An Assessment of the Risk of Transporting Uranium Hexafluoride by Truck and Train

August 1978

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AN ASSESSMENT OF THE RISK
OF TRANSPORTING URANIUM HEXAFLUORIDE
BY TRUCK AND TRAIN

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CONTENTS

1.0	INTRODUCTION	1-1
	REFERENCES.	1-3
2.0	SUMMARY.	2-1
	REFERENCES.	2-5
3.0	TRANSPORTATION RISK ASSESSMENT METHODOLOGY	3-1
3.1	HISTORY	3-1
3.2	RISK ASSESSMENT MODEL	3-2
	3.2.1 System Description	3-4
	3.2.2 Release Sequence Identification.	3-6
	3.2.3 Release Sequence Evaluation	3-7
	3.2.4 Risk Calculation and Assessment.	3-9
	REFERENCES.	3-11
4.0	UF ₆ SHIPPING REQUIREMENTS.	4-1
4.1	UF ₆ PRODUCTION PLANTS	4-1
4.2	ENRICHMENT (GASEOUS DIFFUSION) PLANTS	4-2
4.3	FUEL FABRICATION PLANTS.	4-3
4.4	SHIPPING DISTANCES AND AMOUNTS	4-3
4.5	UF ₆ SHIPPING MODEL	4-4
	REFERENCES.	4-8
5.0	TRANSPORTATION ACCIDENT ENVIRONMENT	5-1
5.1	TRUCK ACCIDENT ENVIRONMENT.	5-1
5.2	TRAIN ACCIDENT ENVIRONMENT.	5-4
	REFERENCES.	5-8

6.0	PACKAGE FAILURE THRESHOLDS	6-1
	REFERENCES.	6-3
7.0	CONDITIONS OF CONTAINERS DURING TRANSPORT	7-1
7.1	SCOPE OF SURVEY	7-1
7.2	RESULTS OF SURVEY.	7-2
8.0	RELEASE SEQUENCE IDENTIFICATION.	8-1
8.1	FAULT TREE CONSTRUCTION.	8-1
8.2	FAULT TREES FOR SHIPMENT OF UF ₆	8-3
8.3	RELEASE SEQUENCES.	8-11
	REFERENCES.	8-23
9.0	RELEASE SEQUENCE EVALUATION	9-1
9.1	BASIC EVENT PROBABILITIES	9-2
9.1.1	Two and One-Half Ton (Type 30B) Cylinder Transported by Truck With Overpack.	9-2
9.1.2	10-Ton (Type 48X) Cylinder Transported by Truck Without Overpack.	9-18
9.1.3	10-Ton (Type 48X) Cylinder Transported by Truck With Overpack	9-25
9.1.4	14-Ton (Type 48Y) Cylinder Transported by Train . . .	9-30
9.1.5	14-Ton (Type 48Y) Cylinder Transported by Truck . . .	9-35
9.2	RELEASE SEQUENCE PROBABILITIES	9-37
9.3	RELEASE FRACTIONS.	9-39
	REFERENCES.	9-42
10.0	EVALUATION OF ENVIRONMENTAL CONSEQUENCES.	10-1
10.1	HEALTH EFFECTS.	10-1
10.1.1	Effects of Hydrogen Fluoride Gas	10-1
10.1.2	Effects of Uranyl Fluoride	10-2

10.2 METEOROLOGY.	10-6
10.3 DEMOGRAPHY	10-8
10.4 ATMOSPHERIC DISPERSION MODEL	10-12
10.5 ESTIMATED EXPOSURE FREQUENCY	10-15
REFERENCES.	10-19
11.0 THE RISK OF SHIPPING URANIUM HEXAFLUORIDE BY TRUCK AND RAIL . .	11-1
11.1 RISK EVALUATION OF UF ₆ SHIPMENTS.	11-1
11.2 MAJOR CONTRIBUTORS TO OVERALL RISK	11-5
11.3 RISK SENSITIVITY STUDIES	11-6
11.4 MULTIPLE CONTAINER FAILURE ANALYSIS.	11-9
REFERENCES.	11-12
APPENDIX A - UF ₆ SHIPPING CONTAINER AND TRANSPORT MODE DESCRIPTION. .	A-1
APPENDIX B - PROPERTIES OF UF ₆	B-1
APPENDIX C - FAILURE THRESHOLD DETERMINATION FOR UF ₆ CONTAINERS. . .	C-1
APPENDIX D - FRACTIONAL MILEAGE OF SHIPPING ROUTE BY POPULATION ZONE .	D-1

TABLES

2.1	Simplified UF ₆ Shipping System Model	2-2
4.1	Fuel Fabrication Plants.	4-4
4.2	Shipping Distances (km).	4-6
4.3	Estimated UF ₆ Shipments (metric tons)	4-6
5.1	Definition of Typical Freight Train as Used in This Study .	5-5
6.1	Summary of UF ₆ Cylinder Failure Thresholds	6-2
7.1	Data Bank-Package Closure Experience Obtained by Survey (For Period 1971-1975).	7-3
8.1	Fault Tree Symbolism.	8-2
8.2	Listing of Basic Events for Analysis of Cylinders Without Overpack.	8-9
8.3	Listing of Basic Events for Analysis of Cylinders With Overpack.	8-18
8.4	Listing of 14-Ton (48Y) UF ₆ Cylinder (Transported by Rail) Fault Tree Release Sequences	8-20
8.5	Listing of 10-Ton (48X) UF ₆ Cylinder (Transported by Truck) Fault Tree Release Sequences. Cylinder Remains Inside the Overpack.	8-21
8.6	Listing of 10-Ton (48X) UF ₆ Cylinder (Transported by Truck) Fault Tree Release Sequences. Cylinder is Lost from the Overpack.	8-22
9.1	Release Sequences and Probabilities for 14-Ton UF ₆ Rail Shipments	9-38
9.2	Release Sequences for 14-Ton Cylinder Grouped According to Release Fraction	9-41
10.1	Health Effects of HF.	10-2
10.2	Assumed Effects of HF on Humans	10-3
10.3	Isotopic Composition of 3.2% ²³⁵ U Enriched UF ₆	10-3

10.4	Dose to Critical Organ Via Inhalation (Soluble) Dose in $\frac{\text{Rem-m}^3}{\text{Ci-Sec}}$	10-4
10.5	Dose to Critical Organ Via Inhalation (Insoluble) Dose in $\frac{\text{Rem-m}^3}{\text{Ci-Sec}}$	10-5
10.6	Assumed Limits and Effects of UO_2F_2	10-6
10.7	Average Windspeed/Stability Characteristics	10-7
10.8	Projected Population Density and Land Area by Zone and Population Classes	10-10
10.9	UF_6 Shipping and Receiving Facilities	10-11
10.10	Fractional Mileage of Shipping Routes by Population Zone.	10-11
10.11	Values of σ_y for Pasquill Stability Categories	10-13
10.12	Values of σ_z for Pasquill Stability Categories	10-13
11.1	Simplified UF_6 Shipping System Model	11-2
11.2	Summary of UF_6 Shipping System Risks	11-2
11.3	Risk Sensitivity Cases for UF_6 Shipments	11-8
A.1	General Data for UF_6 Cylinder Model 30A Other Descriptive Terminology Used - 2 1/2-ton UF_6 , 1-Ton Chlorine	A-2
A.2	General Data for UF_6 Cylinder Model 30B Other Descriptive Terminology Used - 2 1/2-ton	A-3
A.3	General Data for UF_6 Cylinder Model 48X Other Descriptive Terminology Used - 10-Ton	A-4
A.4	General Data for UF_6 Cylinder Model 48Y Other Descriptive Terminology Used - 14-Ton	A-5
D.1	Fractional Mileage of Shipping Routes by Population Zones (Values in Percent)	D-2
D.2	UF_6 Shipping and Receiving Facilities	D-3

FIGURES

2.1	Risk Spectra for Individual Transport Modes and Total for Shipping System	2-4
3.1	Model to Calculate the Risk of Shipping Energy Materials.	3-5
4.1	Simplified Flow Diagram for UF ₆	4-2
4.2	Simplified UF ₆ Shipping Model.	4-7
5.1	Cumulative Distribution of Fire-Accident Duration for Truck Transport of Nonflammable Cargo	5-2
5.2	The Expected Maximum Velocity Change Given a Shipment Truck Subjected to a Random Accident Sample	5-3
5.3	Duration Probability of Train-Fire Accidents Involving Large Packages.	5-4
5.4	Cumulative Distribution for the Expected Severity of Impact Forces in Rail Accidents	5-6
8.1	UF ₆ Fault Tree for Cylinders Transported Without Overpack	8-4
8.2	Fault Tree for the Shipment of UF ₆ Cylinder In Overpacks.	8-12
9.1	Remaining Steps in the Risk Evaluation.	9-1
10.1	Population Zones and UF ₆ Shipping and Receiving Facilities	10-9
10.2	Area Within Isopleths for a Ground-Level Source.	10-14
11.1	Risk Spectra for Individual Transport Modes and Total For Shipping System	11-3
11.2	Risk Spectrum for Shipment of UF ₆ and Other Risk Spectra.	11-4
11.3	Risk Spectra for Sensitivity Cases	11-7
11.4	Number of Cylinders Exposed to Fire as Related to Fuel Pool Size	11-10
11.5	Risk Spectrum of Single and Multiple Container Failure Evaluations.	11-11
A.1	UF ₆ Cylinder Model 30A	A-2

A.2	UF ₆ Cylinder Model 30B	A-3
A.3	UF ₆ Cylinder Model 48X	A-4
A.4	UF ₆ Cylinder Model 48Y	A-5
A.5	Horizontally-Loaded Protective Outer Package for UF ₆ Cylinder Models 30A and 30B	A-6
A.6	Protective Shipping Package for UF ₆ Cylinder Model 48X . . .	A-7
A.7	Four 10-Ton Cylinders	A-9
A.8	Two 10-Ton Cylinders.	A-9
A.9	Five 2 1/2-Ton Cylinders in Protective Outer Packages. . .	A-10
A.10	One 10-Ton Cylinder in a Protective Outer Package	A-10
B.1	Density of Liquid UF ₆	B-2
B.2	Phase Diagram of UF ₆	B-3
C.1	Diagram of 30B Cylinder With Overpack Parted by Impact Forces	C-7

1.0 INTRODUCTION

Radioactive materials, in a variety of physical and chemical forms, have been routinely transported between various nuclear facilities for many years. The safety record for these shipments has been excellent. As the nuclear industry grows, it is expected that the number of shipments made annually will increase. To insure the health and safety of the general public, industry and government agencies are continually improving their level of understanding of the safety-related aspects of transporting nuclear and other energy materials.

Research programs are one method of improving the level of understanding. Such a research program is being conducted by Pacific Northwest Laboratory (PNL) for the Transportation Branch of the Department of Energy in the Division of Environmental Control Technology. The objective of this continuing program is to develop a methodology for quantitatively assessing the safety of transporting energy materials and to apply it to current and future shipping systems. Risk analysis was the technique selected for this assessment. Through analysis of risk, consequences of postulated releases of energy materials during transport can be put into perspective by viewing the events relative to their expected frequency of occurrence.

Risk, as used in the context of this report, is the product of the probability of a release of material to the environment and the consequences resulting from the release. There are two measures of the risk that are of importance in a risk assessment. The first is the total risk, a numerical value which is the sum of the risk associated with each particular loss. In order to perform the summation, all risks must be expressed with respect to the same time interval (e.g., per year). Although the total risk is an important measure, it gives only the loss that would be expected on the average during the reference time interval. The range of losses which could be experienced is not discernable. For example, the risk associated with an accident that occurs once a year and results in one fatality is the same (i.e., one fatality/year) as that from an accident which occurs once in ten years but results in ten fatalities. In a plot of the expected frequency of

N or more fatalities as a function of N, these two accidents would appear as discrete points. The second measure of risk is a curve called a risk spectrum, which is generated by connecting such points. The risks associated with two activities are similar only if they have the same total risk (risk magnitude) and the same risk spectrum. Both risk measures are used in this report.

The risk methodology was initially applied to the shipment of plutonium by truck⁽¹⁾ and has subsequently been applied to the shipment of plutonium by rail⁽²⁾ and air,⁽³⁾ and the shipment of gasoline by truck.⁽⁴⁾ This report presents the results of an assessment of the risk of transporting uranium hexafluoride by truck and rail. The general risk methodology used in this assessment, as well as in the previous risk studies, is also reviewed.

REFERENCES

1. T. I. McSweeney, R. J. Hall et al., An Assessment of the Risk of Transporting Plutonium Oxide and Liquid Plutonium Nitrate by Truck. BNWL-1846, Battelle, Pacific Northwest Laboratories, Richland, WA, August 1975.
2. R. J. Hall et al., An Assessment of the Risk of Transporting Plutonium Dioxide and Liquid Plutonium Nitrate by Train. BNWL-1996, Battelle, Pacific Northwest Laboratories, Richland, WA, February 1977.
3. T. I. McSweeney, J. F. Johnson, An Assessment of the Risk of Transporting Plutonium Dioxide by Cargo Aircraft. BNWL-2030, Battelle, Pacific Northwest Laboratories, Richland, WA, June 1977.
4. R. E. Rhoads and J. F. Johnson, Risks in Transporting Materials for Various Energy Industries. BNWL-SA-6547, prepared for publication in Nuclear Safety, 19(2), Battelle, Pacific Northwest Laboratories, Richland, WA, March 1978.

2.0 SUMMARY

This report is the fifth in a series of studies of the risk of transporting potentially hazardous energy materials.^(a) The report presents an assessment of the risk of shipping uranium hexafluoride (UF_6) by truck and rail.

The general risk assessment methodology, summarized in Section 3, used in this study is that developed for the first study in this series.⁽¹⁾ The assessment includes the risks from release of uranium hexafluoride during truck or rail transport due to transportation accidents. The contribution to the risk of deteriorated or faulty packaging during normal transport was also considered.

The report is sectioned to correspond to the specific analysis steps of the risk assessment model. The transportation system and accident environment are described in Sections 4 and 5. Calculation of the response of the shipping system to forces produced in transportation accidents are presented in Section 6 and the results of a survey to determine the condition of the package during transport are presented in Section 7. Sequences of events that could lead to a release of radioactive material from the shipping cask during transportation are postulated in Section 8 using fault tree analysis. These release sequences are evaluated in Sections 9 through 11, to determine both the likelihood and the possible consequences of each release. Supportive data and analyses are given in the appendices.

The results of the risk assessment have been related to the year 1985, when it is projected that 100 GW of electric power will be generated annually by nuclear power plants. It was estimated that approximately 46,000 metric tons (MT) of natural UF_6 and 14,600 MT of enriched UF_6 would be shipped in the reference year. Additional assumptions used for the analysis are:

- Fuel cycle facilities operating in 1985 are those operating or in the planning/construction stages during 1978.
- Shipping systems and regulations are the same as in 1978.

(a) The others are listed as References 1, 3, 4 and 5.

- No significant changes in the nuclear industry occur which would change the amounts of materials projected for 1985.
- The material transported is used to satisfy the requirements of commercial reactors; military uses have not been considered in this study.

Natural uranium hexafluoride is transported from UF₆ conversion plants to enrichment facilities; enriched UF₆ is transported between the enrichment plants and from the enrichment plants to fuel fabrication facilities. Five container types/transportation modes^(a) have been assumed to be used for these shipments:

- 30B (2 1/2-ton) cylinders with overpack by truck
- 48X (10-ton) cylinders without overpack by truck
- 48X (10-ton) cylinders with overpack by truck
- 48Y (14-ton) cylinders without overpack by truck
- 48Y (14-ton) cylinders without overpack by rail.

Characteristics of the shipping model developed from these assumptions are shown in Table 2.1. Other shipping conditions or different shipping regulations could result in different risks than those reported in this study. However, the methodology is capable of analyzing the risks under any shipping conditions.

TABLE 2.1. Simplified UF₆ Shipping System Model

Shipping Container	Transport Mode	Amount/ Container (MT)	Containers/ Shipment	Shipment Origin/ Destination	Material Shipped/ Year (MT)	Number of Shipments/year	Average Shipment Distance (km)	Accident/km
2.5-ton (30B) With Overpack	Truck	2.28	5	Enrichment/ Fabrication Enrichment/ Exports	7,460	650	1,050	1.55 x 10 ⁻⁶
10-ton (48X)	Truck	9.54	2	Conversion/ Enrichment	9,000	470	1,040	1.55 x 10 ⁻⁶
10-ton (48X) With Overpack	Truck	9.54	1	Enrichment/ Enrichment	1,300	140	420	1.55 x 10 ⁻⁶
14-ton (48Y)	Truck	12.5	1	Conversion/ Enrichment	21,800	1,750	375	1.55 x 10 ⁻⁶
14-ton (48Y)	Rail	12.5	4	Import/ Enrichment Enrichment/ Enrichment	21,000	420	800	6.21 x 10 ⁻⁶

(a) "2 1/2-ton" cylinder has a nominal capacity of 2.27 metric tons (5,000 lb) of UF₆. However, because the design of the container as a "2 1/2-ton" cylinder is common practice in the U.S. nuclear industry, this nomenclature has been used in this document. These remarks also apply to the "10-ton" (9.1 MT) and "14-ton" (12.7 MT) cylinders.

Based on the shipping system outlined above, it is estimated that trucks carrying UF_6 in any of the four cylinder types will be involved in an accident about three times in a year. Train accidents involving UF_6 shipments (in 14-ton cylinders) are expected to occur approximately twice every year. However, most of these accidents would not be severe enough to result in a release of uranium hexafluoride. It was estimated that a truck accident that could result in a release of material from the cylinder would occur once in about 33 years; train accidents resulting in a release would occur once every 100 years. These accidents are not expected to result in measurable consequences to the general public. The frequency of an accident resulting in one or more fatalities from release of UF_6 during a shipment was estimated to be one in about 120,000 years for truck shipments and one about every 10,000 years for rail shipments.

The consequences of the postulated releases were estimated based on the characteristics and amount of radioactive material released to the environs, the weather conditions at the time of the accident, and the population density downwind from the accident scene. The likelihood and the consequences for these postulated releases have been coupled and expressed as risk spectra.

The risk spectrum for transporting UF_6 is shown in Figure 2.1. The risk spectrum is a plot of the estimated number of fatalities versus the estimated frequency of an event resulting in that number of fatalities or greater. For example, the estimated probability that a shipment (by truck or rail) of UF_6 will be involved in an accident resulting in one or more fatalities during the reference year is 1.09×10^{-4} . The estimated probability of an event resulting in ten or more fatalities is 7.00×10^{-6} . Risk spectra for other risks to which society is exposed⁽²⁾ have been included in the figure for comparison. The curves in Figure 2.1 indicate that the risk of transporting UF_6 in the reference year is much less than the risk to society from natural events or man-caused events and comparable to the risks of transporting plutonium.^(1,3,4) It should be noted that fatalities resulting from plutonium releases are long term (30 years or more) while UF_6 release fatalities are acute or short term.

Sensitivity studies were performed to determine the most important contributors to the risk of shipping UF_6 . These studies are described in Section 11. It was found that fatalities were likely to result from the release of UF_6 only when an intact UF_6 cylinder failed explosively in an accident-caused fire. The primary risk associated with transporting UF_6 is chemical in nature, with essentially no contribution to fatalities from its radiological properties. Hydrogen fluoride (HF) gas, produced when UF_6 combines with moisture in the air, was the cause of all fatalities calculated in the risk assessment. The sensitivity studies also showed that the risk is dependent on the level of evacuation assumed.

FIGURE 2.1. Risk Spectra for Individual Transport Modes and Total for Shipping System

REFERENCES

1. T. I. McSweeney, R. J. Hall et al., An Assessment of the Risk of Transporting Plutonium Oxide and Liquid Plutonium Nitrate by Truck. BNWL-1846, Battelle, Pacific Northwest Laboratories, Richland, WA, August 1975.
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4. T. I. McSweeney and J. F. Johnson, An Assessment of the Risk of Transporting Plutonium Dioxide by Cargo Aircraft. BNWL-2030, Battelle, Pacific Northwest Laboratories, Richland, WA, June 1977.
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3.0 TRANSPORTATION RISK ASSESSMENT METHODOLOGY

This risk assessment represents the fifth in a series of analyses of the transportation of hazardous energy materials. The history of the methodology and a brief summary of the risk assessment model used in all studies to date is presented below.

3.1 HISTORY

The risk methodology used in this and earlier transportation risk studies evolved from a number of risk analysis models originally developed for use in the nuclear industry. The risk methodology was initially suggested as a method of selecting an acceptable site for nuclear power facilities.⁽¹⁾ The product of the probability of a radioactive material release, expressed in terms of reactor years between releases, and the consequences of that release, in curies, was used as the measure of risk.

