport Mode: Rail, Inferior Container	Transport Mode: Barge, Superior Container	Transport Mode: Barge, Inferior Container
Spent Fuel	Light	0	0.32E-4	0	0.32E-5	0	0.24E-4
	Medium	0.15E-9	0.65E-3	0.16E-9	0.65E-4	0.13E-7	0.48E-3
	Severe	0.19E-8	0.13E-1	0.33E-7	0.13E-2	0.15E-5	0.96E-2
Plutonium	Light	0	0.9E-6	0	0.57E-7	0	0.65E-6
	Medium	0.3E-7	0.18E-4	0.25E-8	0.12E-5	0.22E-7	0.13E-4
	Severe	0.3E-5	0.36E-3	0.16E-6	0.23E-4	0.11E-5	0.26E-3
High Level Radioactive Solid Waste	Light	0	0.12E-2	0	0.6E-3	0	0.12E-2
	Medium	0.5E-8	0.48E-2	0.11E-6	0.24E-2	0.2E-5	0.48E-2
	Severe	0.23E-7	0.48E-1	0.13E-5	0.24E-1	0.15E-4	0.48E-1
Noble Gas	Light	0	0.82E-3	0	0.18E-3	0	0.8E-3
	Medium	0.26E-6	0.33E-2	0.44E-6	0.73E-3	0.22E-5	0.32E-2
	Severe	0.93E-5	0.33E-1	0.11E-4	0.73E-2	0.2E-4	0.32E-1

TABLE 67: COMPARISON OF RELEASE PROBABILITY CALCULATIONS FOR SPENT FUEL SHIPPING CONTAINERS

Transport Mix: 20 percent Trucks, 75 percent Railroads, 5 percent Barges
Accident Severity: Severe

Year	Curies	Inferior Container[a]		Superior Container[b]	
		Expected Curies Released	Expected Acre-Rems	Expected Curies Released	Expected Acre-Rems
1970	0.70 E+08	0.56 E-03	0.19 E-02	1.38 E-08	4.93 E-08
1975	0.28 E+10	0.19 E-01	0.70 E-01	4.79 E-07	1.72 E-06
1980	0.10 E+11	0.58 E-01	0.21 E+00	1.44 E-06	5.16 E-06
1985	0.22 E+11	0.11 E+00	0.41 E+00	2.83 E-06	1.01 E-05
1990	0.39 E+11	0.18 E+00	0.63 E-01	4.38 E-06	1.57 E-05
1995	0.62 E+11	0.28 E+00	0.99 E+00	6.92 E-06	2.48 E-05
2000	0.84 E+11	0.38 E+00	0.14 E+01	9.48 E-06	3.40 E-05
2005	0.11 E+12	0.49 E+00	0.18 E+01	1.21 E-05	4.35 E-05
2010	0.14 E+12	0.61 E+00	0.22 E+01	1.52 E-05	5.44 E-05
2015	0.16 E+12	0.74 E+00	0.26 E+01	1.83 E-05	6.54 E-05
2020	0.19 E+12	0.88 E+00	0.31 E+01	2.16 E-05	7.75 E-05
Representative Per Shipment Quantities	0.12 E+08	0.54 E-04	0.19 E-03	1.33 E-09	4.76 E-09

[a] Release probabilities recalculated under different assumptions and assignments and given in Table 66 of this report describing an inferior container.

[b] Release probabilities obtained from fault tree analysis described in Section VI and tabulated in Table 47 of this report describing a superior container.

TABLE 68: COMPARISON OF RELEASE PROBABILITY CALCULATIONS FOR PLUTONIUM SHIPPING CONTAINERS

Transport Mix: 20 percent Trucks, 75 percent Railroads, 5 percent Barges
Accident Severity: Severe