Developments in the area of health effects of radiation exposure allowed the use of individual mortality as the measure of release consequences in later studies.^(2,3,4) The units of risk became the probability of an individual mortality in any operation year. Analyses^(5,6) were further expanded to show that the risk level individuals are willing to accept is related to the benefits received by the individual. For small benefits, it was determined that an individual will accept low-risk activities, where the probability of the activity producing a fatality is lower than 10^{-7} per year.⁽⁵⁾ For activities with higher benefits, the individual is willing to accept higher levels of risk. The use of health effects in expressing risk generates more meaningful comparisons among risk assessments. In the Reactor Safety Study,⁽⁷⁾ for example, the risk of operating a nuclear power plant was compared to the risks from natural disasters and man-caused events such as accidents.

The risk assessment methodologies discussed above have been limited to analyses of fixed facilities with a well-defined population distribution. The population in the immediate vicinity of the plant (the exclusion area)

is controlled by the facility operator. The population distribution in the vicinity of a transportation accident, however, is highly variable.

Transportation accidents may occur in rural areas (with very low population densities), in suburban areas, or in urban areas (with relatively high population densities). A variety of geographic and meteorological conditions can also be encountered, since transportation accidents can occur at virtually any location along the shipping route. The variability in population distribution, geography and meteorology in transportation accidents adds a degree of complexity not found in risk assessments of activities at fixed sites.

A number of methodologies have been developed to analyze the transport of hazardous materials. One, used by the University of Southern California⁽⁸⁾ in a study for the Department of Transportation, is based on accident case histories. However, this technique cannot be applied to all energy material shipments since the accident experience may be extremely limited or the accident data may not have been collected in a way that permits accurate assessment.

Another technique, developed by Holmes and Narver, was used to determine the risk of transporting bioweapons⁽⁹⁾ and radioactive material.⁽¹⁰⁾ These analyses were performed for shipments of material along a selected route. However, the methodology is limited in that only one average number for the risk is obtained. It would be more useful to know how the risk varies with route, weather, population, material form and accident severity. The variability of risk with possible transport conditions could then be considered.

3.2 RISK ASSESSMENT MODEL

The risk assessment model used in this analysis of the transport of energy materials was developed in conjunction with a method developed at PNL⁽¹¹⁾ to analyze the risks associated with nuclear fuel cycle operations. The methodology provides a flexibility not available in previous transportation risk studies, since it permits the risk to be analyzed for a spectrum of population densities and weather conditions that can be encountered along shipping routes. The model uses one fundamental equation:

$$R = \sum_i R_i . \quad (3-1)$$

The total system risk R is the sum of the risks of all accidental releases of material as denoted by the subscript i . Only accidental releases are considered in the model. The risk of an individual release is the product of the consequences of the release and the probability of its occurrence. In the current formulation of the model, each term in Equation 1 is expanded into two expressions which have more physical significance. The expanded equation for R_i is:

$$R_i = \left(A F_{R_i} \times P_{R_i} \right) \times \left(\sum_q C_{E_{i,q}} \times P_{E_q} \right) \quad (3-2)$$

The first expression, $A F_{R_i} \times P_{R_i}$, can be thought of as a probabilistic source term for each identified release sequence. The first factor in this term, $A F_{R_i}$, represents the amount of material released in the i^{th} release sequence. It is the product of the amount of material present in a shipment (A) and the fraction of that material lost to the environment in the i^{th} release sequence (F_{R_i}). This factor can be considered a source term for the i^{th} chain of events or failures which end with a release of material. The second factor, P_{R_i} , is the probability that the release sequence will occur during transport.

The second expression in Equation 3-2 ($\sum_q C_{E_{i,q}} \times P_{E_q}$), represents the consequences of a unit release of material (unit source term) under probabilistically weighted weather conditions and population distributions. The consequences of a unit release of material are evaluated in the expression $C_{E_{i,q}}$. The subscript q is added to show that this factor is a function of the specific weather conditions existing at the time of the release and the population exposed to the release. The consequences can be expressed in a variety of ways, depending on the material being studied, although risk comparisons can be more readily made if the consequences are expressed as health effects. The final factor in this expression, P_{E_q} , is the joint probability of encountering a particular set of weather conditions within a specific population zone.

The methodology used to provide input data for solution of the above equations involves four components:

- System Description
- Release Sequence Identification
- Release Sequence Evaluation
- Risk Calculation and Assessment

These four components, shown graphically in Figure 1, are described in detail below. Step numbers correspond to the number shown in the figure.

3.2.1 System Description

The basic information on the shipping system to be analyzed is collected. Most of the information is already available or easily derived. A complete description of the transportation system generally consists of seven steps, which are shown in Figure 3.1.

Project industry characteristics are determined in step 1. Included in this segment is a description of projected facilities and industry needs for the reference year. Material type, amounts, origins, and destinations are specified in the second step. The third step presents a description of the important physical and chemical characteristics of the material being shipped. For example, an important property of liquid materials is the vapor pressure exerted as a result of elevated temperatures in an accident environment. Powdered materials require specification of the particle size distribution. For radioactive materials, isotopic contents must also be included.

In the remaining four steps, the transportation system is described. In step 4, the transportation mode is specified, and the vehicles used are described. Weight and space limitations (and in the case of radioactive materials shipments, heat, geometry, dose and criticality limits) must be specified here so that amount of material per shipment and the required number of shipments can be calculated.

FIGURE 3.1. Model to Calculate the Risk of Shipping Energy Materials

The container used to carry the material is considered in step 5. For DOT Specification or approved containers, the container designation is enough to completely describe the container. Nonstandard containers require sufficient input to permit evaluation of failure paths later in the analysis. Step 6 of the system description involves the calculation of the number of shipments required to transport the amounts of material specified in step 2, in the vehicles and containers given in steps 4 and 5.

In the final step of the system description, the shipping route is divided and each segment is described in terms of type of route, shipping, population and weather characteristics. With the completion of this step, the entire transportation system has been described.

3.2.2 Release Sequence Identification

The next component in the risk assessment process is the identification of the sequences of events that could lead to release of material from the transport vehicle. These release sequences may be identified in a variety of ways. It is felt that the most complete listings of release sequences are obtained by deductive reasoning processes that work backwards from the occurrence of a release to identify the sequences of events that must occur to cause this system failure. Fault tree analysis provides a systematic method for performing these deductive reasoning processes. The fault tree that is constructed in these analyses also provides a compact notation for displaying large numbers of release sequences. Computer codes, such as the Fault⁽¹¹⁾ code used at PNL, can be used to quickly and accurately perform the Boolean algebra that reduces the fault tree to a series of release sequences or "cut sets" required for subsequent steps in the analysis.

Before the possible release sequences are identified (step 9), the scope of the analysis must be delineated (step 8). Only those release sequences within the selected scope of analysis are evaluated in subsequent steps in the model. Completed studies using this risk assessment model have considered releases from two general causes. In addition to releases caused by forces produced in transportation accidents, releases resulting from package closure errors, substandard packaging construction or deterioration in

packaging condition in the normal transportation environment have been considered. Failure associated with deliberate sabotage or diversion attempts has not been considered, but the techniques used in the model are sufficiently general to permit consideration of these events if failure rate (probability) data were available.

3.2.3 Release Sequence Evaluation

This step consists of two basic parts: 1) estimation of release sequence probabilities and 2) evaluation of the potential consequences of each release sequence.

The release sequence factors (denoted by the subscript "R" in Equation 3-2) represent the probability that a certain amount of material will be released. The evaluation of these factors requires information from the following data bases, shown in Figure 3.1 as steps 11-14:

- Package Closure Error Data (11)
- Mechanical Failure Data (12)
- Transport Mode Accident Data (13)
- Data on Environmental Characteristics of Material Shipped (14)

Release sequence probabilities are obtained by estimating the probability of each of the events that must occur to produce a system failure. This requires either historical data or development of information on the response of the shipping system to normal and transport accident forces (to determine the level of forces required to produce a system failure) and knowledge of the forces.

Package closure data (step 11) have been obtained by surveying facilities routinely receiving the material under study. Mathematical analysis or data available from testing programs is generally used to determine system failure thresholds (step 12). This can be combined with accident environment data, such as that developed at Sandia Laboratories⁽¹²⁾, or statistical analysis of other accident data to determine failure probabilities (step 13). The behavior of the material in the environment (step 14) depends entirely upon the material under consideration.

With the information from steps 11 to 14, the probability of a release is evaluated and the source term for each release is characterized (steps 17 and 18 in Figure 3.1). Generally, the probability of a release sequence occurring is first evaluated and the source term is then determined for release sequences which have non-zero probabilities. Release fractions (FR_i) used for various release sequences and environmental conditions are determined after carefully examining the individual release sequences.

The "A" factor in Equation 2 includes terms which relate the total amount of material shipped to the fraction that is potentially dispersible. This fraction is a function of the number of containers damaged and the amount of material spilled. After these terms have been evaluated for each release sequence, the source term analysis is complete.

The consequences of a system failure depend on the type of failure that has occurred, the location of the failure along the shipping route and the weather and population conditions at the time of failure. The consequences of the failure sequences may be determined by mathematical modeling, from historical accident data and/or from information from tests that have been conducted with the material being shipped. In general, consequences must be evaluated for each type of failure that can occur for each combination of weather condition and population distribution that can be encountered along the route. The probability of encountering the various population distributions and weather conditions along the route must also be determined.

The environmental terms in Equation 2 are denoted by a subscript E. The factor P_E represents the probability that a given set of weather and population density characteristics will be encountered in a region, while C_{E_i} represents the consequences of a unit release occurring in that region. The consequences of hazardous chemical releases can be directly expressed as health effects. However, the consequences of radioactive materials must initially be calculated as a population dose in units of man-rem to a selected organ of reference and then converted to health effects.

The evaluation of these two environmental consequences terms requires input from three data bases:

- Data on Environmental Characteristics of Material Shipped (14)
- Data on Route, Population, and Weather Characteristics (15)
- Data on Health Effects of Material Shipped (16)

The environmental behavior characteristics and health effects of the material depend on the material itself and must be developed individually for each study. Data for step 15 are available from U.S. Census data⁽¹³⁾ and summaries of regional weather data compiled by the U.S. Weather Bureau.⁽¹⁴⁾

Information from steps 14 to 16 is used to evaluate the probability of experiencing a given set of weather conditions and population characteristics. (steps 19 and 20) The expanded form of P_E is:

$$P_{E_{j,k,l}} = P_{j/k} \times P_k \times P_l. \quad (3-3)$$

The subscripts j , k and l refer to the multiplicity of environmental conditions which could exist at the location of the accident. For example, the variable $P_{j/k}$ may be the probability of experiencing the j^{th} atmospheric stability classification when the k^{th} wind speed exists, the variable P_k the probability of encountering the k^{th} wind speed category and the variable P_l the probability of encountering a specified population distribution.

3.2.4 Risk Calculation and Assessment

The final component in the risk assessment is to sum and evaluate the risks associated with the applicable release sequences. The steps involved in this component are shown graphically in Figure 3.1.

The overall risk calculation for each release sequence is described by Equations 3-1 and 3-2. These release sequence risks are added to determine the risk associated with individual shipping routes, which are weighted according to the amounts being shipped along each route. The overall transportation risk (total risk) is the sum of risks from these weighted

routes. The risk is also expressed in terms of a risk spectrum (plot of magnitude of consequence versus frequency of events resulting in that magnitude consequence or a more severe consequence).

The results are then analyzed to determine the primary contributors to the risk (step 23) and to specify and evaluate alternatives that could reduce the system risk, if the current risk is judged by society to be unacceptable. Since the information to perform the risk assessment has been developed in discrete data blocks, sensitivity studies can also be carried out to test the effect on the system risk of assumptions and approximations that were made to develop key pieces of information. This may identify areas where further analysis is required or delineate the limitations of the assessment.

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4.0 UF₆ SHIPPING REQUIREMENTS

As discussed in Section 3, the UF₆ risk assessment is based on a specific set of UF₆ shipping requirements. In using such a shipping model, a year of interest is required as an input specification. The particular year considered in this study is 1985, or a year in which 100 one-thousand megawatt electric capacity reactors are expected to be operating in the U.S. This basis of 100 reactors was chosen to allow comparisons with relative risks involved in shipping plutonium dioxide and plutonium nitrate, which were determined in earlier studies.^(1,2,3)

The materials to be shipped are natural and slightly enriched UF₆. The enriched UF₆ transported in this shipping model is assumed to be enriched to 3.03% ²³⁵U.^(a) Although small quantities of UF₆ enriched to 93% ²³⁵U will be transported in 1985, the amounts involved are projected to be insignificant compared to the amounts of natural and slightly enriched materials. The shipping regulations for these highly enriched materials also differ greatly from those used in this study. For these reasons, shipments of 93% enriched UF₆ were not included in this study. A simple flow diagram for the interplant movement of UF₆ is shown in Figure 4.1.

4.1 UF₆ PRODUCTION PLANTS

Uranium hexafluoride is produced from uranium ore concentrates at two production plants, located at Metropolis, Illinois, and Sequoyah, Oklahoma. The total amount of natural UF₆ required to meet existing U.S. enrichment contracts in 1985 is about 46,000 metric tons (MT).⁽⁴⁾ Two-thirds of this total (30,820 MT) is assumed to be produced at domestic plants, and will be used to satisfy domestic fuel and stockpile requirements. The remaining amount (15,180 MT) is assumed to be imported from foreign sources, enriched in the

(a) It is expected that two-thirds of the reactors in the reference year will be pressurized water reactors, requiring UF₆ enriched to approximately 3.2% ²³⁵U; one-third will be boiling water reactors, requiring 2.7% uranium enrichment. The enriched UF₆ transported in this shipping model is thus assumed to be enriched to 3.03% ²³⁵U.

U.S. and returned to the country of origin. For the purposes of this study, foreign UF_6 will not be used to satisfy domestic requirements.

FIGURE 4.1. Simplified Flow Diagram for UF_6

Although it is possible that some UF_6 may be supplied by recycle from reprocessing plants in the future, current policies and events suggest this alternative to be unlikely by 1985. Thus, recycled uranium was not included as a source of UF_6 for this study.

4.2 ENRICHMENT (GASEOUS DIFFUSION) PLANTS

From the production plants, the UF_6 is sent to an enrichment facility. There are currently three enrichment (gaseous diffusion) plants operating in the U.S. Each plant is capable of producing a different maximum enrichment of UF_6 : the Paducah, Kentucky plant, a 0.96% enrichment product; Oak Ridge, Tennessee, 4% enriched UF_6 ; and Portsmouth, Ohio, a maximum of 96% enriched material. It is assumed that the current allocation of UF_6 between enrichment plants prevails in the reference year. The Paducah facility thus receives 20% of the natural UF_6 , while the other two plants receive equal portions of the remaining material. The UF_6 is enriched to 0.96% ^{235}U at the Paducah

plant. Each of the other enrichment facilities receives half of this product and completes the enrichment to 3.03%. Interplant shipments originating at the Paducah facility total 5,825 MT in the reference year. Some enriched UF_6 also travels between Oak Ridge and Portsmouth.⁽¹⁵⁾ Shipments from Oak Ridge to Portsmouth total 1,340 MT.

The depleted UF_6 (tails) left over after the enrichment process is a potential resource if it is decided to manufacture mixed oxide fuels in the future. Projections for the 1980s, however, are for 100% storage of tails at the enrichment plants.

For the purposes of this study, it will be assumed that 50% of the slightly enriched UF_6 (less than 5% ^{235}U) produced in the 1980s will come from each of the plants at Oak Ridge and Portsmouth. As mentioned earlier, the Portsmouth plant can enrich UF_6 to 93%, but projections show that less than 20 MT of material of this type will be needed in the reference year.⁽⁶⁾ Since this is less than 0.3% of the total amount of UF_6 produced, it will be neglected in this analysis.

4.3 FUEL FABRICATION PLANTS

Current fuel fabrication plants and their locations are shown in Table 4.1. Having announced no expansion plans, these facilities are assumed to be the same as those that will be operating in 1985. Of the estimated 7,460 MT of enriched UF_6 produced in the reference year, 67%, or some 5,000 MT, will be distributed to these plants. The remaining 33% (2,460 MT) will be shipped to foreign users. The allocation of enriched UF_6 between fuel fabrication plants is based on approximate market shares as reflected in 1976 deliveries to these plants from enrichment facilities.⁽⁵⁾

4.4 SHIPPING DISTANCES AND AMOUNTS

Shipping distances between the various facilities are shown in Table 4.2. For this analysis, it was assumed that all foreign material enters and leaves the United States through the ports of Baltimore, Maryland and Norfolk,

Virginia. All shipments of enriched UF_6 currently leave from the east coast. Amounts shipped, based on industry characteristics presented above, are summarized in Table 4.3.

TABLE 4.1. Fuel Fabrication Plants

General Electric	Wilmington, NC
Babcock & Wilcox	Apollo, PA
Exxon Nuclear Company	Richland, WA
Nuclear Fuel Services	Erwin, TN
Westinghouse	Columbia, SC
Combustion Engineering ^(a)	Hematite, MO

(a) This plant is presently being used as a conversion facility to change UF_6 to UO_2 . It is a major receiver, and for the purposes of this study will be considered a fabrication plant.

4.5 UF_6 SHIPPING MODEL

This study represents a departure from the format used in earlier risk assessments. Previous studies^(1,2,3) analyzed the risk involved in shipping all material used in the reference year by one transportation mode. Results of a survey of current receivers of UF_6 (Section 7) showed that certain transportation modes dominate certain portions of the system. For example, the survey showed that 100% of the UF_6 received by fuel fabricators in the period 1971-1975 was shipped by truck. Other facilities, such as the enrichment plants, generally receive materials both by truck and rail, and occasionally by piggyback (truck trailer mounted on rail car). To further complicate matters, UF_6 is shipped in a variety of containers (Appendix A). For enrichment

levels below 1%, bare 10-ton^(a) and 14-ton capacity cylinders are used. When the enrichment level exceeds 1% (but is less than 4.5%) 2 1/2-ton and 10-ton-cylinders with protective overpacks must be used. When considering the four different types of packages and three modes of transportation, a total of 12 combinations are possible.

To accurately represent and yet reasonably evaluate the UF₆ shipment system, some simplifying assumptions were made. Piggyback shipments were combined with rail shipments to reduce transportation modes to two. Assumptions on container types reduced the number of cylinder configurations to four: 1) 14-ton cylinders; 2) 10-ton cylinders without overpack; 3) 10-ton cylinders with overpacks; and 4) 2 1/2-ton cylinders with overpacks. A diagram of the modified shipping system is shown in Figure 4.2.

(a) A "10-ton" cylinder has a nominal capacity of 9.1 MT (20,000 lb) of UF₆. However, because the designation of the container as a "10-ton" cylinder is common practice in the U.S. nuclear industry, this nomenclature has been used in this document. These remarks also apply to the "14-ton" (12.7 MT) and "2 1/2-ton" (2.3 MT) cylinders.

TABLE 4.2. Shipping Distances (km)

From	To Enrichment Plants			To Fuel Fabrication Plants							Foreign Users	
	Paducah, KY	Oak Ridge, TN	Portsmouth, OH	Wilmington, NC	Apollo, PA	Richland, WA	Erwin, TN	Columbia, SC	Hematite, MO	Baltimore, MD	Norfolk, VA	
<u>Production Plants</u>												
Metropolis, IL	20	500	610									
Sequoyah, OK	720	1080	1310									
Foreign Sources:												
Baltimore-P.O.E.	1290	870	690									
Norfolk-P.O.E.	1170	730	630									
<u>Enrichment Plants</u>												
Paducah, KY		480	590									
Oak Ridge, TN			420	720	880	3840	230	460	780	870	730	
Portsmouth, OH				850	480	3660	420	730	770	690	630	

TABLE 4.3. Estimated UF₆ Shipments (Metric Tons)

From	To Enrichment Plants			To Fuel Fabrication Plants							Foreign Users	
	Paducah, KY	Oak Ridge, TN	Portsmouth, OH	Wilmington, NC	Apollo, PA	Richland, WA	Erwin, TN	Columbia, SC	Hematite, MO	Baltimore, MD	Norfolk, VA	
<u>Production Plants</u>												
Metropolis, IL	3600	7200	7200									
Sequoyah, OK	2560	5130	5130									
Foreign Sources:												
Baltimore-P.O.E.	1520	3040	3040									
Norfolk-P.O.E.	1520	3040	3040									
<u>Enrichment Plants</u>												
Paducah, KY		2910	2910									
Oak Ridge, TN			1340	870	170	170	100	1000	170	610	610	
Portsmouth, OH				870	170	170	100	1000	170	610	610

FIGURE 4.2. Simplified UF₆ Shipping Model

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5.0 TRANSPORTATION ACCIDENT ENVIRONMENT

Shipping container failure during an accident occurs when the forces generated in the accident exceed the mechanical strength of the container. Since this risk assessment is concerned with the shipment of UF_6 via two modes, truck and rail, this section discusses the forces or stresses which may be generated in both truck and rail accident environments. Section 6 discusses the mechanical strength of the various UF_6 containers. The use of results from Sections 5 and 6 to estimate the likelihood of container failure in an accident is demonstrated in Section 9.