Year	Curies	Inferior Container[a]		Superior Container[b]	
		Expected Curies Released	Expected Acre-Rems	Expected Curies Released	Expected Acre-Rems
1970	0	0	0	0	0
1975	0	0	0	0	0
1980	0.50 E+9	0.72 E-4	0.14 E+0	0.55 E-6	0.10 E-2
1985	0.34 E+9	0.44 E-4	0.83 E-1	0.33 E-6	0.62 E-3
1990	0.16 E+8	0.18 E-5	0.34 E-2	0.14 E-7	0.26 E-4
1995	0.87 E+8	0.10 E-4	0.19 E-1	0.76 E-7	0.14 E-3
2000	0.21 E+9	0.24 E-4	0.46 E-1	0.18 E-6	0.34 E-3
2005	0.40 E+9	0.45 E-4	0.88 E-1	0.34 E-6	0.64 E-3
2010	0.57 E+9	0.66 E-4	0.12 E+0	0.50 E-6	0.93 E-3
2015	0.77 E+9	0.88 E-4	0.16 E+0	0.66 E-6	0.12 E-2
2020	0.96 E+9	0.11 E-3	0.20 E+0	0.83 E-6	0.15 E-2
Representative Per Shipment Quantities	0.28 E+5	0.32 E-8	0.57 E-5	0.24 E-10	0.45 E-7

[a] Release probabilities recalculated under different assumptions and assignments and given in Table 66 of this report describing an inferior container.

[b] Release probabilities obtained from fault tree analysis described in Section VI and tabulated in Table 47 of this report describing a superior container.

TABLE 69: COMPARISON OF RELEASE PROBABILITY CALCULATIONS FOR HIGH LEVEL RADIOACTIVE SOLID WASTE SHIPPING CONTAINERS

Transport Mix: 20 percent Trucks, 75 percent Railroads, 5 percent Barges
Accident Severity: Severe

Year	Curies	Inferior Container[a]		Superior Container[b]	
		Expected Curies Released	Expected Acre-Rems	Expected Curies Released	Expected Acre-Rems
1970	0	0	0	0	0
1975	0	0	0	0	0
1980	0.50 E+07	0.53 E-02	0.19 E-01	3.03 E-07	1.09 E-06
1985	0.18 E+09	0.19 E+00	0.67 E+00	1.08 E-05	3.87 E-05
1990	0.65 E+09	0.60 E+00	0.22 E+01	3.47 E-05	1.25 E-04
1995	0.15 E+10	0.14 E+01	0.50 E+01	8.04 E-05	2.88 E-04
2000	0.27 E+10	0.25 E+01	0.91 E+01	1.46 E-04	5.25 E-04
2005	0.45 E+10	0.42 E+01	0.15 E+02	2.40 E-04	8.60 E-04
2010	0.64 E+10	0.54 E+01	0.19 E+02	3.09 E-04	1.11 E-03
2015	0.83 E+10	0.70 E+01	0.25 E+02	4.03 E-04	1.44 E-03
2020	0.10 E+11	0.86 E+01	0.31 E+02	4.97 E-04	1.78 E-03
Representative Per Shipment Quantities	0.10 E+08	0.93 E-02	0.34 E-01	5.34 E-07	1.92 E-06

[a] Release probabilities recalculated under different assumptions and assignments and given in Table 66 of this report describing an inferior container.

[b] Release probabilities obtained from fault tree analysis described in Section VI and tabulated in Table 47 of this report describing a superior container.

TABLE 70: COMPARISON OF RELEASE PROBABILITY CALCULATIONS FOR NOBLE GAS SHIPPING CONTAINERS

Transport Mix: 20 percent Trucks, 75 percent Railroads, 5 percent Barges
Accident Severity: Severe

Year	Curies	Inferior Container[a]		Superior Container[b]	
		Expected Curies Released	Expected Acre-Rems	Expected Curies Released	Expected Acre-Rems
1970	0	0	0	0	0
1975	0	0	0	0	0
1980	0.32 E+8	0.30 E+1	0.78 E-3	0.24 E-2	0.64 E-6
1985	0.63 E+8	0.60 E+1	0.16 E-2	0.49 E-2	0.13 E-5
1990	0.11 E+9	0.90 E+1	0.23 E-2	0.73 E-2	0.19 E-5
1995	0.14 E+9	0.12 E+2	0.32 E-2	0.99 E-2	0.26 E-5
2000	0.18 E+9	0.15 E+2	0.40 E-2	0.13 E-1	0.33 E-5
2005	0.22 E+9	0.18 E+2	0.48 E-2	0.15 E-1	0.39 E-5
2010	0.25 E+9	0.19 E+2	0.50 E-2	0.16 E-1	0.41 E-5
2015	0.28 E+9	0.22 E+2	0.56 E-2	0.18 E-1	0.46 E-5
2020	0.31 E+9	0.24 E+2	0.62 E-2	0.19 E-1	0.50 E-5
Representative Per Shipment Quantities	0.11 E+7	0.91 E-1	0.23 E-4	0.74 E-4	0.19 E-7

[a] Release probabilities recalculated under different assumptions and assignments and given in Table 66 of this report describing an inferior container.