5.1 TRUCK ACCIDENT ENVIRONMENT

For the purpose of this analysis, the stresses present in a truck accident have been divided into three categories: fire, impact and puncture. Other stresses, such as crush and immersion, contributed insignificantly to the likelihood of UF_6 cylinder failures and were not included. The three significant accident stresses are discussed below.

Fire

Fire accident environment data used in this study were developed by Sandia Laboratories from accident reports compiled by the Bureau of Motor Carrier Safety. These data were also used in a Monte Carlo program to model the probability distribution of fire durations.

Based on the Sandia compilation of the truck accident environment, fire can be expected to occur in 1.6% of all truck accidents. The mean temperature of the fire is 1000°C (1840°F) and the duration of the fire can range from a few minutes to several hours. The expected duration of fires for nonflammable cargos is shown in Figure 5.1.

Because of the fire pool sizes and the general nature of the truck accidents used in the Sandia analysis, it was conservatively assumed that in all truck accident fires, the cargo was at least partially exposed to the fire.

FIGURE 5.1. Cumulative Distribution of Fire-Accident Duration for Truck Transport of Nonflammable Cargo (from Reference 1)

Impact

The impact environment for an accident involving a truck carrying a large container is taken from information developed at Sandia Laboratories.⁽¹⁾ The statistical information provided by Sandia was developed from Bureau of Motor Carrier Safety (BMCS) data. The BMCS data were used by Sandia Laboratories in a Monte Carlo computer simulation to estimate the impact environment experienced by a large truck in an accident. The results of this analysis for a truck with a gross weight of 32,000 kg (70,000 lbs) are presented in Figure 5.2, which shows the magnitude of the velocity change versus the expected frequency of occurrence of that velocity change in an accident.

FIGURE 5.2. The Expected Maximum Velocity Change Given a Shipment Truck Subjected to a Random Accident Sample (From Reference 1)

Puncture

A general description of the puncture environment present in accidents involving large truck-mounted containers is not available. However, the Office of Hazardous Materials (OHM) of the U.S. Department of Transportation (DOT) collects data on releases of hazardous materials during transportation. An incident report is required to be made by all carriers of hazardous materials in interstate commerce whenever a release occurs from the package or transport vehicle. The reported release does not have to be the result of a transportation accident. Unfortunately, insufficient data are available on UF_6 cylinder (or other similar container) failures in accidents to accurately describe the puncture environment.

To obtain an understanding of the puncture environment, it was necessary to modify material used in a previous risk assessment on the shipment of

gasoline.⁽²⁾ In that study, DOT-OHM figures for gasoline tank failures were used to describe the puncture environment in gasoline truck accidents. Compared to UF_6 containers, gasoline tankers are relatively fragile; therefore, it was necessary to modify the gasoline puncture rates. By taking into account the difference in energy needed to puncture these two different containers, an estimate of the puncture frequency of 1.35×10^{-4} per accident was derived.

5.2 TRAIN ACCIDENT ENVIRONMENT

As in the truck accident environment, only three categories of accident stresses were considered in the train accident environment: fire, impact and puncture. Other stresses were not considered because of their insignificant contributions to the likelihood of a UF_6 container failure.

Fire

Data from Sandia's accident environment study⁽¹⁾ indicate that approximately 1% of the collision and derailment accidents involving trains resulted in fire. Sandia further determined that the average fire temperature is approximately $1000^{\circ}C$ ($1840^{\circ}F$). Fire durations shown in Figure 5.3 range from minutes to hours.

FIGURE 5.3. Duration Probability of Train-Fire Accidents Involving Large Packages (From Reference 1)

The data shown in Figure 5.3 do not attempt to address the question of how frequently a container will be exposed to these fires (as is required for a risk analysis). If the fire source is primarily locomotive fuel, a boxcar near the end of the train obviously has a low probability of being threatened; if the commodities within the boxcar are on fire, the exposure probability is much greater.

Using the sample train described in the Sandia analysis and presented in Table 5.1,⁽¹⁾ and assuming: 1) a random distribution of cars in the train except for locomotives and caboose, and 2) that a car carrying UF₆ cylinders is threatened by fire only if one of the cars adjacent to it is a loaded tank car or locomotive, it was determined that the UF₆-carrying car would be exposed to a fire in 14% of all accidents involving fire. This means that a fire will occur in train accidents at a rate of approximately 1.74×10^{-8} per car km.

TABLE 5.1. Definition of Typical Freight Train
as Used in This Study

<u>Type of Car</u>	<u>Number Full</u>	<u>Other</u>	<u>Number Empty</u>
Locomotive		3	
Plain Boxcar	7		6
Equipped Boxcar	4		3
Gondola	4		3
Open Hopper	8		6
Covered Hopper	4		3
Flat Car	3		2
Refrigerator Car	2		2
Tank Car	4		3
Other Car	1		1
Caboose		1	

Impact

A description of the impact environment for accidents involving large railcar-mounted shipping containers was derived from information supplied by Sandia.⁽¹⁾ As was done in the case for truck impact, existing accident data were analyzed and a cumulative distribution for the expected severity of impact forces in rail accidents determined. Such a distribution is shown in Figure 5.4. In this case, the severity of the impact forces is expressed as a net velocity change.

FIGURE 5.4. Cumulative Distribution for the Expected Severity of Impact Forces in Rail Accidents

Puncture

A description of the puncture environment associated with large railcar-mounted containers was obtained from information developed by Sandia.⁽¹⁾ Existing accident data on tank car punctures were used to estimate the expected frequency of a puncture situation, given a train accident. These estimates represent conservative judgments of puncture probabilities for the rail-mounted UF₆ cylinders. Estimated probabilities of puncture are 6.4×10^{-4} per train accident, or 7.1×10^{-4} per collision or derailment accident.

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6.0 PACKAGE FAILURE THRESHOLDS

The previous section described the environment imposed on containers during truck and rail accidents. Estimates of failure thresholds for UF_6 shipping containers are presented in this section. The concept of a failure threshold (a point below which all "identical" packages will survive and above which they will all fail) is a simplification of this application of the risk model since mechanical failure points of containers are distributed in stress level. There is a most probable level that will result in failure, but in any group of "identical" containers there are some that will fail above or below this most probable value. It is felt that the simplifications in this section are consistent with the detail in the knowledge of the accident environment and that the analysis gives a reasonable estimate of the risk of package failure in an accident. The results of this section must be used in conjunction with other information on the stresses to which the package may be exposed in order to assess whether or not the package will fail in the accident environment. These assessments are made in Sections 9 and 11.

The package failure threshold estimates presented here were obtained using mathematical analysis, the results of tests which have been conducted on the containers, and engineering estimates. Only thresholds relating to the accident environment and posing a threat to the cylinder (fire, impact, puncture) were evaluated. Where assumptions were required to carry out the analysis, conservative assumptions were made.

Fire failure threshold estimates were determined using the results of tests conducted at Oak Ridge, TN⁽¹⁾ and a simplified heat transfer model. The fire tests were carried to failure; results were scaled to determine estimates of failure times for various sized cylinders.

Impact failure threshold estimates were derived from the results of full-scale experiments on 10-ton cylinders conducted at Paducah, KY.^(2,3) Failure thresholds for cylinders with overpacks were estimated using mathematical models and data from tests conducted at Oak Ridge.⁽⁴⁾ The impact analysis was limited to cases of side drop or loading (i.e., the axis of the

package perpendicular to the direction of the applied load). Side loading was assumed to be the predominant orientation in an accident environment.

Puncture failure thresholds were estimated through the use of data obtained from the tests conducted at Paducah.^(2,3) Puncture failure of overpacks and cylinders was estimated using the results of prototype overpack tests.^(4,5)

Details of these analyses are presented in Appendix C. Failure threshold estimates are summarized in Table 6.1.

TABLE 6.1. Summary of UF₆ Cylinder Failure Thresholds

	Fire (time to failure in 800°C fire)		Impact (drop height onto unyielding surface)		Puncture (drop height onto 15-cm diameter puncture piston)	
	Without Overpack	With Overpack	Without Overpack	With Overpack	Without Overpack	With Overpack
30B (2 1/2- ton)	29 min.	83 min.	9 m	22.5 m	3.2 m	4.2 m
48X (10-ton)	46 min.	156 min.	9 m	12.4 m	1.0 m	1.6 m
48Y (14-ton)	48 min.	---	9 m	---	80 cm	---

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7.0 CONDITIONS OF CONTAINERS DURING TRANSPORT

To adequately analyze the response of a UF_6 cylinder to an accident situation, it was necessary to determine the general package condition during normal transport. To obtain a data bank of container conditions during normal transport for use in the risk analysis, a survey was conducted of facilities which routinely receive UF_6 . This section presents the results of that survey.

7.1 SCOPE OF SURVEY

The initial step in developing the survey was to determine its contents: the areas to be covered and the container types to be evaluated. Determination of the package condition information required was carried out simultaneously with development of the release sequence evaluation fault trees (Section 8). It was determined to evaluate the package condition of the four containers considered in this study: the model 30(A&B) - 2 1/2-ton cylinder with overpack; the 48X - 10-ton cylinder with overpack; the 48X cylinder without overpack; and the 48Y - 14-ton cylinder without overpack. Each of the cylinders was examined in detail to determine packaging conditions which would contribute to a material release. A list of these conditions was developed into the survey questionnaire.

In an attempt to determine the relative use of different UF_6 shipment modes, a short section on type of transport used was added to the questionnaire.

Since this study considered all of the expected major receivers of UF_6 (see Section 5), these facilities were asked to participate in the survey. A list of the participants include:

Westinghouse Electric Corporation
Columbia, SC

General Electric Company
Wilmington, NC

EXXON Nuclear Corporation
Richland, WA

Babcock and Wilcox
Apollo, PA

Kerr-McGee Nuclear Corporation
Oklahoma City, OK

Nuclear Fuel Services, Inc.
Erwin, TN

Combustion Engineering, Inc.
Hematite, MO

Union Carbide Corporation
Paducah, KY

Union Carbide Corporation
Oak Ridge, TN

Goodyear Atomic Corp.
Portsmouth, OH

The survey was designed to cover the period from 1971 to 1975. However, since many replies to specific questions were made using best recollections, information received in the survey could easily be from outside of this time period.

7.2 RESULTS OF SURVEY

A copy of the questionnaire with overall results of the survey is shown in Table 7.1.

Even though the information obtained in the survey provides a reasonably good base for the risk assessment model, certain limitations should be recognized. First, as previously mentioned, many of the observations were made from personnel recollections and, as such, the time period of all of the observations is not certain. Second, in the years since 1971, quality assurance (QA) and quality control (QC) requirements have been strengthened, resulting in a significant reduction in packaging errors. Because of these factors, the results presented in Table 7.1 are considered to be conservative and not necessarily representative of current packaging conditions during transport.

TABLE 7.1. Data Bank-Package Closure Experience Obtained by Survey (For Period 1971-1975)^(a)

	2 1/2-Ton Model		10-Ton Model	14-Ton Model
	30A	30B	48X	48Y
A. PACKAGES RECEIVED				
1975	431	526	1104	1967
1974	579	691	825	1447
1973	461	688	1032	1029
1972	324	750	1383	1205
1971	695	517	2644	663
TOTAL	2540	3172	6988	6311
B. GENERAL CONDITION OF SHIPMENT (1971-1975)				
1. Do you formally examine and record the condition of received cylinders?	Yes = 8 1 = No Ans. No = 1			
2. Is the H/U ratio verified upon receipt?	Yes = 2 2 = No Ans. No = 6 (Inspect but do not record)			
3. Number of times H/U ratio exceeded specified limits.	0	0	0	0
4. Number of times enrichment exceeded specified limits.	0	1	0	0
5. Number of cylinders received overfilled.	0	0	0	0
6. Number of cylinders received overpressurized	1	0	20	56
7. Number received with contamination (UF ₆ , UO ₂ F ₂ , etc.) outside cylinder.	0	0	0	0
C. CYLINDER CONDITION (1971-1975)				
1. Number of cylinders removed from service due to deterioration.	1	2	0	0
2. Number of cylinders with badly corroded shells	0	0	0	0
3. Number of cylinders received without required protective valve cover.	0	0	0	0
4. Number of cylinders received with welds damaged (example, vessel freshly dented in area of weld resulting in possible partial weld failure, etc.).	7	0	1	0
D. VALVE CONDITION (1971-1975)				
1. Number of cylinders requiring valve replacement.	13	28	60	86
2. Number of cylinders with valve and/or vessel threads partially stripped.	0	5	0	0
3. Number of cylinders with valve crossthreaded	0	7	0	0
4. Number of cylinders with valve not completely closed.	0	0	0	0
5. Number of cylinders with valve loose or insufficient threads engaged.	0	0	7	19
6. Number of cylinders received with valve damaged (example, valve bent and fresh metal exposed at coupling, etc.).	0	14	1	5

TABLE 7.1. (Contd)

E. PLUG CONDITION (1971-1975)

1. Number of cylinders requiring plug replacement.	0	0	0	0
2. Number of cylinders with plug loose or with insufficient threads engaged.	0	0	0	0
3. Number of vessels with plug and or vessel threads partially stripped.	0	0	0	0
4. Number of vessels with plug crossthreaded	0	0	0	0
5. Number of cylinders received with plug damaged from rough treatment during handling or shipping (example, plug bent and fresh metal exposed at coupling, etc.).	0	0	0	0

F. OVERPACK CONDITIONS (1971-1975)

1. Number of cylinders received in overpack.	2480	3164	878	0
2. Number of cylinders received without overpack when required.	0	0	0	0
3. Number of cylinders received with gross damage to overpack.	0	0	0	0
4. Number of cylinders received without sealing gasket in overpack	0	0	0	0
5. Number received with deteriorated gasket.	3	1	0	0
6. Number received with closure bolts loose.	~40	~40	0	0
7. Number with missing closure bolts:				
a. all closure bolts missing	0	0	0	0
b. some closure bolts missing	~20	~16	0	0
8. Number received with damaged overpack mating surface.	7	5	0	0

G. TRANSPORTATION MODE

Approximate Percentage of Cylinders Received By:

1. Rail	0	3	12	14
2. Truck	88	97	88	62
3. Piggyback (Truck on Rail car)	12	0	0	24
4. Other (please specify)	<u>0</u>	<u>0</u>	<u>0</u>	<u>0</u>
TOTAL	100%	100%	100%	100%

H. DO FUTURE PLANS (NEXT 10 YEARS) INCLUDE FACILITIES TO HANDLE 10-AND/OR 14-TON UF₆ CYLINDERS IF SUCH FACILITIES DO NOT CURRENTLY EXIST?

Yes = 3 No = 7

(a) If accurate numbers are not available, approximate values or estimates based on best recollections can be used and are requested.

COMMENTS _____

8.0 RELEASE SEQUENCE IDENTIFICATION

Very few transportation accidents involving large containers filled with UF_6 have occurred in the past. Therefore, possible ways that releases could occur (release sequences) must be identified by a reasoning process. The information presented in Sections 5.0, 6.0 and 7.0 gives a basis for identifying events or combinations of events which could result in the release of UF_6 .

This section describes a formalized procedure for identifying combinations of conditions which could result in a release. The first step in the procedure is to develop fault trees using the techniques described in Section 8.1. Section 8.2 presents the fault trees developed for truck and train shipment of UF_6 in large containers. The second step in the procedure is to develop a list of release sequences from the fault tree. The development of these release sequences will be discussed in Section 8.3.

8.1 FAULT TREE CONSTRUCTION

The fault tree analysis technique was developed in the 1960s in the aerospace industry to identify equipment design deficiencies before actual space flight. The procedure assumes a failure and works backwards to identify basic component failures which could cause or contribute to that failure. These failure sequences are also called cut sets. The fault tree should be related to individual components for which failure data are available. For instance, in an electronic circuit the basic failure might occur in a resistor. However, fault trees are seldom developed to that degree of detail, but rather are constructed in terms of basic system modules. Using the electronic example, one would trace the possible failure only to the amplifier which contained the resistor. Such a fault tree is called a Top Level Fault Tree since it usually identifies only large systems which could result in a failure. Table 8.1 gives the various fault tree symbols and their meanings.

The methodology applied to transportation of UF_6 involves the postulation of a release of UF_6 during transport and the examination of the series of events which must have occurred to cause the release. Quantification of

TABLE 8.1. Fault Tree Symbolism

Symbol	Meaning and Use
<p>output</p> <p>inputs</p>	"AND" logic gate. The simultaneous occurrence of inputs is required to cause an output.
<p>output</p> <p>inputs</p>	"OR" logic gate. The occurrence of any one of the inputs will result in an output.
Fault event that results from the logical operation of two or more fault events. It is always the output from a logic gate.
Basic fault event. It requires no further development. Data regarding frequency and mode of failure can be derived empirically.
Inferred fault event. Any failure except a primary failure which is not developed further due to lack of information, time or money or due to the low probability of occurrence. It can also be used where other analyses give sufficient information to indicate that further analysis would be redundant.
<p>Output</p> <p>Input</p>	"Inhibit" gate. The condition specified in the oval is required for an input fault event to result in an output event. This condition is frequently a design limit which will not transmit a failure until the design limits have been exceeded.
Transfer symbol denoting that failure also impacts on other branches of fault tree. A line at the apex of the triangle represents a "transfer in." A line in the side represents a "transfer out." A number is placed in the triangle to identify transfer locations.
"House" defines an event that must occur, or is expected to occur, due to design and normal operating conditions.

the release requires specifications of an ordered sequence of events or accident scenarios. The fault tree is used as the basis for estimating the total release probability. The tree is then broken down into all the possible release sequences, to obtain essentially all the accident scenarios. When properly applied, the accident scenarios obtained from using the fault tree methodology are likely to be more complete than an alternative method of trying to list all the accident scenarios without the aid of any formalized reasoning process.

8.2 FAULT TREES FOR SHIPMENT OF UF₆

The system studied in this risk assessment involves four shipping packages (30B-cylinders with overpack, 48X-cylinders, 48X-cylinders with overpack, 48Y-cylinders) and two transportation modes, truck and rail. It would therefore seem obvious to develop eight fault trees to determine all possible release sequences. In an effort to reduce the number of fault trees required for the analysis, fault trees which were not dependent on the mode of transportation were developed. Furthermore, it was found that the cylinders were all basically similar except for size. Therefore, only two fault trees were needed: one for cylinders shipped with protective packages and one for cylinders without.

Fault Tree for Cylinder Without Overpack

The fault trees for UF₆ shipments in cylinders without protective overpacks were developed for normal truck and rail transport on primary highways and railways in the United States. The effects of sabotage or natural disasters were not included in this analysis. The analysis considers the combined effects of the accident environment and packaging condition. Based on these criteria, the fault tree shown in Figure 8.1 was developed to determine applicable failure sequences for the bare cylinders. A list of identified events or failure elements which could contribute to a release are shown in Table 8.2.

FIGURE 8.1. UF_6 Fault Tree for Cylinders Transported Without Overpack

FIGURE 8.1, Page 2. (Cont'd)

FIGURE 8.1, Page 4. (Cont'd)

FIGURE 8.1, Page 5. (Cont'd)

TABLE 8.2. Listing of Basic Events for Analysis
of Cylinders Without Overpacks

X	1	ACCIDENT OCCURS WITH FIRE
X	2	WFLD DEFECTIVE FROM CORROSION
X	3	WFLD HIT AND DAMAGED DURING HANDLING
X	4	CYLINDER NON-DEFECTIVE
I	5	FRACT FIRES CAUS SUFF PRESS TO FAIL DEF CYL
X	6	CYLINDER EXPOSED TO FORCE
X	7	ACCIDENT OCCURS WITHOUT FIRE
I	8	FRACT FIRES CAUS SUFF PRESS TO FAIL NON-DEF CYL
X	9	FLYING OBJECT GENERATED IN ACCIDENT
X	10	FLYING OBJECT STRIKES CYLINDER
X	11	CYLINDER DEFECT NOT DETECTED
I	12	FRACT OF IMPACT FORCES FAILING DEF CYL
X	13	NORMAL TRANSPORT FORCES CAUSE DEF CYLINDER FAILURE
X	14	VALVE PROPERLY CLOSED
I	15	FRACT OF IMPACT FORCES FAILING NON-DEF CYL
X	16	VALVE NOT CLOSED TIGHTLY
X	17	VALVE DEFECTIVE
X	18	VALVE AND VESSEL THREADS MISMATCHED
I	19	FRACT OF FLYING OBJ FAILING DEF CYL
X	20	VALVE THREADS STRIPPED
I	21	FRACT OF FLYING OBJ FAILING NON-DEF CYL
X	22	VALVE ASSEMBLY LOOSE
X	23	VESSEL SHIPPED WITHOUT PROTECTIVE VALVE COVER
X	24	VALVE HIT DURING HANDLING
I	25	FRACT OF CRITICALITIES FAILING DEF CYL
X	26	VALVE PROPERLY SITUATED ON CYLINDER
X	27	FLYING OBJECT STRIKES VALVE
I	28	FRACT OF CRITICALITIES FAILING NON-DEF CYL
X	29	VALVE COVER DISLODGED
X	30	VALVE EXPOSED TO IMPACT FORCE
X	31	PACKAGING ERROR NOT DETECTED
X	32	NORMAL TRANSPORTATION FORCES CAUSE DEF VALVE TO FAIL
X	32	NORMAL TRANSPORTATION FORCES CAUSE VALVE TO FAIL
X	33	PLUG CLOSURE NON-DEFECTIVE
I	34	FRACTION FIRES FAILING PROPERLY CLOSED VALVE -PRES
X	35	PLUG AND VESSEL THREADS MISMATCHED
I	36	FRACTION FIRES FAILING IMPROP CLOSED VALVE BY PRES
X	37	PLUG THREADS STRIPPED
X	38	PLUG NOT TIGHT
I	39	FRACTION FIRES FAILING IMPROP SITUATED VALVE -PRES
X	40	PLUG HIT AND LOOSENEED DURING HANDLING
X	41	PLUG EXPOSED TO IMPACT FORCE
X	42	FLYING OBJECT STRIKES PLUG
X	43	PLUG CLOSURE PACKAGING ERROR NOT DETECTED
X	44	NORMAL TRANSPORT FORCES CAUSE PLUG TO FAIL
X	45	PROBE STRIKES CYLINDER
I	46	FRACTION OF IMPACT FORCES FAILING PROP SIT VALVE
X	47	V/R SUFFICIENT TO PUNCTURE CYLINDER

TABLE 8.2. (Continued)

I	48	FRACTION OF IMPACT FORCES FAILING IMPROP SIT VALVE
X	49	PUNCTURE PROBE GENERATED BY ACCIDENT
X	50	NATURAL PUNCTURE PROBE PRESENT
X	51	HIGH H/U FACTOR
I	52	FRACTION FLYING OBJECTS FAILING PROP SIT VALVE
X	53	PACKAGING ERROR IN H/U FACTOR NOT DETECTED
I	54	FRACTION FLYING OBJECTS FAILING IMPROP SIT VALVE
X	55	CYLINDER SEVERELY CORRODED
X	56	CYLINDER DETERIORATED
I	60	FRACTION CRITICALITIES FAILING PROP CLOSED VALVE
I	62	FRACTION CRITICALITIES FAILING IMPROP CLOSED VALVE
I	64	FRACTION CRITICALITIES FAILING IMPROP SIT VALVE
I	70	FRACTION FIRES FAILING NON-DEFECTIVE PLUG BY PRES
I	72	FRACTION FIRES FAILING DEFECTIVE PLUG BY PRESSURE
I	78	FRACTION IMPACT FORCES FAILING DEFECTIVE PLUG
I	80	FRACTION IMPACT FORCES FAILING NON-DEFECTIVE PLUG
I	84	FRACTION FLYING OBJECTS FAILING DEFECTIVE PLUG
I	86	FRACTION FLYING OBJECTS FAILING NON-DEFECTIVE PLUG
I	90	FRACTION CRITICALITIES FAILING DEFECTIVE PLUG
I	92	FRACTION CRITICALITIES FAILING NON-DEFECTIVE PLUG
X	102	TIEDOWNS FAIL
X	103	WELD DEFECTIVE FROM POOR WELDING PROCEDURE

Fault Tree for Cylinders With Overpack

The fault tree for UF_6 shipments in cylinders with overpacks was developed using the same criteria as the non-overpack fault tree, the only major difference being inclusion of a branch describing the failure of the overpack. Since it is possible for a cylinder to be lost from the overpack during the accident (and to keep the size of the tree manageable), it was necessary to analyze the overpack case in two steps. First, the tree was analyzed assuming that the cylinder remained in the overpack. The second step assumed that the cylinder was lost from the overpack and utilized the fault tree for the non-overpack case with appropriate event probabilities. The entire cylinder with overpack analysis included the combined results of the two cases. The fault tree developed to describe the cylinder with overpack is shown in Figure 8.2. A list of failure elements is presented in Table 8.3.

8.3 RELEASE SEQUENCES

The fault tree can be thought of as a compact notation for identifying and displaying large numbers of release sequences. For larger trees, it is often helpful to utilize computer programs to perform the Boolean algebra that reduces the fault tree to a series of release sequences or "cut sets". The computer code MFAULT⁽¹⁾ was used for this analysis.

Partial listings of the release sequences identified by fault tree analysis are presented in Tables 8.4, 8.5 and 8.6. Table 8.4 presents the release sequences for the 14-ton (48Y) UF_6 cylinder transported by train as an example of the release sequences found for cylinders without overpacks. A sample of the release sequences for cylinders with overpacks is shown in Tables 8.5 and 8.6; these particular sequences are for the 10-ton cylinder with overpack transported by truck. Only those cut sets which are expected to occur once in every 10^{15} shipments are presented. Duplicate cut sets are automatically eliminated by the computer code. A list of release sequences for other combinations of container types and transport modes was also developed, but has not been presented here.

URANIUM HEXAFLUORIDE TRANSPORTATION (WITH OVERPACK) FAULT TREE

FIGURE 8.2. Fault Tree for the Shipment of UF₆ Cylinder in Overpacks

FIGURE 8.2, Page 2. (Cont'd)

FIGURE 8.2, Page 3. (Cont'd)

FIGURE 8.2, Page 4. (Cont'd)

FIGURE 8.2, Page 5. (Cont'd)

TABLE 8.3. Listing of Basic Events for Analysis of
Cylinders with Overpacks

X	1	ACCIDENT OCCURS WITH FIRE
X	2	WELD DEFECTIVE FROM CORROSION
X	3	WELD HIT AND DAMAGED DURING HANDLING
X	4	CYLINDER NON-DEFECTIVE
I	5	FRACT FIRES CAUS SUFF PRESS TO FAIL DEF CYL
X	6	CYLINDER EXPOSED TO FORCE
X	7	ACCIDENT OCCURS WITHOUT FIRE
I	8	FRACT FIRES CAUS SUFF PRESS TO FAIL NON-DEF CYL
X	9	FLYING OBJECT GENERATED IN ACCIDENT
X	10	FLYING OBJECT STRIKES CYLINDER
X	11	CYLINDER DEFECT NOT DETECTED
I	12	FRACT OF IMPACT FORCES FAILING DEF CYL
X	13	NORMAL TRANSPORT FORCES CAUSE DEF CYLINDER FAILURE
X	14	VALVE PROPERLY CLOSED
I	15	FRACT OF IMPACT FORCES FAILING NON-DEF CYL
X	16	VALVE NOT CLOSED TIGHTLY
X	17	VALVE DEFECTIVE
X	18	VALVE AND VESSEL THREADS MISMATCHED
I	19	FRACT OF FLYING OBJ FAILING DEF CYL
X	20	VALVE THREADS STRIPPED
I	21	FRACT OF FLYING OBJ FAILING NON-DEF CYL
X	22	VALVE ASSEMBLY LOOSE
X	23	VESSEL SHIPPED WITHOUT PROTECTIVE VALVE COVER
X	24	VALVE HIT DURING HANDLING
I	25	FRACT OF CRITICALITIES FAILING DEF CYL
X	26	VALVE PROPERLY SITUATED ON CYLINDER
X	27	FLYING OBJECT STRIKES VALVE
I	28	FRACT OF CRITICALITIES FAILING NON-DEF CYL
X	29	VALVE COVER DISLODGED
X	30	VALVE EXPOSED TO IMPACT FORCE
X	31	PACKAGING ERROR NOT DETECTED
X	32	NORMAL TRANSPORTATION FORCES CAUSE DEF VALVE TO FAIL
X	32	NORMAL TRANSPORTATION FORCES CAUSE VALVE TO FAIL
X	33	PLUG CLOSURE NON-DEFECTIVE
I	34	FRACTION FIRES FAILING PROPERLY CLOSED VALVE -PRES
X	35	PLUG AND VESSEL THREADS MISMATCHED
I	36	FRACTION FIRES FAILING IMPROP CLOSED VALVE BY PRES
X	37	PLUG THREADS STRIPPED
X	38	PLUG NOT TIGHT
I	39	FRACTION FIRES FAILING IMPROP SITUATED VALVE -PRES
X	40	PLUG HIT AND LOOSENEED DURING HANDLING
X	41	PLUG EXPOSED TO IMPACT FORCES
X	42	FLYING OBJECT STRIKES PLUG
X	43	PLUG CLOSURE PACKAGING ERROR NOT DETECTED
X	44	NORMAL TRANSPORT FORCES CAUSE PLUG TO FAIL
X	45	PROBE STRIKES CYLINDER
I	46	FRACTION OF IMPACT FORCES FAILING PROP SIT VALVE
X	47	V/R SUFFICIENT TO PUNCTURE CYLINDER
I	48	FRACTION OF IMPACT FORCES FAILING IMPROP SIT VALVE

TABLE 8.3. (Continued)

X 49 PUNCTURE PROBE GENERATED BY ACCIDENT
 X 50 NATURAL PUNCTURE PROBE PRESENT
 X 51 HIGH H/U FACTOR
 I 52 FRACTION FLYING OBJECTS FAILING PROP SIT VALVE
 X 53 PACKAGING ERROR IN H/U FACTOR NOT DETECTED
 I 54 FRACTION FLYING OBJECTS FAILING IMPROP SIT VALVE
 X 55 CYLINDER SEVERELY CORRODED
 X 56 CYLINDER DETERIORATED
 I 60 FRACTION CRITICALITIES FAILING PROP CLOSED VALVE
 I 62 FRACTION CRITICALITIES FAILING IMPROP CLOSED VALVE
 I 64 FRACTION CRITICALITIES FAILING IMPROP SIT VALVE
 I 70 FRACTION FIRES FAILING NON-DEFECTIVE PLUG BY PRES
 I 72 FRACTION FIRES FAILING DEFECTIVE PLUG BY PRESSURE
 I 78 FRACTION IMPACT FORCES FAILING DEFECTIVE PLUG
 I 80 FRACTION IMPACT FORCES FAILING NON-DEFECTIVE PLUG
 I 84 FRACTION FLYING OBJECTS FAILING DEFECTIVE PLUG
 I 86 FRACTION FLYING OBJECTS FAILING NON-DEFECTIVE PLUG
 I 90 FRACTION CRITICALITIES FAILING DEFECTIVE PLUG
 I 92 FRACTION CRITICALITIES FAILING NON-DEFECTIVE PLUG
 X 102 TIEDOWNS FAIL
 X 103 WELD DEFECTIVE FROM POOR WELDING PROCEDURE
 X 104 OVERPACK DAMAGED FROM HANDLING
 X 105 CLOSURE BOLTS LOOSE
 X 106 MATING SURFACES DAMAGED
 X 107 SEALING GASKET NOT PRESENT
 X 108 SEALING GASKET DETERIORATED
 X 109 CYLINDER LOST FROM OVERPACK
 X 110 IMPACT FORCES EXCEED LIMITS OF OVERPACK
 X 111 FIRE SUFFICIENT TO FAIL GASKET
 X 112 PROBE WITH SUFFICIENT FORCE TO BREACH OVERPACK
 X 113 UF6 CYLINDER BREACH FAILS OVERPACK

TABLE 8.4. Listing of 14-Ton (48Y) UF₆ Cylinder
(Transported by Rail) Fault Tree
Release Sequences

Cut Set Components					
X 1	X 4	X 8			
X 1	X 5	X 55			
X 1	X 3	X 5			
X 1	X 5	X103			
X 1	X 16	X 36			
X 1	X 35	X 72			
X 1	X 17	X 36			
X 1	X 18	X 39			
X 1	X 20	X 39			
X 1	X 22	X 39			
X 35	X 43	X 44			
X 1	X 37	X 72			
X 1	X 38	X 72			
X 1	X 40	X 72			
X 11	X 13	X 55			
X 3	X 11	X 13			
X 11	X 13	X103			
X 18	X 31	X 32			
X 20	X 31	X 32			
X 22	X 31	X 32			
X 37	X 43	X 44			
X 38	X 43	X 44			
X 40	X 43	X 44			
X 1	X 45	X 47	X 49		
X 1	X 23	X 24	X 39		
X 7	X 45	X 47	X 49		
X 1	X 45	X 47	X 50		
X 1	X 4	X 6	X 15		
X 1	X 6	X 12	X 55		
X 1	X 3	X 6	X 12		
X 1	X 6	X 12	X103		
X 23	X 24	X 31	X 32		
X 7	X 45	X 47	X 50		
X 4	X 6	X 7	X 15		
X 6	X 7	X 12	X 55		
X 3	X 6	X 7	X 12		
X 6	X 7	X 12	X103		
X 1	X 23	X 26	X 30	X 46	
X 7	X 23	X 26	X 30	X 46	
X 1	X 23	X 24	X 30	X 48	
X 1	X 26	X 29	X 30	X 46	
X 7	X 23	X 24	X 30	X 48	
X 7	X 26	X 29	X 30	X 46	
X 1	X 22	X 23	X 30	X 48	
X 7	X 18	X 23	X 30	X 48	
X 7	X 20	X 23	X 30	X 48	
X 7	X 22	X 23	X 30	X 48	
X 1	X 18	X 29	X 30	X 48	
X 1	X 20	X 29	X 30	X 48	
X 1	X 22	X 29	X 30	X 48	
X 7	X 18	X 29	X 30	X 48	
X 7	X 20	X 29	X 30	X 48	
X 7	X 22	X 29	X 30	X 48	

TABLE 8.5. Listing of 10-ton (48X) UF₆ Cylinder
(Transported by Truck) Fault Tree
Release Sequences. Cylinder Remains
Inside the Overpack

Cut Set Components					
X 1	X 4	X 8			
X 1	X 5	X 55			
X 1	X 3	X 5			
X 1	X 5	X 103			
X 1	X 16	X 36			
X 1	X 35	X 72			
X 1	X 17	X 36			
X 1	X 18	X 39			
X 1	X 20	X 39			
X 1	X 22	X 39			
X 35	X 43	X 44			
X 1	X 37	X 72			
X 1	X 38	X 72			
X 1	X 40	X 72			
X 11	X 13	X 55			
X 3	X 11	X 13			
X 11	X 13	X 103			
X 18	X 31	X 32			
X 20	X 31	X 32			
X 22	X 31	X 32			
X 37	X 43	X 44			
X 38	X 43	X 44			
X 40	X 43	X 44			
X 1	X 23	X 24	X 39		
X 1	X 4	X 6	X 15		
X 1	X 6	X 12	X 55		
X 1	X 3	X 6	X 12		
X 1	X 6	X 12	X 103		
X 23	X 24	X 31	X 32		
X 4	X 6	X 7	X 15		
X 6	X 7	X 12	X 55		
X 3	X 6	X 7	X 12		
X 6	X 7	X 12	X 103		
X 1	X 45	X 47	X 49	X 112	
X 1	X 23	X 26	X 30	X 46	
X 7	X 45	X 47	X 49	X 112	
X 1	X 45	X 47	X 50	X 112	
X 7	X 23	X 26	X 30	X 46	
X 1	X 23	X 24	X 30	X 48	
X 7	X 45	X 47	X 50	X 112	
X 7	X 23	X 24	X 30	X 48	
X 1	X 18	X 23	X 30	X 48	
X 1	X 20	X 23	X 30	X 48	
X 1	X 22	X 23	X 30	X 48	
X 7	X 18	X 23	X 30	X 48	
X 7	X 20	X 23	X 30	X 48	
X 7	X 22	X 23	X 30	X 48	
X 1	X 45	X 47	X 49	X 50	X 112
X 7	X 45	X 47	X 49	X 50	X 112

TABLE 8.6. Listing of 10-ton (48X) UF₆ Cylinder
(Transported by Truck) Fault Tree
Release Sequences. Cylinder is Lost
from the Overpack

Cut Set Components						
X 1	X 4	X 8				
X 1	X 5	X 55				
X 1	X 3	X 5				
X 1	X 5	X 103				
X 1	X 16	X 36				
X 1	X 35	X 72				
X 1	X 17	X 36				
X 1	X 18	X 39				
X 1	X 20	X 39				
X 1	X 22	X 39				
X 35	X 43	X 44				
X 1	X 37	X 72				
X 1	X 38	X 72				
X 1	X 40	X 72				
X 11	X 13	X 55				
X 3	X 11	X 13				
X 11	X 13	X 103				
X 18	X 31	X 32				
X 20	X 31	X 32				
X 22	X 31	X 32				
X 37	X 43	X 44				
X 38	X 43	X 44				
X 40	X 43	X 44				
X 1	X 23	X 24	X 39			
X 1	X 4	X 6	X 15			
X 1	X 6	X 12	X 55			
X 1	X 3	X 6	X 12			
X 1	X 6	X 12	X 103			
X 23	X 24	X 31	X 32			
X 4	X 6	X 7	X 15			
X 6	X 7	X 12	X 55			
X 3	X 6	X 7	X 12			
X 6	X 7	X 12	X 103			
X 1	X 23	X 26	X 30	X 46		
X 7	X 23	X 26	X 30	X 46		
X 1	X 23	X 24	X 30	X 48		
X 7	X 23	X 24	X 30	X 48		
X 1	X 18	X 23	X 30	X 48		
X 1	X 20	X 23	X 30	X 48		
X 1	X 22	X 23	X 30	X 48		
X 7	X 18	X 23	X 30	X 48		
X 7	X 20	X 23	X 30	X 48		
X 7	X 22	X 23	X 30	X 48		
X 1	X 9	X 23	X 26	X 27	X 52	
X 7	X 9	X 23	X 26	X 27	X 52	
X 1	X 9	X 23	X 24	X 27	X 54	
X 7	X 9	X 23	X 24	X 27	X 54	
X 1	X 9	X 18	X 23	X 27	X 54	
X 1	X 9	X 20	X 23	X 27	X 54	
X 1	X 9	X 22	X 23	X 27	X 54	
X 7	X 9	X 18	X 23	X 27	X 54	
X 7	X 9	X 20	X 23	X 27	X 54	
X 7	X 9	X 22	X 23	X 27	X 54	

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9.0 RELEASE SEQUENCE EVALUATION

The previous chapter presented the fault trees for the shipment of UF_6 in cylinders with and without protective overpacks. The fault tree can be thought of as a compact notation for summarizing several thousand release sequences. These release sequences are the common element in the risk assessment. As shown in Figure 9.1, based on the release sequence, both the occurrence frequency and amount released (release fraction) must be determined for each release sequence. This section presents the basic data required to evaluate all release sequences.

FIGURE 9.1. Remaining Steps in the Risk Evaluation

The fault trees in Section 8 were developed to a point where data on basic events could be obtained through either analysis or from survey results. The estimated basic event probabilities are presented in Section 9.1. The probability data are then used to develop the information on release sequence probabilities, which are summarized in Section 9.2. Release fractions are evaluated in Section 9.3.

9.1 BASIC EVENT PROBABILITIES

The following paragraphs provide a sequential description of failure probability estimates for UF_6 shipments in the five container configurations considered in this risk assessment. The numbering sequence used here corresponds to the numbering sequence used in the fault trees. Since the numbering system used in the two fault trees is identical (except that the "with overpack" fault tree has some additional events) many of the basic events will have identical probabilities. These will be noted in the text.

The analysis of shipping packages utilizing overpacks involves two segments: one which considers failure of the UF_6 cylinder in an accident after it has been lost from the protective overpack; and a second which deals with failure of the cylinder while it is still within the overpack. For this reason, the descriptions of probability estimates for the packages utilizing overpacks consist of two sections, corresponding to the two segments described above.

The fault tree was developed independently of the accident environment data. In determining probabilities for specific events, it was often necessary (because of accident environment information limitations) to combine one or more events. This results in the use of zero and one for certain event probabilities to avoid double counting. These instances will be noted. In all cases, the best available information was used in determining failure event probabilities. In many instances, only rough estimates were available for certain inputs. Risk sensitivity analyses were performed to yield insight to the contributions of these events.

The explanation "not used" following an event number simply means that the event number was not used in the numbering sequence.

9.1.1 Two and One-Half Ton (Type 30B) Cylinder Transported by Truck With Overpack

The analysis for this cylinder consists of two parts: the first dealing with the cylinder when it is lost from the overpack, the second dealing with the cylinder which remains inside the protective outer package.