[b] Release probabilities obtained from fault tree analysis described in Section VI and tabulated in Table 47 of this report describing a superior container.

In the case of spent fuel, the expected annual number of curies released for the inferior container is on the order of 10^{+5} higher than for the superior container. This result reflects the great use of rails in the transport mix, since the ratio of inferior to superior release probabilities for severe rail accidents is about 10^{+5}, while it is 10^{+7} for truck and 10^{+3} for barge.

Similarly, the number of curies released from the inferior container compared to the superior container is about 10^2 for plutonium, about 10^5 for solid waste, and about 10^3 for noble gas.

EFFECT OF CHANGING POPULATION DISTRIBUTION

The role of the population density distribution is discussed in Section VI. As long as the population density is assumed to be the same for all areas bounded by isodose contours, the exposure to risk may be calculated by multiplying the average population density by a factor derived from the linear distribution along the transport route. Such a distribution is shown in Figure 29, and it yields a factor of 26.3. If some other distribution is assumed, then the factor is different. For example, if 10 percent of the transport distance passes through an urban area of population density that is 21 times as large as the average density and 90 percent of the route lies in the average density area, then the factor is $0.1 \times 21 + 0.9 \times 1 = 3$. Use of this factor reduces the calculations of expected man-rems, expected fatalities, and expected injuries by a factor of $3/26.3 = 0.114$.

HAZARDS OF A SINGLE ACCIDENT

The probability of an accidental release of radiation from a shipment of radioactive material is small. Yet when an accident does occur, the consequences can be great. It is, thus, of interest to assess the magnitude of the hazard of a single accident. In the model, an actual accident can be described by setting the accident probability equal to one. To obtain a measure of the maximum hazard, the release probability can then also be set to one. The hazard associated with any other release probability then can be found by multiplying the maximum hazard by that release probability.

It is not realistic to consider a uniform population density distribution around the scene of an accident. Assuming that the shipment has a right-of-way of about 1,000 feet in which only two persons are found in every square mile, and that the population density in the area bounded by the isopleths at 10^{-1} mi^2 and 10^2 mi^2 is 5 times the average population density, the exposure to risk becomes:

$$X_\ell = \sum_{i=1}^{6} D_\ell (A_i) A_i (2) + \sum_{i=7}^{9} D_\ell (A_i) A_i (5p)$$

$$D_\ell (A_i) = 0.924 \times 10^{-6} K_\ell Q_\ell^* A_i^{-0.93001}$$

$$Q_\ell^* = Q_\ell r_\ell f_\ell$$

(See Table 41 for an explanation of the symbols.) Setting the release probability r equal to unity and using the release fractions for severe accidents given in Table 40, the expected hazards are calculated for the source carried in a representative shipment and an average population density of 100 persons per square mile. The results are tabulated in Table 71.

The expected number of fatalities are calculated with the $LD_{50/60}$ guide under the assumption that the fatalities occur shortly after the accident release, when radiation levels are high. The expected number of non-lethal cancers are calculated with the EPA guides under the assumption that the cancers are produced by chronic exposure to low levels of radiation.

A representative shipment of curies of radiation is given in Table 71 by the quotient of curies released and release fraction. Typical shipment radiation capacities are spent fuel $\sim 10^7$Ci, plutonium $\sim 10^4$Ci, solid waste $\sim 10^7$Ci, and noble gas $\sim 10^6$Ci. Given the assumed release fractions, accidents to solid waste and spent fuel yield radiation releases of about 10^4Ci. The release from a plutonium shipment accident is 1,000 times less severe, but the release from a noble gas shipment accident is 10 times more severe. Due to the differences in dose coefficient, however, the noble gas release presents the smallest health hazard, even though it involves the most radiation of all the materials.