Cylinder Lost from Overpack

Accident Occurs with Fire (X1). From data developed by Sandia,⁽¹⁾ it can be shown that approximately 1.6% of all truck accidents involve fire. Using a truck accident rate of 1.55×10^{-6} accident per kilometer, it was determined that accidents involving fire could be expected at a rate of 2.48×10^{-8} per kilometer. For an average trip length of 1050 kilometers, the rate was expressed as 2.60×10^{-5} per shipment. It was assumed that cylinders were exposed to the fire in all truck accidents with fire.

Weld Defective from Corrosion (X2). Responses from the packaging survey did not differentiate between corroded welds and deteriorated cylinders. Therefore this event and X56, Cylinder Deteriorated, were combined, with a value being used for X56. The value of X2 was set at zero.

Weld Hit and Damaged During Handling (X3). Since the 30A and 30B cylinders are quite similar, the survey results of both were combined to give a greater sample size. The survey showed a total of 7 cylinders out of a sample size of 5712 which were received with damaged welds. An expected frequency of 1.23×10^{-3} per cylinder was used.

Cylinder Nondefective (X4). For the purposes of this analysis, a conservative value of 1.00 was assumed.

Fraction of Fires Causing Sufficient Pressure to Fail Defective Cylinder (I5). For this portion of the 2 1/2-ton cylinder analysis, it was assumed that the cylinder has been lost from the protective overpack. The failure thresholds presented in Section 6 show that a nondefective cylinder will fail after being exposed to the fire environment for approximately 29 minutes. It is very difficult to quantify the degree of defectiveness of a cylinder. Taking into account the time necessary to heat up the cylinder, heat transfer rates of UF_6 , etc., it was assumed that all defective cylinders would fail after 22 minutes (approximately 75% of the time for a nondefective cylinder). This assumption is conservative because the pressure tends to rise quickly shortly before the cylinder fails. The description of the fire accident environment presented in Section 5 indicates that approximately 11% of all truck accident fires burn longer than 22 minutes. Therefore a fraction of 0.11 was used for this inhibit element.

Cylinder Exposed to Force (X6). Based on material presented in Reference 1, it was determined that the cylinders were exposed to impact forces in 89% of all accidents. Therefore a frequency of 0.89 per accident was used for this event.

Accident Occurs Without Fire (X7). This element was evaluated using the same data as event X1. An expected rate of 1.53×10^{-6} per kilometer or 1.60×10^{-3} per 1050 kilometer average shipment distance.

Fraction of Fires Causing Sufficient Pressure to Fail Non-Defective Cylinder (I8). In Section 6, it was shown that a 2-1/2 ton cylinder exposed to the fire environment without a protective overpack could be expected to rupture from excess internal pressure after approximately 29 minutes. Fire environment information presented in Section 5 indicates that approximately 5% of all truck accident fires can be expected to last longer than this. Therefore, a fraction of 0.05 was used to describe fires capable of failing the non-defective cylinders.

Flying Object Generated in Accident (X9). Moving vehicle accidents account for 89% of all truck accidents. It was conservatively assumed that puncture probes or flying objects of one type or another are present in all moving vehicle accidents. A value of 0.89 per accident was given this event.

Flying Object Strikes Cylinder (X10). Because puncture failures are lumped together in event X47, a value of 1.00 was assigned to this event.

Cylinder Defect Not Detected (X11). Since information on cylinder defects was obtained from a survey of containers actually shipped, it was assumed that these defects were not detected before or during shipment. A value of 1.00 was used for X11.

Fraction of Impact Forces Failing Defective Cylinder (I12). As was the case in event I5, it was difficult to determine the "defectiveness" of a cylinder. A non-defective cylinder without overpack was assumed to fail in a drop from a height of 9 meters. It was arbitrarily assumed that the defective cylinder would fail at half this height, or 4.5 meters. Using the information presented in Section 5, 96% of the truck accidents sampled involved impact energy changes which were less than a value corresponding to this drop height. Therefore a value of 0.04 was used for this event.

Normal Transport Forces Cause Defective Cylinder Failure (X13). Any cylinder sufficiently defective to fail from normally imposed transport forces would most likely fail during normal handling and filling operations. This is thus a very unlikely event, and it was assigned a frequency of occurrence of 10^{-6} per cylinder.

Valve Properly Closed (X14). This event was conservatively assigned a probability of 1.0.

Fraction of Impact Forces Failing Non-Defective Cylinder (I15). An impact failure threshold equivalent to a drop from 9 meters was shown in Section 6. Using Figure 5.2, approximately 98% of the accidents sampled involved energy changes due to impact of lesser or equal magnitude. A fraction of 0.02 was therefore used for this inhibit element.

Valve Not Tightly Closed (X16). No incidence of partially open valves was found in the survey. This does not mean, however, that this condition will never be present. At a 50% confidence level, for the sample size involved, we would expect this packaging error to occur at a rate of 1.21×10^{-4} per cylinder.

Valve Defective (X17). The survey showed that a total of 41 valves required replacement during the time period covered by the survey. It was learned that approximately 1/3 of these valves were replaced due to clogged ports, etc. and did not involve defective parts. If we assume that all the remaining valves were replaced due to defects, a rate of 2.39×10^{-3} per cylinder is indicated.

Valve and Vessel Threads Mismatched (X18). The survey showed a total of 7 cylinders received with valve threads cross threaded. This implies an expected frequency of 1.23×10^{-3} per cylinder.

Fraction of Flying Objects Failing Defective Cylinder (I19). Due to the nature of the available information describing the puncture accident environment, it was impossible to distinguish between punctured defective and non-defective cylinders. The puncture frequency is presented in X47. Therefore, the value assigned to this event is zero.

Valve Threads Stripped (X20). A total of five examples of cylinders with stripped valve threads was found in the package survey. This implies an occurrence rate of 8.75×10^{-4} per cylinder. This value was used for event X20.

Fraction of Flying Objects Failing Non-Defective Cylinder (I21). A breach caused by a flying object and puncture caused by a puncture probe were not differentiated in this analysis. Because of the nature of the puncture accident environment description, all puncture failures of both defective and non-defective cylinders will be included in event X47. Therefore, the value used for this element was zero.

Valve Assembly Loose (X22). No occurrences of loose valve assemblies were reported on the survey forms. At a 50% confidence level, an occurrence rate of 1.21×10^{-4} per cylinder is expected.

Vessel Shipped Without Protective Valve Cover (X23). In this study, it is assumed that all 2-1/2 ton cylinders are shipped in overpacks, and therefore always shipped without a valve cover. The event was assigned a rate of 1.00 per cylinder.

Valve Hit During Handling (X24). The survey showed a total of 14 cylinders received with damaged valves. It was assumed that this failure occurred during normal handling. A value of 2.45×10^{-3} was used for this event.

Fraction of Criticalities Failing Defective Cylinder (I25). It was conservatively assumed that all criticalities would cause a failure of the cylinder. A value of 1.00 was used.

Valve Properly Situated on Cylinder (X26). This element was conservatively given a value of 1.00.

Flying Object Strikes Valve (X27). The valve is partially protected from flying objects by the cylinder skirts. Considering the relative size of the valve to the cylinder and the angles from which the flying objects can strike the valve, few flying objects would be able to hit the valve. A value of 1.6×10^{-3} per accident was used for this event.

Fraction of Criticalities Failing Non-Defective Cylinder (I28). It was assumed that all criticalities would fail all cylinders, both defective and non-defective. A conservative fraction of 1.00 was used here.

Valve Cover Dislodged (X29). In this portion of the 2-1/2 ton cylinder analysis, it is assumed that the cylinder has been lost from the overpack. This means that the valve is exposed, as it was in event X23. To avoid counting this type of failure twice, the value assigned to this event was zero.

Valve Exposed to Impact Force (X30). Accidents in which the cylinder receives an end-on impact force (acting on valve end) represent 67% of all accidents. It was arbitrarily assumed that in these accidents, the valve was twice as likely to be exposed to the impact force as with other types of accidents where impact forces are assumed to act. For the valve to be exposed to an impact force, the force must be applied so that it fails the cylinder skirt, which is partially protecting the valve. Forces acting within 30° of "end-on" would be applied in a manner to threaten the valve. Taking all of these factors into consideration, a frequency of 1.3×10^{-1} per accident was determined for this event.

Packaging Error Not Detected (X31). Since information on packaging errors was derived from a survey of containers actually shipped, it was assumed that the errors were not detected. A value of 1.00 was used here.

Normal Transportation Forces Cause Defective Valve to Fail (X32). Normal transportation forces usually are not of sufficient level to cause failure of a defective valve. A valve defective to the point of failing at these levels would almost certainly be discovered during routine filling operations. For this reason a frequency of 10^{-6} per cylinder was used.

Plug Closure Non-Defective (X33). This element was conservatively set at 1.00.

Fraction of Fires Failing Properly Closed Valves Due to Pressure (I34). Valves are rated and tested at the same level as the cylinder. It is therefore assumed that the valve will fail at the same time the cylinder fails. To avoid double counting a failure mode, the fraction used here is zero.

Plug and Vessel Threads Mismatched (X35). The survey of packaging errors showed no occurrences of cross threaded plugs. A frequency of 1.21×10^{-4} per cylinder (at a 50% confidence level) was used here.

Fraction of Fires Failing Improperly Closed Valve by Pressure (I36). Using the results of tests and calculations presented in Appendix C, it was determined that the cylinder would reach atmospheric pressure after approximately 17 minutes of exposure to the fire. After that time cylinder internal pressure would increase until cylinder failure. It was assumed that all improperly closed valves would begin to leak as soon as the cylinder internal pressure exceeded atmospheric. The fraction of fires lasting long enough to cause this type of failure was found to be 0.20.

Plug Threads Stripped (X37). No plugs were found to have stripped threads during the time period covered by the survey. At a 50% confidence level, a frequency of 1.21×10^{-4} per cylinder would be expected.

Plug Not Tight (X38). No loose plugs were reported in the survey. A frequency of 1.21×10^{-4} per cylinder was assumed.

Fraction of Fires Failing Improperly Situated Valve by Pressure (I39). The assumptions made in analyzing this event are the same as those for event I36. As a result, the same fraction, 0.20 was used.

Plug Hit and Loosened During Handling (X40). This event was not observed during the time period covered by the survey. A rate of 1.21×10^{-4} per cylinder was used, based on a 50% confidence level.

Plug Exposed to Impact Forces (X41). Since the valve and plug are similarly located at opposite ends of the cylinder, the same value used for valve exposure to impact forces was used here. A value of 0.13 per accident was given to event X41.

Flying Object Strikes Plug (X42). Because of the size of the plug relative to the overall cylinder size, and the fact that it occupies a position on the cylinder similar to the valve, a value of 1.6×10^{-3} (the same as for event X27) was used.

Plug Closure Packaging Error Not Detected (X43). This element was given an expected occurrence of 1.00 since values used for package conditions were derived from survey data.

Normal Transport Forces Cause Plug to Fail (X44). A normal plug would not be expected to fail under normal transport conditions. A plug so defective as to possibly fail in the normal transportation mode would almost certainly fail or be detected during normal filling and handling operations. Because this is such an improbable event, a frequency of 10^{-6} per container was used.

Probe Strikes Cylinder (X45). Because all cylinder punctures are considered in event X47, this event was assigned a frequency of 1.00 per accident.

Fraction of Impact Forces Failing Properly Situated Valve (X46). Based on the results of actual cylinder tests (References 2, 3, and 4), it was assumed that impact forces equivalent to those present in a 3-meter drop test would be sufficient to cause valve failure. Figure 5.2 indicates that a fraction of 0.05 of the impact forces are severe enough to cause this type of failure.

V/R Sufficient to Puncture Cylinder (X47). The velocity to probe radius ratio (V/R) of a puncture probe is a measure of its ability to puncture the cylinder. Detailed information on the puncture environment and V/R distributions for large cylinders were not available for this study. Therefore, as explained in Section 5, an estimate of the frequency of puncture based on data from the accident records of gasoline shipments was derived. A puncture frequency of 1.35×10^{-4} per accident was determined. This represents only an estimate of the puncture environment, and to determine the full effect of using this estimate a sensitivity analysis was carried out and results shown in Section 11. Due to the nature of the analysis, it was impossible to distinguish between defective cylinders, non-defective cylinders, defective valves, non-defective valves, etc. Therefore, all of the values for the puncture events are combined here.

Fraction of Impact Forces Failing Improperly Situated Valve (I48). If the overpack is not present, the valve is exposed to impact forces without a

protective cover. It was arbitrarily assumed that an improperly situated valve would fail at one half the failure level of a properly installed valve, a drop of 1.5 meters. The distribution curve shown in Section 5 gives a fraction of 0.07 for this event.

Puncture Probe Generated by Accident (X49). This event was conservatively assumed to occur in all accidents. Therefore a value of 1.00 was used.

Natural Puncture Probe Present (X50). It was assumed here that puncture probes of some form are always present in the area of an accident. The value for this event was set at 1.00.

High H/U Factor (X51). Although no occurrences were noted in the survey, a total of zero observations in a sample size of 5712 cylinder implies an occurrence rate of 1.21×10^{-4} per cylinder at a 50% confidence level.

Fraction of Flying Objects Failing Properly Situated Valve (I52). The valve is one of the weakest points of the cylinder. If we assume that it is relatively fragile (as the skin of a gasoline tanker), then a frequency of 3.3×10^{-2} per object strike can be used. Based on the results of tests conducted at Paducah, Kentucky on valves similar to those used on the 2 1/2-ton cylinders, it is felt that the use of this frequency is conservative.

Packaging Error in H/U Factor Not Detected (X53). Packaging procedures for filling UF_6 cylinders require that the cylinder be inspected before filling, double samples be taken and analyzed, and that the cylinder interior pressure be subatmospheric before shipment. Sufficient contaminants inside the UF_6 cylinder to cause criticality at the enrichment levels considered here would be detected at any one or all of the above three steps. Only if all three of these required steps were omitted from the filling and handling procedures could the error go undetected. The probability of one of these steps being left out of the sequence is very small, therefore a probability of doing so was assigned a frequency of 10^{-4} per cylinder. The frequency of missing all three steps, therefore, is on the order of 10^{-12} per cylinder. This value was used for event X53.

Fraction of Flying Objects Failing Improperly Situated Valve (I54). An explanation of the failure frequency for properly situated valves was presented

in event I52. Since it was impossible to assess the degree of the packaging error, it was arbitrarily assumed that forces required to fail the improperly positioned valve occur 10 times more frequently in the accident environment. A fraction of 0.33 per flying object strike was used for event I54.

Cylinder Severely Corroded (X55). Results from the container survey indicate that a total of three cylinders were removed from service due to corrosion or deterioration. Based on this, a frequency of 5.25×10^{-4} per cylinder was used.

Cylinder Deteriorated (X56). This element was included in event X55 and its value set to zero here.

X57 Through X59. Not used.

Fraction of Criticalities Failing Properly Closed Valve (I60). It was assumed that all criticalities would cause failure of the valve. Therefore the value used here was 1.00.

X61. Not used.

Fraction of Criticalities Failing Improperly Closed Valve (I62). For reasons set forth in the evaluation of elements I60, the value used here was set at 1.00.

X63. Not used.

Fraction of Criticalities Failing Improperly Situated Valve (I64). As was done in elements I60 and I62, the value used here was set at 1.00.

X65 Through X69. Not used.

Fraction of Fires Failing Non-Defective Plug By Pressure (I70). As was the case with fire-caused pressure failing the non-defective valve, this event has been included in the cylinder failure event. This was done because the cylinder, valve, and plug are all rated, built, and tested to the same pressure level. It is therefore impossible to say which element will cause failure of the shipping package in the fire environment. The cylinder was conservatively chosen as the failure element. The fraction used here was therefore set at zero.

X71. Not used.

Fraction of Fires Failing Defective Plug by Pressure (I72). It was assumed that a defective plug would fail at the same level as a defective valve. For the reasons presented in the analysis of event I36, the fraction used for this event was 0.20.

X73 Through X77. Not used.

Fraction of Impact Forces Failing Defective Plug (I78). The location of the plug in the cylinder is such that any impact or flying object striking the plug would tend to drive the plug into the cylinder. It was therefore felt that a flying object would not cause failure of the plug, either defective or non-defective. Therefore the value associated with this event was zero.

X79. Not used.

Fraction of Impact Forces Failing Non-Defective Plug (I80). For the reasons detailed in the explanation of element I78, this event was also assigned a value of zero.

X81 Through X83. Not used.

Fraction of Flying Objects Failing Defective Plug (I84). For the reasons outlined in the description of event I78, this event was given a value of zero.

X85. Not used.

Fraction of Flying Objects Failing Non-Defective Plug (I86). For the reasons cited in the analysis of event I78, this event was assigned a value of zero.

X87 Through X89. Not used.

Fraction of Criticalities Failing Defective Plug (I90). This event was conservatively given a value of 1.00.

X91. Not used.

Fraction of Criticalities Failing Non-Defective Plug (I92). This element was conservatively assigned a fraction of 1.00.

X93 Through X101. Not used.

Tiedowns Fail (X102). In order for this event to contribute to the release of UF_6 , the cylinder must also fall from the vehicle after becoming unattached. The size of the cylinders dictates that such an event be classified as an accident. The frequency of this event was therefore included with the accident rates and this event has a value of zero to avoid double counting the event.

Weld Defective from Poor Welding Procedures (X103). Cylinder welds are inspected using x-ray techniques during manufacture. A weld defective enough to cause a serious weakness in the cylinder should be detected during these inspections. It is remotely possible, however, that such a weld could slip through the Q/C process. For that reason a probability of 10^{-6} per cylinder was used.

X104 Through 108, X110 Through X113. These events relate to the cylinder remaining inside the overpack during the accident. They will be covered in the next section.

Cylinder Lost from Overpack (X109). The protective overpack is designed to remain intact in all but the most severe accidents. Overpack drop tests conducted at Oak Ridge, Tennessee⁽²⁾ included end-on and corner over center of gravity tests from a height of 9 m. The overpack was able to withstand these tests without coming apart. Based on energy calculations, an impact equivalent to an 18-meter drop onto the corner of the overpack could cause shearing of the closure bolts and a release of the cylinder from the overpack. Impact forces acting in the right orientation are expected in approximately 67% of all accidents (end-on impacts). Approximately 0.5% of all accidents involve impact forces equivalent to an 18-meter drop. (Corresponding to a velocity change of approximately 68 kph.) Based on these observations, a frequency of 3.35×10^{-3} per accident was determined.

Cylinder Stays in Overpack

As previously noted, the analysis of release sequences for the 2 1/2-ton cylinder with overpack was carried out in two parts. This, the second part, deals with release sequences occurring when the cylinder remains inside the overpack during the accident. In analyzing the sequences, the following

events were reassessed and assigned values different from those in the first part of the analysis.

Fraction of Fires Causing Sufficient Pressure to Fail Defective Cylinder (I5). In the fire environment, heat is added more slowly and evenly to a UF_6 cylinder inside an overpack than when the cylinder is directly exposed. Because of this, and because of a lack of data from actual fire tests of UF_6 cylinders in overpacks (to failure), the cylinder failure analysis assumed that the vessel would fail when its contents reached a temperature of 138°C . At this temperature, the UF_6 would be in a liquid state and would completely fill the container. The internal cylinder pressure was assumed to be approximately atmospheric. An exposure of 83 minutes to a fire temperature of 800°C was calculated as the failure point. However, the duration curve for fires shown in Section 5 is based on a fire temperature of 1000°C . The radiant heat flux from a 1000°C fire is double that from a 800°C fire. The container failure analysis assumed that the entire surface of the overpack was exposed to the fire. However, for objects the size of UF_6 cylinders, it was felt that a smaller exposed fraction was more realistic. It was assumed for the purpose of this analysis that 50% of the surface area of the overpack was exposed to the fire. Therefore, the failure times (50% exposure at 1000°C versus 100% exposure at 800°C) are identical, and the curve shown in Section 5 is suitable. Following the same line of reasoning used in the evaluation of event I5 in the first portion of the analysis (i.e., the defective cylinder will fail in $3/4$ the time necessary for a non-defective one) a failure time of approximately 62 minutes was calculated. The duration curve shown in Figure 5.1 gives a value of less than 0.01 for fires lasting longer than this time. Therefore a value of 0.01 was used for I5.

Fraction of Fires Causing Sufficient Pressure to Fail Non-Defective Cylinder (I8). As explained in the evaluation of event I5, a failure time of 83 minutes was calculated for a non-defective cylinder with overpack. The duration curve shown in Figure 5.1 does not go past 40 minutes. If it is assumed that the curve is linear between 40 and 83 minutes, then a fraction of approximately 9×10^{-3} fires lasting longer than 83 minutes is indicated. This value was used for event I8.

Fraction of Impact Forces Failing Defective Cylinder (I12). Based on the calculated failure thresholds, an overpack adds the equivalent of approximately 13.5 meters (drop height) to the failure threshold of the 2 1/2-ton cylinder. A failure threshold of 4.5 meters was used for the defective cylinder without overpack. Adding the protection afforded by the overpack, a total failure level equivalent to an 18-meter drop was determined. Figure 5.2 shows that only about 0.5% of all expected truck accidents exceed this level. A value of 0.005 was used for this event.

Fraction of Impact Forces Failing a Non-Defective Cylinder (I15). An impact force equivalent to a drop of 22.5 meters was assumed to cause failure of the cylinder-overpack combination. Forces of this intensity are not expected to occur in truck accidents. A value of 10^{-3} was used for this improbable event.

Flying Object Strikes Valve (X27). Because the overpack acts as a valve protector, flying objects cannot strike the valve directly. A value of zero was used for event X27.

Valve Cover Dislodged (X29). The value used for this event was zero. Since no valve cover is used with cylinders in overpacks, no valve cover can be dislodged.

Fraction of Fires Failing Improperly Closed Valve by Pressure (I36). Earlier analyses (events I5 and I8) explained the mechanisms by which the cylinder fails explosively due to excess internal pressure. It was assumed in the first portion of the analysis that defective and improperly closed valves would fail when the pressure inside the vessel reached atmospheric. To maintain consistency, the same assumption was made here. Therefore, a defective valve will fail after an 83-minute exposure to the fire. A fraction of 9×10^{-3} was used for this event.

Fraction of Fires Failing Improperly Situated Valve by Pressure (I39). This event is similar to event I36. The reasoning used in evaluating that event is used here also. A value of 9×10^{-3} was used here also.

Flying Object Strikes Plug (X42). The overpack protects the plug from flying objects. If the cylinder remains inside the overpack, flying objects cannot directly strike the plug. The value assigned to this event was zero.

Fraction of Impact Forces Failing Properly Situated Valve (I46). Tests conducted on a prototype overpack (virtually identical to those used now⁽⁴⁾) showed that in a 9-m end-on drop test, no damage was done to the cylinder inside. If we assume conservatively that this is the limit of protection given by the overpack, then an equivalent drop height to fail the valve can be determined. In the previous part of the analysis, a failure height of 3 m was used for the valve when the cylinder was not protected by the overpack. Therefore, it was assumed that an impact equivalent to a 12-m drop would be sufficient to cause valve failure if the cylinder remains in the overpack. The accident environment information indicates that approximately 1% of all accidents exceed this level. A value of 0.01 was used.

V/R Sufficient to Puncture Cylinder (X47). The summary of failure thresholds shown in Section 6 indicates that an increase of approximately 30% in the puncture probes energy is required to break the cylinder when it is in the overpack. Based on the frequency used to describe bare cylinder puncture failures, and arbitrarily assuming a linear puncture frequency curve, a puncture frequency of 1.04×10^{-4} per accident was determined and used for this event. A sensitivity study was done (Section 11) to determine the effect of this value on the overall risk calculation.

Fraction of Impact Forces Failing Improperly Situated Valve (I48). The evaluation of this event is similar to that of event I46. As was done in the first portion of the analysis, a failure threshold of 1.5-m drop height was used for an unprotected improperly situated valve. Adding the protection provided by the overpack yields an expected failure threshold of 10.5 m for a protected valve. Forces of this magnitude are expected in about 1.5% of all accidents. A value of 0.015 was used.

Fraction of Flying Objects Failing Properly Situated Valve (I52). A flying object causing valve failure through the overpack would be classified as a puncture probe. All puncture failures were considered in the evaluation of event X47. The value used for event I52 was zero.

Fraction of Flying Objects Failing Improperly Situated Valve (I54). See Event I52. Value used here was zero.

Fraction of Fires Failing Defective Plug By Pressure (I72). Defective plugs were assumed to fail at the same pressure as defective valves. Therefore, a fraction of 9×10^{-3} was used for this event.

Overpack Damaged From Handling (X104). No grossly damaged overpacks were observed during the survey period. At a 50% confidence level, a damaged overpack can be expected at a rate of 1.23×10^{-4} per container.

Closure Bolts Loose (X105). Approximately 80 overpacks were received with loose closure bolts during the period covered by the survey. This implies an occurrence rate of 1.42×10^{-2} per cylinder.

Mating Surfaces Damaged (X106). A total of twelve occurrences were observed during the survey period. A frequency of 2.13×10^{-3} was therefore used.

Sealing Gasket Not Present (X107). Since no observations of this event were recorded, an expected frequency of 1.23×10^{-4} per cylinder was used (at a 50% confidence level).

Sealing Gasket Deteriorated (X108). This event was noted four times on the survey resulting in a frequency of 7×10^{-4} per cylinder.

Cylinder Lost From Overpack (X109). For this portion of the analysis, it was assumed that the cylinder remained inside the overpack. Therefore a value of zero was assigned to this event.

Impact Forces Exceed Limit of Overpack (X110). This event was included in the analysis of events I12 and I15 and given a value of zero here.

Fire Sufficient to Fail Gasket (X111). The foam rubber gasket between the halves of the overpack at the mating surface were conservatively assumed to fail in any fire situation. A value of 1.00 was used for this event.

Probe With Sufficient Force to Break Overpack (X112). The energy required to puncture the overpack is approximately 1/3 that required to puncture the cylinder. Again, assuming a linear probability distribution, a probability of 4.05×10^{-4} per accident was calculated.

UF₆ Cylinder Break Fails Overpack (X113). It was assumed that all accident forces causing failure of the UF₆ cylinder would also cause failure of the overpack. A value of 1.00 was used.

9.1.2 10-Ton (Type 48X) Cylinder Transported by Truck Without Overpack

This analysis uses the basic format set as in the 2 1/2-ton cylinder analysis. Since both types of shipping packages are transported by truck, many of the basic event probabilities remain the same. The following paragraphs describe only the events whose probabilities are different from those used in the previous (2 1/2-ton cylinder) analysis.

Accident Occurs With Fire (X1). The average shipment distance for this configuration is approximately 1040 km. Using the accident frequencies described in the previous analysis, a rate of 2.58×10^{-5} accidents with fire per shipment was determined.

Weld Defective From Corrosion (X2). This event was included with event X56 and given a value of zero here.

Weld Hit and Damaged During Handling (X3). Results of the survey indicate a rate of 1.43×10^{-4} per container.

Cylinder Non-Defective (X4). This event was conservatively assigned a value of 1.00.

Fraction of Fires Causing Sufficient Pressure to Fail Defective Cylinder (I5). The description of failure thresholds from Section 6 shows a failure time of 46 minutes for a non-defective 48X cylinder exposed to a petroleum fire. Using the reasoning described in the bare 2 1/2-ton cylinder analysis, a time to failure of 35 minutes was calculated for a defective cylinder. Based on the fire duration curve presented in Section 5, 96% of all truck accident fires are expected to burn less than this time. A value of 0.04 was used.

Cylinder Exposed to Force (X6). For the reasons given in the 2 1/2-ton cylinder analysis, this event was given a value of 0.89 per accident.

Accident Occurs Without Fire (X7). The same rate used in the Type 30B cylinder analysis (1.53×10^{-6} per kilometer) was used for this event. Based

on an average shipment distance of 1040 km, the expected frequency of accidents without fire is 1.59×10^{-3} per shipment.

Fraction of Fires Causing Sufficient Pressure to Fail Non-Defective Cylinder (I8). A petroleum fire of 46 minutes duration is required to overpressurize the 48X cylinder, causing a cylinder rupture. Figure 5.1 shows that approximately 1.3% of all expected fires burn for this length of time. A fraction of 0.013 was used for this event.

Flying Object Generated in Accident (X9). For the reasons presented in the evaluation of this event in the 2 1/2-ton cylinder analysis, a value of 0.89 per accident was used.

Flying Object Strikes Cylinder (X10). Puncture failures are considered in event X47. This event was incorporated with event X47. Therefore the value used here is 1.00.

Cylinder Defect Not Detected (X11). Because frequencies of cylinder defects were derived from survey information, a value of 1.00 was conservatively applied to this event.

Fraction of Impact Forces Failing Defective Cylinder (I12). Since the same failure threshold was used for both the 48X and Type 30B cylinders, a fraction of 0.04 was used for this event also.

Normal Transport Forces Cause Defective Cylinder Failure (X13). This event is identical to its counterpart in the 2 1/2-ton cylinder analysis. The same value was used for both, 10^{-6} per cylinder.

Valve Properly Closed (X14). A value of 1.00 was conservatively assumed for this event.

Fraction of Impact Forces Failing Non-Defective Cylinder (I15). Again, because identical impact failure thresholds were used for both 48X and Type 30B cylinders (bare), the fraction of impact forces failing both is the same, 0.02.

Valve Not Closed Tightly (X16). Because no events of this nature were recorded during the survey period, a value of 9.9×10^{-5} per container (based on a 50% confidence level) was used.

Valve Defective (X17). The survey results showed that 60 Type 48X cylinders had valves replaced during the period 1971-1975. It was learned that only a third of these were replaced due to defective valves; the others required replacement because of clogged ports, etc. Therefore, an expected occurrence rate of 2.86×10^{-3} per cylinder was used.

Valve and Vessel Threads Mismatched (X18). Because no examples of this packaging defect were observed, a rate of 9.9×10^{-5} per cylinder was used (based on a 50% confidence level).

Fraction of Flying Objects Failing Non-Defective Cylinder (I19). Because failures caused by flying objects and puncture probes are all combined in event X47, this event was given a zero value.

Valve Threads Stripped (X20). Again, because no observations of this event were noted in the survey, a frequency of 9.9×10^{-5} was used.

Fraction of Flying Objects Failing Non-Defective Cylinder (I21). This event was combined with event X47 and given a value of zero here.

Valve Assembly Loose (X22). Loose valve assemblies were noted seven times during the survey period for a frequency of 10^{-3} per cylinder.

Vessel Shipped Without Protective Valve Cover (X23). A valve cover missing from a fuel cylinder would be rather conspicuous. No observations were made by those plants surveyed; therefore a value of 9.9×10^{-5} was used with a 50% confidence level.

Valve Hit During Handling (X24). One occurrence was noted in the survey for an expected frequency of 1.43×10^{-4} per cylinder.

Fraction of Criticalities Failing Defective Cylinder (I25). It was conservatively assumed that all criticalities would cause cylinder failure, whether the cylinder was defective or not. A fraction of 1.00 was used here.

Valve Properly Situated on Cylinder (X26). This element was conservatively assigned a value of 1.00.

Flying Object Strikes Valve (X27). The same valve is used on all cylinders studied in the risk analysis, and on all cylinders, the valve is partially protected by the cylinder skirts. The same value for this event was used for all cylinders, i.e., 1.6×10^{-3} per accident.

Fraction of Criticalities Failing Non-Defective Cylinder (I28). It was assumed that all criticalities would cause cylinder failure. This element was given a value of 1.00.

Valve Cover Dislodged (X29). Impact forces required to dislodge the valve cover were assumed to be the same as forces required to cause valve failure. A frequency of 9.50×10^{-3} per accident was used. This is equivalent to the product of values assigned to events X30 and I46.

Value Exposed to Impact Force (X30). The analysis of this event was identical to its counterpart in the Type 30 cylinder analysis. A value of 0.19 per accident was used.

Packaging Error Not Detected (X31). Because frequencies for packaging errors were derived from observed data, this event was assumed to have a value of 1.00.

Normal Transportation Forces Cause Defective Valve to Fail (X32). Since this event is identical to event X32 of the 2 1/2-ton cylinder analysis, a value of 10^{-6} was used.

Plug Closure Non-Defective (X33). This event was given a value of 1.00. In the context of the fault tree, this value is conservative.

Fraction of Fires Failing Properly Closed Valve by Pressure (I34). This event was combined with Event I8 for reasons given in the 2 1/2-ton cylinder analysis. Its value here is zero.

Plug and Vessel Threads Mismatched (X35). Because no observations of this event were made during the survey, a value of 9.9×10^{-5} was used.

Fraction of Fires Failing Improperly Closed Valve by Pressure (I36). Throughout the entire analysis it was assumed that defective valves and plugs would fail when the internal cylinder pressure exceeded atmospheric. From the results of tests performed on smaller cylinders⁽⁵⁾ it was determined that the 48X cylinder would be at approximately atmospheric pressure (internally) after 27 minutes exposure to the fire. Figure 5.1 shows that less than 6% of all truck fires are expected to last that long. A value of 0.06 was used for this event.

Plug Threads Stripped (X37). Since no stripped plug threads were observed during the survey, a value of 9.9×10^{-5} was used.

Plug Not Tight (X38). This event was also assigned a value of 9.9×10^{-5} because no events were observed in the survey.

Fraction of Fires Failing Improperly Situated Valves by Pressure (I39). The evaluation of this event is identical to that of I36. The same assumptions were made in both. The value used here, therefore, is 0.06.

Plug Hit and Loosened During Handling (X40). This event was not observed during the survey period. A value of 9.9×10^{-5} (at a 50% confidence level) was used.

Plug Exposed to Impact Forces (X41). As was done in the 2 1/2-ton cylinder analysis, this event was given the same frequency as event X30, or 0.19 per accident.

Flying Object Strikes Plug (X42). Since the valve and plug are located in similar positions on opposite ends of the cylinder, the same value was used in the plug as was used for the valve. A frequency of 1.6×10^{-3} per accident was used.

Plug Closure Packaging Error Not Detected (X43). Because packaging closure error frequency rates were determined from survey data, this element was given a value of 1.00.

Normal Transport Forces Cause Plug to Fail (X44). This event was given a value of 10^{-6} . The same frequency was used for the 2 1/2-ton cylinder.

Probe Strikes Cylinder (X45). Because all cylinder punctures are considered in event X47, the value used for this event was set at 1.00.

Fraction of Impact Forces Failing Properly Situated Valve (I46). The evaluation of this event is identical to that of event I46 in the 2 1/2-ton cylinder analysis. Therefore an expected frequency of 0.05 per accident was used here.

V/R Sufficient to Puncture Cylinder (X47). A value of 1.34×10^{-4} per accident was used for this event. See the 2 1/2-ton cylinder analysis of event X47 for a full explanation.

Fraction of Impact Forces Failing Improperly Situated Valve (I48). This event was handled in the same manner as its counterpart in the 2 1/2-ton cylinder analysis. The valves used on both cylinders are the same. Assumptions concerning failure levels were also the same. A value of 0.07 was used for this event.

Puncture Probe Generated by Accident (X49). A value of 1.00 was conservatively applied to this event.

Natural Puncture Probe Present (X50). This event was also conservatively given a value of 1.00.

High H/U Factor (X51). No occurrences of this event were recorded, therefore a frequency of 9.9×10^{-5} per container was used.

Fraction of Flying Objects Failing Properly Situated Valve (I52). This event was evaluated in the same manner as for the Type 30B cylinder. A value of 3.3×10^{-2} per strike was used here also.

Packaging Error in H/U Factor Not Detected (X53). A value of 10^{-12} was used for this event frequency. See event X53 of the 2 1/2-ton (Type 30B) analysis for details.

Fraction of Flying Objects Failing Improperly Situated Valve (I54). A factor of 0.33 per strike was used for this event. See the analysis of event I54 in the 2 1/2-ton cylinder section for a more complete evaluation.

Cylinder Severely Corroded (X55). No examples of this event were recorded during the survey period. At a 50% confidence level, a value of 9.9×10^{-5} was used.

Cylinder Deteriorated (X56). This element was included in event X55 and was given a zero value here.

X57 through X59. Not used.

Fraction of Criticalities, Failing Properly Closed Valve (I60). It was conservatively assumed that all criticalities would cause valve failure. A value of 1.00 was used.

X61. Not used.

Fraction of Criticalities Failing Improperly Closed Valve (I62). This event was conservatively given a value of 1.00.

X63. Not used.

Fraction of Criticalities Failing Improperly Situated Valve (I64). This event was conservatively assigned a value of 1.00.

X65 through X69. Not used.

Fraction of Fires Failing Non-Defective Plug by Pressure (I70). This event was included with the cylinder failure event. Its value here is zero. See the 2 1/2-ton cylinder analysis for further explanations.

X71. Not used.

Fraction of Fires Failing Defective Plug by Pressure (I72). It was assumed that a defective plug would fail at the same pressure level as a defective valve. For reasons presented in the evaluation of event I36, a value of 0.06 was used.

X73 through X77. Not used.

Fraction of Impact Forces Failing Defective Plug (I78). This event was given a value of zero. See the 2 1/2-ton cylinder evaluation for analysis.

X79. Not used.

Fraction of Impact Forces Failing Non-Defective Plug (I80). This event was given a value of zero. See the 2 1/2-ton cylinder evaluation for analysis.

X81 through X83. Not used.

Fraction of Flying Objects Failing Defective Plug (I84). For reasons cited in the 2 1/2-ton cylinder analysis, this event was given a value of zero.

X85. Not used.

Fraction of Flying Objects Failing Non-Defective Plug (I86). For reasons cited in the 2 1/2-ton cylinder analysis, this event was given a value of zero.

X87 through X89. Not used.

Fraction of Criticalities Failing Defective Plug (I90). This event was conservatively given a value of 1.00.

X91. Not used.

Fraction of Criticalities Failing Non-Defective Plug (I92). This event was conservatively assigned a value of 1.00.

X93 through X101. Not used.

Tiedowns Fail (X102). The incidences of tiedown failure were considered to be included with the accident rate, and a value of zero was used for this event. The evaluation is detailed in the 2 1/2-ton cylinder analysis.

Weld Defective From Poor Welding Procedure (X103). A value of 10^{-6} per container was used for this event, the same value used in the 2 1/2-ton cylinder analysis.

9.1.3 10-Ton (Type 48X) Cylinder Transported by Truck With Overpack

The third shipping container configuration analyzed in the risk assessment was the 10-ton (Type 48X) cylinder with overpack transported by truck. The addition of an overpack changes this configuration somewhat from the previous one. However, since the same basic cylinder was used, many of the event frequencies are identical.

The analysis for the overpack cylinder configuration was handled in two parts. The first part was concerned with a cylinder which had been lost from the overpack during a transport accident. The second portion dealt with the case where the cylinder remains in the overpack during the transportation accident.

Cylinder Lost From Overpack

Since this portion of the analysis is nearly identical to the analysis performed for the bare 48X cylinder shipped by truck, only those events with values different from the previous analysis were addressed here. All other values remain the same, as presented in Section 9.1.2.

Accident Occurs With Fire (X1). Information from Sandia studies⁽¹⁾ show that approximately 1.6% of all truck accidents involve fire. Using a truck

accident rate of 1.55×10^{-6} accident per kilometer, it was determined that accidents involving fire could be expected at a rate of 2.48×10^{-8} per kilometer. For an average trip length of 420 kilometers, the rate was expressed as 1.04×10^{-5} per shipment. It was assumed that cylinders were exposed to the fire in all truck accidents with fire.

Accident Occurs Without Fire (X7). The same rate used in the Type 48X cylinder analysis (1.53×10^{-6} per kilometer) was used for this event. Based on an average shipment distance of 420 km, the expected frequency of accidents without fire is 6.43×10^{-4} per shipment.

Vessel Shipped Without Protective Valve Cover (I23). Since the vessels are shipped initially in a protective overpack, no valve cover as such is used. The value used for this event is 1.00.

Valve Cover Dislodged (X29). Since no valve cover is used, this event is impossible. The value assigned to this event was zero.

Tiedowns Fail (X102). No information is available on the frequency of tiedown failures expected during the transport of UF_6 cylinders. Past accidents have shown, however, that an accident situation is usually present when the container's tiedowns fail and the container falls from the vehicle. For this study, the incidences of tiedown failure were considered to be included with the accident rate, and a value of zero was used for this event.

Cylinder Lost From Overpack (X109). A corner or end-on drop from a height of 18 meters was assumed to cause failure of the latching mechanism and allow the cylinder to escape from the overpack (see 2 1/2-ton cylinder with overpack analysis, event X109). The fraction of accidents with impact forces acting in the right orientation is 0.67. Approximately 5×10^{-3} accidents involve impact forces equivalent to an 18-meter drop. A frequency of 3.35×10^{-3} per accident was used for this event.

Cylinder Remains in Overpack

The previous portion of the 10-ton cylinder, with overpack, by truck analysis dealt with the loss of the container from the overpack during an accident. This portion of the analysis examines the changes in values assigned to the basic fault tree events when the cylinder is not lost from the overpack

during the accident. The elements discussed below are only those whose values were changed from the values used in the first (bare cylinder) portion of the analysis. All other events retained their previous values.

Fraction of Fires Causing Sufficient Pressure to Fail Defective Cylinder (I5). The analysis carried out in Appendix C and summarized in Section 6 estimated that a non-defective cylinder inside a protective overpack would fail after a 156-minute exposure to fire. Following the same line of reasoning used in the analysis of the 2 1/2-ton cylinder with overpack (event I5), a time to failure of 117 minutes was determined for a defective 10-ton cylinder. The duration curve in Figure 5.1 shows that less than 0.1% of all fires are expected to last 117 minutes or longer. A value of 0.001 was therefore used for this event.