The key index of the hazard vector for a single accident is the expected number of man-rems. Inspecting the values in Table 71 for this index, the materials are ordered with respect to danger as solid waste, plutonium, spent fuel, and noble gas. The first three materials present nearly equal hazards ($\sim 10^4$ man-rem), but noble gas yields only 1 percent of that hazard.

The index of greatest interest is the anticipated number of fatalities resulting from an accident. From Table 71, the shipment of solid waste produces

TABLE 71: IMPACT OF SINGLE SHIPPING ACCIDENT*

Material	Expected Curies Released	Expected Acre-Rems	Expected Man-Rems	Expected Fatalities	Expected Nonlethal Cancers
Spent Fuel	0.12 E5	0.42 E5	0.16 E5	26.7	3.2
Recycled Plutonium	0.28 E2	0.51 E5	0.20 E5	33.3	4.0
High Level Radioactive Solid Waste	0.50 E5	0.18 E6	0.70 E5	116.7	14.0
Noble Gas	0.11 E7	0.28 E3	0.11 E3	0.2	0.02

* Assumptions: Accident probability = 1.

Release probability = 1.

The population density in the immediate area of the accident ($0.1 mi^2$) is 2 persons / mi^2, and is 500 persons/mi^2 outside this area.

Source = Representative Curies/Shipment

Severe accident release fractions (Table 21):

Spent Fuel: 1E-3
Plutonium: 1E-3
Solid Waste: 5E-3
Noble Gas: 1

nearly 117 lethal cases if 0.5 percent of its radiation cargo leaks out in an accident and is absorbed by the assumed spatial distribution of people. Spent fuel and plutonium produce nearly 27 and 34 lethalities, respectively, with 0.1 percent of their radiation cargoes. Noble gas is least dangerous, yielding less than one fatality even when all its radiation is absorbed.

SECTION VIII

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SECTION IX

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SECTION X

GLOSSARY

Accident Probability - Fraction of shipments observed to encounter accidents; usually expressed in reciprocal distance units.

Accident Severity - Qualitative scale for magnitude of accident characteristics. Accidents are grouped into light (minor), medium (moderate), and severe classes of severity. For truck and rail transport modes, the relative collision velocity and the duration of fires provide a basis for a quantitative classification. For barge freight, the duration of fires provide a meaningful basis for severity analysis.

AND Gate - Connection in fault tree requiring at least two events to occur simultaneously.

Area-Dose - Dose absorbed by single human being in a unit area around the accident source. Interpreted as exposure to environment; usually expressed in acre-rems.

Consequence - Magnitude of effects, such as loss or damage, resulting from undesirable events.

Fault Tree - Logical relation between elementary events, such as occurrence of impact, puncture, excessive heat, vibration, or human error, potential barriers for these events, and an ultimate undesirable event, such as rupture of a shipping container.

Hazard - Product of risk and consequence.

Hazard Vector - Description of accident hazards using the components denoting the number of curies released, the expected area-dose, the expected population dose, the expected number of excess lethal cases, and the expected number of excess injuries (such as nonlethal cancers). The hazard vector is a function of a number of system variables, including time, geographical location, population distribution, radioactive commodity, transport mode, container technology, and route characteristics.

Inhibit Gate - Potential barrier to elementary event connected to the elementary event with the logic of an AND gate. For example, if the elementary event is impact to a container, the inhibit gate condition on the magnitude of the impact must be satisfied before the container ruptures from impact.

$LD_{50/60}$ - Lethal dose causing demise of 50 percent of exposed population within 60 days of accident.

OR Gate - Connection in fault tree requiring only one of several events to occur.

Population-Dose - Dose absorbed by population of human beings near the accident source. A measure of exposure to risk; usually expressed in man-rems or person-rems.

Radiation Dose Radiation absorbed by receptors, such as human beings; usually expressed in rems if the absorbers are men or animals.

Release Fraction - Part of cargo that is released through the container rupture caused by an accident and dispersed through environment.

Release Probability Probability that a shipping container will rupture. It is evaluated by means of fault tree analysis of the component barriers of the container.

Release Severity Release associated with an accident of the given severity. Unfortunately, a severe accident does not necessarily imply a release of large magnitude. In this report, release fractions, which are not well-known, have been assigned values, based on engineering judgment, that do vary directly with increasing magnitude of accident severity.

Risk - Probability that undesirable events, such as an accident to a shipment of radioactive material, will occur.

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