Fraction of Fires Causing Sufficient Pressure to Fail Non-Defective Cylinder (I8). A 156-minute exposure to a 1000°C fire was estimated as the failure threshold for a non-defective cylinder within an overpack. Information presented in Section 5 shows that essentially no fires are expected to burn longer than 156 minutes. A value of 1.0×10^{-4} was used for this inhibit event.

Fraction of Impact Forces Failing Defective Cylinder (I12). In previous analyses, it was assumed that a defective cylinder would fail at one half the impact failure threshold of a non-defective cylinder. In the case of the 10-ton cylinder, this corresponds to an impact equivalent of a 4.5-m drop. Analysis of the overpack showed that it raised the container's failure threshold by the equivalent of approximately 3.4 m. Therefore, a defective cylinder protected by an overpack was assumed to fail when subjected to an impact equivalent to a drop from a height of 7.9 m. This corresponds to a velocity change of approximately 45 kph. Using Figure 5.2, it was determined that impacts of this severity would occur at a rate of 3.0×10^{-2} per accident.

Fraction of Impact Forces Failing Non-Defective Cylinder (I15). A failure threshold equivalent to a drop from 12.4 m was calculated for a non-defective cylinder protected by an overpack. This corresponds to a velocity change of 56.5 kph. The corresponding rate for impacts of this severity is approximately 1.50×10^{-2} per accident (from Figure 5.2).

Flying Object Strikes Valve (X27). The valve is protected from direct flying object strikes by the overpack. A value of zero was therefore used for this event.

Fraction of Fires Failing Improperly Closed Valve by Pressure (I36). This event was analyzed in the same manner as its corresponding event in the 2 1/2-ton cylinder with overpack analysis. Time to failure for the defective or improperly closed valve is 156 minutes. The fraction of fires lasting this long was determined to be 0.01%. A value of 1.0×10^{-4} was used for this gate.

Fraction of Fires Failing Improperly Situated Valve by Pressure (I39). See event I36 for the reasoning used in the analysis of the event. A value identical to that of event I36 was used here, 1.0×10^{-4} .

Flying Object Strikes Plug (I42). The plug is protected from flying object strikes by the protective overpack. A value of zero was used for this event.

Fraction of Impact Forces Failing Properly Situated Valve (I46). Using the failure threshold for a properly situated valve (a drop from 3 m) and adding the protection of the overpack (3.4 m), a failure threshold of 6.4 m was determined. Figure 5.2 shows an expected frequency of 3.5×10^{-2} per accident for the velocity change (40 kph) associated with a drop from this height.

V/R Sufficient to Puncture Cylinder (X47). The summary of failure thresholds presented in Section 6 indicates that an increase of approximately 60% in the puncture probe energy is required to breach the cylinder while it is in the overpack. Based on the frequency used for unprotected cylinder punctures (1.34×10^{-4} per accident) and assuming that because of the increase in puncture probe energy required to breach the cylinder, the frequency is decreased by a factor of 0.6, a puncture frequency of 8×10^{-5} was used. Sensitivity studies were performed (see Section 11) which showed that the puncture events contributed relatively little to the overall risk, thereby justifying the use of this approximate value.

Fraction of Impact Forces Failing Improperly Situated Valve (I48). An impact failure level of 1.5 meters has been used for an improperly situated

valve. Adding the protection provided by the overpack, assumed to be 3.4 m, a projected failure level of 4.9 m was determined. The fraction of impact forces exceeding this level are expected to occur at a rate of 3.9×10^{-2} per accident.

Fraction of Flying Objects Failing Improperly Situated Valve (I52). Because of a general lack of information with which to distinguish between flying objects and puncture probes, this element was combined with event X47. A value of zero was used here.

Fraction of Flying Objects Failing Improperly Situated Valve (I54). This event was also combined with event X47. Its value here is zero.

Fraction of Fires Failing Defective Plug by Pressure (I72). Defective valves and plugs were assumed to fail at the same pressure level. In event I36, a value of 1.0×10^{-4} was used to describe the fraction of fires causing sufficient pressure to fail an improperly closed valve. This value was also used to describe plug failures.

Overpack Damaged From Handling (X104). No examples of this event were observed during the survey time period, therefore a value of 7.9×10^{-4} was used (at a 50% confidence level).

Closure Bolts Loose (X105). Again, no incidences of this occurrence were reported during the survey. Based on the sample size of 878 overpacks received, a value of 7.9×10^{-4} per container was used.

Mating Surfaces Damaged (X106). The survey reported zero occurrences of this element. A value of 7.9×10^{-4} per container was used.

Sealing Gasket Not Present (X107). This element was given a value of 7.9×10^{-4} per container for reasons cited in the analysis of event X106.

Sealing Gasket Deteriorated (X108). This element was not experienced during the time period covered by the packaging survey. A value of 7.9×10^{-4} per container was used.

Cylinder Lost From Overpack (X109). In this portion of the analysis, it was assumed that the cylinder remained inside the overpack. Therefore, a value of zero was used for event X109 in this case.

Impact Forces Exceed Limits of Overpack (X110). This event was included in events I12 and I15. It was given a zero value here.

Fire Sufficient to Fail Gasket (X111). As was done in the 2 1/2-ton cylinder with overpack analysis, this event was conservatively assigned a frequency of 1.00 per fire.

Probe With Sufficient Force to Breach Overpack (X112). Using the logic discussed in the analysis of event X112 of the 2 1/2-ton cylinder with overpack analysis, a value of 2.67×10^{-5} was determined.

UF₆ Cylinder Breach Fails Overpack (X113). It was assumed that an explosive breaching of the cylinder caused by fire or criticality would also breach the overpack. A value of 1.00 was assigned to this event.

9.1.4 14-Ton (Type 48Y) Cylinder Transported by Train

The fourth segment of the analysis involved evaluation of the fault tree for the shipment of 14-ton (Type 48Y) cylinders (without overpacks) by train. Following is a description of the basic events input to the fault tree. The 48Y cylinder is very similar to the 10-ton 48X cylinder; many of the event frequencies are thus identical. Only those events whose values were changed will be described. All other values remain the same.

Accident Occurs With Fire (X1). The accident analysis work performed by Sandia⁽¹⁾ concludes that fire will occur in train accidents at a rate of approximately 1.74×10^{-8} per car km. For an average trip distance of 800 km, a frequency of 1.4×10^{-5} per shipment is expected.

Weld Defective From Corrosion (X2). This event was included with event X56 and was given a value of zero here.

Weld Hit and Damaged During Handling (X3). No occurrences of this event were reported in the survey. A value of 1.1×10^{-4} per cylinder was assigned (at a 50% confidence level).

Cylinder Non-Defective (X4). This element was conservatively assigned a value of 1.00.

Fraction of Fires Causing Sufficient Pressure to Fail Defective Cylinder (I5). As explained in Section 6, calculations based on small

size cylinder tests to failure indicated a 48-minute time-to-failure for a non-defective cylinder exposed to a petroleum fire. As in the previous analyses, it was assumed that all defective cylinders would fail within 75% of the time necessary to cause non-defective cylinder failures. A failure time of 36 minutes was thus determined. Fire environment information presented in Section 5 indicates that approximately 40% of all train accident fires are expected to last longer than this time. A value of 0.40 was used for this element.

Cylinder Exposed to Force (X6). This element was combined with elements I12 and I15 for the purpose of this study. Its value here is therefore 1.00.

Accident Occurs Without Fire (X7). Using an accident rate of 6.21×10^{-6} accidents per kilometer and the fraction of accidents involving no fires, a rate of 6.20×10^{-6} accidents without fire per kilometer was determined. For an average trip length of 800 km, the expected occurrence frequency is 4.97×10^{-3} per shipment.

Fraction of Fires Causing Sufficient Pressure to Fail Non-Defective Cylinder (I8). As mentioned in the explanation of event I5, the fire failure threshold for a non-defective 14-ton cylinder is 48 minutes exposure to a 1000°C fire. Information presented in Section 5 indicates that 24% of all fires are expected to last longer than this time. A value of 0.24 was used.

Flying Object Generated in Accident (X9). This event was included with event X47 and was therefore given a value of 1.00 here.

Fraction of Impact Forces Failing Defective Cylinder (I12). An impact failure threshold of 9 m for a non-defective cylinder was listed in Section 6. A defective cylinder is expected to fail at half that, or 4.5 m. This drop height corresponds to a velocity change of about 34 kph. The expected frequency of an impact force of this magnitude is 6×10^{-3} . This value was used for event I12.

Fraction of Impact Forces Failing Non-Defective Cylinder (I15). The impact failure threshold of the non-defective 14-ton cylinder is equivalent to a drop height of 9 m, or a velocity change of 48 kph. Using the information presented in Figure 5.4, it was determined that forces of this magnitude occur at a rate of 2.50×10^{-3} per accident. This value was used for event I15.

Valve Not Closed Tightly (X16). No occurrences were noted during the survey period. At a 50% confidence level, with the same size involved in the survey, a rate of 1.1×10^{-4} per cylinder can be used.

Valve Defective (X17). Results of the packaging condition survey show that 86 valves required replacement during the time period 1971-1975. It was learned that only a third of these valves required replacement because they are defective. The rest required replacement because of clogged ports, etc., and cannot be counted as defective. Based on the sample size, an expected frequency of defective valves of 4.5×10^{-3} per container was determined.

Valve and Vessel Threads Mismatched (X18). No instances of mismatched or crossed threads were reported on the survey forms. For that reason, a value of 1.1×10^{-4} per cylinder was assigned to the event.

Valve Threads Stripped (X20). As was the case in event X18, no instances of this packaging error were reported. Again, a value of 1.1×10^{-4} was used for this event.

Valve Assembly Loose (X22). Nineteen instances of loose valve assemblies were noted during the survey. This implies an expected frequency of 3.0×10^{-3} per cylinder.

Vessel Shipped Without Protective Valve Cover (X23). This element was not observed during the survey. A value of 1.1×10^{-4} was assigned (at a 50% confidence level).

Valve Hit During Handling (X24). Based on the results of the packaging condition survey, a value of 7.9×10^{-4} per cylinder was used.

Flying Object Strikes Valve (X27). A value of 1.6×10^{-3} per accident was used. For more detail see the analysis of event X27 in the bare 10-ton cylinder, Section 9.1.2.

Valve Cover Dislodged (X29). Impact forces required to dislodge the valve cover were assumed to be the same as those required to cause valve failure. A frequency of 7.5×10^{-4} per accident was used. This is equivalent to the product of values assigned to events X30 and I46.

Valve Exposed to Impact Force (X30). Ninety percent of all train accidents can be classified as impact or derailment accidents (the remainder are basically non-moving accidents). As in previous cylinder analyses, a 30° acceptance angle was used. Assuming random orientation of the cylinder during the accident, a ratio of 7.5×10^{-2} was determined.

Plug and Vessel Threads Mismatched (X35). No occurrences of mismatched or cross threaded plugs were noted on the survey. A value of 1.1×10^{-4} was used.

Fraction of Fires Failing Improperly Closed Valve by Pressure (I36). As was done throughout the analysis, it was assumed that defective and improperly closed valves would leak when the internal pressure of the cylinder reached atmospheric. Using the results of small-size UF_6 cylinder fire tests, it was determined that the internal pressure of the cylinder would reach atmospheric after approximately 28 minutes exposure to the fire. Results shown in Section 5 indicate that less than 58% of all expected fires will last this long. A value of 0.58 was used.

Plug Threads Stripped (X37). Based on results gathered from the container packaging survey, a value of 1.1×10^{-4} was used for this event.

Plug Not Tight (X38). A value of 1.1×10^{-4} was used for this event (at a 50% confidence level).

Fraction of Fires Failing Improperly Situated Valve by Pressure (X39). This event was given the same value as event I36, 5.8×10^{-1} .

Plug Hit and Loosened During Handling (X40). Since no incidences of this event were noted during the survey, a value of 1.1×10^{-4} was used.

Flying Object Strikes Plug (X42). Flying object strikes and puncture probes were combined in event X47. The value of this event is zero here.

Fraction of Impact Forces Failing Properly Situated Valve (I46). An impact force equivalent to a 3-m drop was assumed to cause valve failure. From Figure 5.4, it is evident that impact forces of this level can be expected in 1.0×10^{-2} of all accidents.

V/R Sufficient to Puncture Cylinder (X47). All puncture elements were combined in this event. Since no V/R distribution was available (the velocity-to-radius ratio is the measure of a puncture probe's ability to break the cylinder) a single rate, based on rail accident data, was used. The train accident environment summary in Section 5 shows an expected frequency of punctures of 6.4×10^{-4} per accident.

Fraction of Impact Forces Failing Improperly Situated Valve (I48). A defective or improperly situated valve was arbitrarily assumed to fail at a level of 1/2 that of a non-defective or properly installed valve. Impact forces equivalent to a drop of 1.5 m can be expected in 7.5×10^{-2} of all train accidents.

Puncture Probe Generated by Accident (X49). It was determined from accident information presented in Reference 3 that 90% of all train accidents involve derailment or collisions (the remaining 10% are mostly fires, or non-moving type accidents). Only in the moving accidents would a puncture probe be generated. A value of 0.90 per accident was used for this event.

Fraction of Flying Objects Failing Properly Situated Valve (I52). Due to a lack of information concerning flying objects, this event was combined with event X47. The value used here is therefore zero.

Fraction of Flying Objects Failing Improperly Situated Valve (I54). This event was also combined with event X47 because of lack of information on flying object punctures. Data used to generate a frequency for X47 did not detail the type of puncture, i.e., puncture to cylinder or valve dislodged by puncture probe. This being the case, a value of zero was used here.

Cylinder Severely Corroded (X55). No badly corroded or deteriorated cylinders were reported during the survey period. Therefore a value of 1.1×10^{-4} was used.

Cylinder Deteriorated (X56). This element was included with event X55 and given a value of zero here.

Fraction of Fires Failing Defective Plug by Pressure (I72). Because defective plugs and valves were all assumed to fail at the same level, a value of 0.58 was used here.

Tiedowns Fail (X102). No information is available on the frequency of tiedown failures expected during the transport of UF_6 cylinders. Past accidents have shown that when the container's tiedowns fail and the container falls from the vehicle, an accident is usually the result. For this study, the incidences of tiedown failure were considered to be included with the accident rate, and a value of zero used for this event.

9.1.5 14-Ton (Type 48Y) Cylinder Transported by Truck

The fifth and final segment of the analysis involved evaluation of the fault tree for the shipment of 14-ton (Type 48Y) cylinders (without overpacks) by truck. Following is a description of the basic events, many of which are the same as in Section 9.1.4 because of the similarity of the 10-and 14-ton cylinders. Only those events whose values were changed will be described. All other values remain the same as in the previous section.

Accident Occurs With Fire (X1). The average shipment distance for this configuration is about 375 kilometers. Using the accident frequency of 2.48×10^{-8} per kilometer derived in Section 9.1.1 (event X1), a value of 9.3×10^{-6} accidents with fires is expected.

Fraction of Fires Causing Sufficient Pressure to Fail Defective Cylinder (I5). A failure time of 36 minutes was determined in the previous analysis. Information in Section 5 suggests that approximately 3% of all truck accident fires are expected to last longer than this time. A value of 0.03 was used for this event.

Cylinder Exposed to Force (X6). For reasons given in Section 9.1.1, this event was given a value of 0.89 per accident.

Accident Occurs Without Fire (X7). Based on an average shipment distance of 375 km, the expected frequency of accidents without fire is 5.74×10^{-4} per shipment (see Section 9.1.1, event X7, for further explanation).

Fraction of Fires Causing Sufficient Pressure to Fail Non-Defective Cylinder (I8). The fire failure threshold for a non-defective 14-ton cylinder is 48 minutes exposure to a $1000^{\circ}C$ fire. Information presented in Section 5 indicates that approximately 1.3% of all expected fires burn for this length of time. A fraction of 0.013 was used for this event.

Flying Object Generated in Accident (X9). For reasons presented in Section 9.1.1, a value of 0.89 per accident was used.

Fraction of Impact Forces Failing Defective Cylinder (I12). An impact failure threshold of 4.5 m, or 34 kph, was derived in the previous analysis for a defective cylinder. The expected frequency of an impact force of this magnitude is 0.04. This value was used for event I12.

Fraction of Impact Forces Failing Non-Defective Cylinder (I15). The impact failure threshold of the non-defective 14-ton cylinder is equivalent to a drop height of 9 m, or a velocity change of 48 kph. Using the information presented in Figure 5.2, it was determined that forces of this magnitude occur at a rate of 0.02 per accident. This value was used for event I15.

Valve Cover Dislodged (X29). Impact forces required to dislodge the valve cover were assumed to be the same as those required to cause valve failure. A frequency of 6.5×10^{-3} per accident was used. This is equivalent to the product of values assigned to events X30 and I46.

Valve Exposed to Impact Force (X30). The analysis of this event was identical to its counterpart in Section 9.1.1. A value of 0.13 per accident was used.

Fraction of Fires Failing Improperly Closed Valve by Pressure (I36). In the previous analysis, a failure threshold of 28 minutes exposure to a 1000°C fire was determined. Data shown in Section 5 indicate that less than 6% of all expected fires will last this long. A value of 0.06 was used.

Fraction of Fires Failing Improperly Situated Valve by Pressure (X39). This event was given the same value as event I36, 6.0×10^{-2} .

Fraction of Impact Forces Failing Properly Situated Valve (I46). An impact force equivalent to a 3-m drop was assumed to cause valve failure. From Figure 5.2, it is evident that impact forces of this level can be expected in 5.0×10^{-2} of all accidents.

V/R Sufficient to Puncture Cylinder (X47). All puncture elements were combined in this event, for which a value of 1.35×10^{-4} per accident was used. See Section 9.1.1 for a full explanation.

Fraction of Impact Forces Failing Improperly Situated Valve (I48). A defective or improperly situated valve was arbitrarily assumed to fail at one-half the level of a non-defective or properly installed valve. Impact forces equivalent to a drop of 1.5 m can be expected in 7×10^{-2} of all truck accidents.

Puncture Probe Generated by Accident (X49). A value of 1.00 was conservatively applied to this event.

Fraction of Flying Objects Failing Properly Situated Valve (I52). This event was evaluated in the same manner as for the Type 30B cylinder. A value of 3.3×10^{-2} per strike was also used here.

Fraction of Flying Objects Failing Improperly Situated Valve (I54). A factor of 0.33 per strike was used for this event. See the analysis of event I54 in the 2 1/2-ton cylinder section for a more complete evaluation.

Fraction of Fires Failing Defective Plug by Pressure (I72). Because defective plugs and valves were all assumed to fail at the same level, a value of 0.06 was used here.

9.2 RELEASE SEQUENCE PROBABILITIES

The basic event probabilities presented in Section 9.1 provide the basis for evaluating the probability of each release sequence identified in the fault trees. The probabilities of the release sequences for 14-ton UF_6 truck shipments are shown in Table 9.1. Lists of release sequence probabilities for the four other cases were produced but not shown. Only the release sequences with a frequency of occurrence greater than 10^{-15} per shipment are listed in the table. All release sequences were retained in the actual risk calculation.

**TABLE 9.1. Release Sequences and Probabilities
for 14-Ton UF₆ Rail Shipments**

Release Sequence Probability	Release Sequence					
3.360E-06	X 1	X 4	X 8			
6.160E-10	X 1	X 5	X 55			
6.160E-10	X 1	X 3	X 5			
5.600E-12	X 1	X 5	X103			
8.932E-10	X 1	X 16	X 36			
8.932E-10	X 1	X 35	X 72			
3.654E-08	X 1	X 17	X 36			
8.932E-10	X 1	X 18	X 39			
8.932E-10	X 1	X 20	X 39			
2.436E-08	X 1	X 22	X 39			
1.00E-10	X 35	X 43	X 44			
8.932E-10	X 1	X 37	X 72			
8.932E-10	X 1	X 38	X 72			
8.932E-10	X 1	X 40	X 72			
1.100E-10	X 11	X 13	X 55			
1.100E-10	X 3	X 11	X 13			
1.000E-12	X 11	X 13	X103			
1.100E-10	X 18	X 31	X 32			
1.100E-10	X 20	X 31	X 32			
3.000E-09	X 22	X 31	X 32			
1.100E-10	X 37	X 43	X 44			
1.100E-10	X 38	X 43	X 44			
1.100E-10	X 40	X 43	X 44			
8.064E-09	X 1	X 45	X 47	X 49		
7.056E-13	X 1	X 23	X 24	X 39		
2.857E-06	X 7	X 45	X 47	X 49		
8.960E-09	X 1	X 45	X 47	X 50		
3.500E-08	X 1	X 4	X 6	X 15		
9.240E-12	X 1	X 6	X 12	X 55		
9.240E-12	X 1	X 3	X 6	X 12		
8.400E-14	X 1	X 6	X 12	X103		
8.690E-14	X 23	X 24	X 31	X 32		
3.174E-06	X 7	X 45	X 47	X 50		
1.240E-05	X 4	X 6	X 7	X 15		
3.274E-09	X 6	X 7	X 12	X 55		
3.274E-09	X 3	X 6	X 7	X 12		
2.976E-11	X 6	X 7	X 12	X103		
6.661E-14	X 1	X 23	X 26	X 30	X 46	
2.783E-10	X 7	X 23	X 26	X 30	X 46	
1.597E-15	X 1	X 23	X 24	X 30	X 48	
5.355E-12	X 1	X 26	X 29	X 30	X 46	
5.657E-13	X 7	X 23	X 24	X 30	X 48	
1.897E-09	X 7	X 26	X 29	X 30	X 46	
6.064E-15	X 1	X 22	X 23	X 30	X 48	
7.877E-14	X 7	X 18	X 23	X 30	X 48	
7.877E-14	X 7	X 20	X 23	X 30	X 48	
2.148E-12	X 7	X 22	X 23	X 30	X 48	
1.031E-15	X 1	X 18	X 29	X 30	X 48	
1.031E-15	X 1	X 20	X 29	X 30	X 48	
2.811E-14	X 1	X 22	X 29	X 30	X 48	
3.652E-13	X 7	X 18	X 29	X 30	X 48	
3.652E-13	X 7	X 20	X 29	X 30	X 48	
9.960E-12	X 7	X 22	X 29	X 30	X 48	

9.3 RELEASE FRACTIONS

The final step in the evaluation of release sequences is the determination of release fractions. For the purpose of this risk analysis, the lists of release sequences were broken down into four categories and release fractions were assigned to each:

- All release sequences involving a breach of the cylinder with no fire present were assigned a release fraction of 10^{-3} . This value was based on interviews with personnel experienced in UF_6 emergencies and information found in Reference 9. It was assumed, in this instance, that all products of the release, HF gas and particulate UO_2F_2 , would be airborne following the release, with the source at ground level. The duration of the release was assumed to be 15 minutes, limited because the particulate UO_2F_2 tends to plug up the release pathway. The fact that there is no driving force (such as a fire) to keep the cylinder pressurized also limits the release duration.
- Release sequences in which the cylinder was breached (excluding explosive ruptures) with fire present were assigned a release fraction of 0.1. This release mechanism is similar to the failure of a valve while the cylinder is being heated in a steam chest. It was assumed that all of the released materials would be elevated to a height of 230 m by the fire plume. The duration was assumed to be 20 minutes in length. Again, the amount released is limited by clogging of the release path by UO_2F_2 .
- The explosive failure of a cylinder without overpack in the fire environment was assigned two release fractions: an initial release of 0.1 with a duration of 1 minute, and a secondary release of 0.9 over a span of 4 hrs. This corresponds to case 2a in Reference 9. The cylinder explodes with 10% of the UF_6 in molten form, which is elevated in the fire plume to a height of 230 m. The remaining 90% of the material is scattered on the ground around the accident site (the fire having been extinguished by the explosion) and slowly hydrolyzes over the 4-hr time span. It was assumed that the UO_2F_2

remained on the ground at the accident site during this second portion of the release.

- The explosive failure of a cylinder with overpack in the fire environment was also assigned two release fractions: an initial release of 0.8 with a duration of 1 minute, and a secondary release of 0.2 over a 4-hr time period. This corresponds to case 2b in Reference 9. In this situation the cylinder explodes with 80% of the UF_6 in molten form. This fraction is elevated in the fire plume to a height of 230 m. The remaining 20% is broken into small solid pieces and scattered around the accident site (the fire is out) and slowly hydrolyzes over the 4-hr time span. Again, it was assumed that the UO_2F_2 resulting from this second portion of the release remained on the ground at the accident site.

Table 9.2 shows the release sequences from Table 9.1 broken down into the various categories along with assigned release fractions. Similar tables for the remaining cylinder type-transportation mode combinations are made, but not shown.

TABLE 9.2. Release Sequences for 14-Ton Cylinder Grouped According to Release Fraction

Group 1 - Release With No Fire (R.F. = 10^{-3})				
Release Sequence Probability	Release Sequence			
1.100E-10	X 11	X 13	X 55	
1.100E-10	X 3	X 11	X 13	
1.000E-12	X 11	X 13	X 103	
1.100E-10	X 18	X 31	X 32	
1.100E-10	X 20	X 31	X 32	
3.000E-09	X 22	X 31	X 32	
1.100E-10	X 37	X 43	X 44	
1.100E-10	X 38	X 43	X 44	
1.100E-10	X 40	X 43	X 44	
1.100E-10	X 35	X 43	X 44	
2.857E-06	X 7	X 45	X 47	X 49
8.690E-14	X 23	X 24	X 31	X 32
3.174E-13	X 7	X 45	X 47	X 50
1.240E-05	X 4	X 6	X 7	X 15
3.274E-09	X 6	X 7	X 12	X 55
3.274E-09	X 3	X 6	X 7	X 12
2.976E-11	X 6	X 7	X 12	X 103
5.657E-13	X 7	X 23	X 24	X 30 X 48
1.897E-09	X 7	X 26	X 29	X 30 X 46
7.877E-14	X 7	X 18	X 23	X 30 X 48
7.877E-14	X 7	X 20	X 23	X 30 X 48
2.148E-12	X 7	X 22	X 23	X 30 X 48
3.652E-13	X 7	X 18	X 29	X 30 X 48
3.652E-13	X 7	X 20	X 29	X 30 X 48
9.960E-12	X 7	X 22	X 29	X 30 X 48
4.092E-10	X 7	X 23	X 26	X 30 X 46
Group 2 - Release With Fire (R.F. = 10^{-1})				
	Release Sequence			
8.932E-10	X 1	X 16	X 36	
8.932E-10	X 1	X 35	X 72	
3.654E-08	X 1	X 17	X 36	
8.932E-10	X 1	X 18	X 39	
8.932E-10	X 1	X 20	X 39	
2.436E-08	X 1	X 22	X 39	
8.932E-10	X 1	X 37	X 72	
8.932E-10	X 1	X 38	X 72	
8.932E-10	X 1	X 40	X 72	
8.960E-09	X 1	X 45	X 47	X 50
8.064E-09	X 1	X 45	X 47	X 49
7.056E-13	X 1	X 23	X 24	X 39
3.500E-08	X 1	X 4	X 6	X 15
9.240E-12	X 1	X 6	X 12	X 55
9.240E-12	X 1	X 3	X 6	X 12
8.400E-14	X 1	X 6	X 12	X 103
1.155E-12	X 1	X 23	X 26	X 30 X 46
1.597E-15	X 1	X 23	X 24	X 30 X 48
5.355E-12	X 1	X 26	X 29	X 30 X 46
1.973E-15	X 1	X 22	X 29	X 30 X 48
6.064E-15	X 1	X 22	X 23	X 30 X 48
1.031E-15	X 1	X 18	X 29	X 30 X 48
1.031E-15	X 1	X 20	X 29	X 30 X 48
2.811E-14	X 1	X 22	X 29	X 30 X 48
Group 3 - Explosive Release in Fire (R.F. = 0.10 - 1 min., R.F. = 0.90 - 4 hr)				
	Release Sequence			
3.360E-06	X 1	X 4	X 8	
6.160E-10	X 1	X 5	X 55	
6.160E-10	X 1	X 3	X 5	
5.600E-12	X 1	X 5	X 103	
Group 4 - Explosive Release in Fire (R.F. = 0.80 - 1 min., R.F. = 0.20 - 4 hr)				
	Release Sequence			

No 14-ton cylinder release sequences in this group.

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10.0 EVALUATION OF ENVIRONMENTAL CONSEQUENCES

In Section 9, individual release sequences were identified and evaluated by determining their expected frequency of occurrence and the corresponding release fraction. At this point, a risk number could be obtained by multiplying the individual release sequence probabilities and release fractions together, and summing overall release sequences. The resulting risk number, however, would not be in a suitable form for comparison with other societal risks, which is one of the objectives of the risk assessment.

To express the risk in a more useful form, conversion factors must be developed to allow modification of the consequence portion of the risk number (in this case, to fatalities). The purpose of this section is to develop these conversion factors. Areas which must be evaluated include: health effects of a material release, meteorology, demography, and quantity of the release made airborne and dispersed. The final portion of this section will show how these factors are applied to the risk number.

10.1 HEALTH EFFECTS

When released to the atmosphere, uranium hexafluoride (UF_6) combines chemically with the moisture present in the air to form HF (hydrogen fluoride) gas and UO_2F_2 (uranyl fluoride), a particulate. All products of a UF_6 release represent a health hazard when inhaled. Hydrogen fluoride gas presents a danger which is chemical in nature only, while the effects of inhaling UO_2F_2 are both chemical and radiological. However, for UF_6 releases involving material with an enrichment of less than 10% ^{235}U , the chemical toxicity is generally considered a far greater threat than the radiotoxicity.⁽¹⁾ Although enrichment levels greater than 3.5-4.0% were not considered in this analysis, this section will address both chemical and radiological hazards.

10.1.1 Effects of Hydrogen Fluoride Gas

Hydrogen fluoride gas presents a danger which is chemical in nature and has the potential for injurious effects to man, animal life and vegetation. Because the risk in this study is to be expressed in terms of health effects, only insults to the human body were considered.

Much has been written concerning the health effects of HF on humans; however, precise quantification of these effects is difficult. Hydrogen fluoride gas causes severe irritation of the eyes and respiratory system. If sufficient quantities of the gas are inhaled, death from pulmonary edema can occur. HF damage is a function of both the concentration of gas inhaled and the duration of exposure. Table 10.1 gives some reported values for health effects of HF.

TABLE 10.1. Health Effects of HF

0.1 mg/m ³	perceptive odor concentration ⁽²⁾
2.5 mg/m ³	8-hr daily exposure ACGIH Threshold ⁽²⁾ limit value
25.0 mg/m ³	tolerable for several minutes with ⁽²⁾ respirator irritation
>40.0 mg/m ³	possibility of being fatal to humans ⁽³⁾ at 1-hr exposure
100.0 mg/m ³	highest tolerable concentration for ⁽²⁾ 1 minute with severe eye and respirator irritation
245.0 mg/m ³	laboratory animal death from exposures ⁽⁴⁾ > 2-hr

Because of the wide range of release durations considered in this study (1 minute to 4 hours) it was necessary to develop two sets of limits for HF health effects. The release durations were divided into two categories; short term (less than 20 minutes) and long term (20 minutes to 4 hours). The limits and effects assumed for each category in this study are presented in Table 10.2.

10.1.2 Effects of Uranyl Fluoride

Uranyl fluoride presents both a chemical and radiological hazard. The chemical effects of UO₂F₂ involve the toxicity of both fluoride and uranium. As with HF gas, the greatest damage is caused by the effects of the fluoride compound on the respiratory system. Radiological effects result from exposure to the radioactive elements contained in the UF₆, most notably the isotopes of uranium.

TABLE 10.2. Assumed Effects of HF on Humans
Short Term Release (20 Min.)

$<2.5 \frac{\text{mg}}{\text{m}^3}$	no effect
$25.0 \frac{\text{mg}}{\text{m}^3}$	respiratory discomfort and minor health effects
$100.0 \frac{\text{mg}}{\text{m}^3}$	health effects requiring two weeks medical care
$400.0 \frac{\text{mg}}{\text{m}^3}$	assumed fatal

Long Term Release (20 Min. - 4 hr.)

$<2.5 \frac{\text{mg}}{\text{m}^3}$	no effect
$10.0 \frac{\text{mg}}{\text{m}^3}$	health effects requiring two weeks medical care
$40.0 \frac{\text{mg}}{\text{m}^3}$	assumed fatal

This study considers the shipment of two types of UF_6 : unenriched and enriched. For the purpose of determining the health effects of UO_2F_2 , it was conservatively assumed that all UF_6 shipped had an isotope inventory equivalent to 3.2% enriched UF_6 . The inventory is given in Table 10.3, based on values given in ERDA-1543⁽⁵⁾.

TABLE 10.3. Isotopic Composition of 3.2% ^{235}U Enriched UF_6

Isotope	Ci/Kg-U
^{232}U	4.67×10^{-5}
^{233}U	2.36×10^{-7}
^{234}U	3.57×10^{-3}
^{235}U	6.92×10^{-5}
^{236}U	8.84×10^{-4}
^{238}U	3.21×10^{-4}
^{239}Pu	2.43×10^{-7}
^{237}Np	4.32×10^{-7}
^{106}Ru	4.22×10^{-7}
$^{95}\text{Zr}, ^{95}\text{Nb}$	9.3×10^{-7}
^{137}Cs	6.9×10^{-8}
^{144}Ce	6.9×10^{-8}
^{90}Tc	3.16×10^{-5}
^{90}Sr	1.72×10^{-8}

Dose conversion factors, as calculated by the computer program DACRIN,⁽⁶⁾ for the uranium isotopes and the residual fission products and actinides are shown in Tables 10.4 and 10.5. Since UO_2F_2 is very soluble, soluble uranium factors have been used.

TABLE 10.4. Dose to Critical Organ via Inhalation^(a)
(Soluble) - Dose in $\frac{\text{Rem-m}^3}{\text{Ci-Sec}}$

Radionuclides	Dose Time (Years)	Organ		
		Kidneys	Bone	Lungs
$^{95}\text{Zr}^{(b)}$	50	---	$4.0\text{E}+1^{(b)}$	---
^{95}Nb	50	---	$1.8\text{E}-4$	---
^{99}Tc	50	$8.6\text{E}-1$	---	---
^{106}Ru	50	$2.6\text{E}+1$	---	---
^{137}Cs	50	---	$1.7\text{E}+1$	---
^{144}Ce	50	---	---	$2.0\text{E}+2$
^{232}U	50	---	---	$2.5\text{E}+4$
^{233}U	50	---	---	$1.6\text{E}+4$
^{234}U	50	---	---	$1.6\text{E}+4$
^{235}U	50	---	---	$1.5\text{E}+4$
^{236}U	50	---	---	$1.5\text{E}+4$
^{238}U	50	---	---	$1.4\text{E}+4$
^{237}Np	50	---	$5.1\text{E}+5$	---
^{239}Pu	50	---	$5.5\text{E}+5$	---

(a) Task Group on Lung Dynamics Model, 7.5-hr inhalation duration, 350 cc/sec. breathing rate.

(b) Read 4.0×10^1 .

TABLE 10.5. Dose to Critical Organ via Inhalation^(a)
(Insoluble) - Dose in $\frac{\text{Rem-m}^3}{\text{Ci-Sec}}$

Radionuclides	Dose Time (Years)	Organ		
		Kidneys	Bone	Lungs
⁹⁵ Zr	50	---	---	1.183E+2 ^(b)
⁹⁵ Nb	50	---	1.774E-4	---
⁹⁹ Tc	50	---	---	1.709E+2
¹⁰⁶ Ru	50	---	---	1.076E+3
¹³⁷ Cs	50	---	1.720E+1	---
⁴⁴ Ce	50	---	---	8.601E+2
²³² U	50	---	---	5.948E+5
²³³ U	50	---	---	1.594E+5
²³⁴ U	50	---	---	1.562E+5
²³⁶ U	50	---	---	1.449E+5
²³⁸ U	50	---	---	1.371E+5
²³⁷ Np	50	---	1.930E+5	---
²³⁹ Np	50	---	2.081E+5	---

(a) Task Group on Lung Dynamics Model - 7.5-hr inhalation duration, 350 cc/sec breathing rate.

(b) Read 1.183×10^2 .

The chemical effects of UO_2F_2 involve the toxicity of both fluoride and uranium. The maximum permissible concentration (MPC) (air) of fluoride particulates as F^- is 2.5 mg/m^3 . The MPC of uranium is 0.210 mg/m^3 . Limits based on soluble uranium were assumed to apply to UO_2F_2 . The International Commission of Radiological Protection (ICRP) gives a value of 2.5 mg inhaled as acceptable⁽⁷⁾. Ten (10) mg inhaled is suggested as a maximum emergency planned occupational dose.⁽¹⁸⁾ A case history of 13 mg of UO_2F_2 inhaled resulted in several days hospitalization, with recoverable effects.⁽⁹⁾ Little information is available on fatal inhalation levels. One hundred (100) mg inhaled is assumed to result in eventual death. Table 10.6 gives the UO_2F_2 levels and effects assumed for this study.

TABLE 10.6. Assumed Limits and Effects of UO_2F_2

<2.5 mg inhaled	No effect
10.0 mg inhaled	Minimal health effects
20.0 mg inhaled	Clinical effects requiring two weeks medical care
100.0 mg inhaled	Assumed fatal

10.2 METEOROLOGY

The diffusion climatology along the transport route must be incorporated into any risk analysis where the atmosphere is an important pathway for dosage to man. The important atmospheric variables are: 1) wind direction, which indicates the initial direction of travel; 2) wind speed, which indicates the rate of transport; and 3) atmospheric stability, which indicates the rate of dilution and plume rise potential. Certain characteristics of release (e.g., height and temperature) are also important in the evaluation of the atmospheric pathway.

Assuming a postulated accident with a surface release and little or no release-related plume rise, the immediate and greatest impact will be in the region surrounding the location of the event. Transport and diffusion are often determined by local influences. Wind speeds and directions show considerable variation that cannot be always summarized by large geographic regions. Local influences include topography (surface roughness, channeling), heat island effects, and proximity to large bodies of water. The inclusion of such influences in the present analysis is not feasible, principally because the information is not available either from a data base or from current modeling capabilities.

For estimates of long-term diffusion averages, the average persistence of winds by sectors are used. Considering wind direction persistences alone, the actual sector annual-average air concentrations can be considerably higher or lower than an average. Based on reported values from 129 weather bureau surface stations in the continental U.S., the concentrations range on the order of from half to 5 times the average. The air concentrations near a particular

population center can be expected to vary by the same factor depending on the direction of the population center from the selected route. Such a factor could be quite important in determining the effects of releases near large population centers. Over a sufficiently long route, the effects of different wind direction persistences may tend to cancel if there is a random relationship between the prevailing wind directions and population centers. The alternative of picking a route based on known diffusion climatologies to minimize risk could be beneficial; however, at the present time it is not included in the model.

The meteorological data used in this analysis are shown in Table 10.7. The values were developed from micrometeorological data collected for diffusion calculations for reactor sites. Seven sets of micrometeorological data were selected from about 26 compilations from reactor sites to account for the range of conditions that could reasonably occur along the route. The use of a single averaged distribution allows for the typical range of wind speeds without undue weighting to any particular site. Although this result cannot be expected to necessarily represent any particular portion of the route, it does represent the type of conditions that may be encountered on the average.

TABLE 10.7. Average Wind Speed/Stability Characteristics

Wind Speed			Pasquill Stability Classification			
U_k			$P_{j/k}$			
m/sec	k	P_k	B(j=1)	D(j=2)	E(j=3)	F(j=4)
1	1	0.255	0.136	0.202	0.299	0.363
3.5	2	0.508	0.243	0.274	0.272	0.211
7	3	0.161	0.190	0.290	0.339	0.181
10	4	0.052	0.240	0.312	0.358	0.090
18	5	0.024	0.276	0.348	0.356	0.020

10.3 DEMOGRAPHY

To determine the number of people affected by a UF_6 release resulting from a transportation accident, the population distribution along the shipping route must be characterized. Population densities used in this study were originally developed for use in a study of the risk of shipping plutonium by truck.⁽¹⁰⁾

The population distribution along shipping routes was characterized by dividing the continental U.S. into four zones based roughly on population density and degree of urbanization. The zones are shown in Figure 10.1. Population densities were grouped into three classes: urban, for densely populated urban areas, suburban, for areas of moderate population density, and rural, for the nonurbanized areas. The suburban data were obtained from Bureau of the Census information for the Standard Metropolitan Statistical Area (SMSA). The SMSA includes urban areas. The population and land area of cities inside the SMSA were subtracted to obtain the data for suburban population zones.

To establish population data for the representative zones, Bureau of the Census information for 1960 was used as a base. This information was extended to 1970 with data from the 1970 census. Population projections were made to 1980, 1990, and 2000, using the compound interest formula to model population growth. Projected population densities and land areas used in this study are presented in Table 10.8.

A second factor in the characterization of the demography is to relate the shipment route to the population zones. UF_6 shipment routes were previously determined in Section 4.

FIGURE 10.1. Population Zones and UF_6 Shipping and Receiving Facilities
(See Table 10.9)

TABLE 10.8. Projected Population Density and Land Area by Zone and Population Classes

	Zone and Population Classes	Land Area, %	Density People/km ²
I	Urban	3.8	3587
	Suburban ^(a)	66.9	317
	Rural	29.3	236
II	Urban	11.5	1224
	Suburban ^(a)	35.5	326
	Rural	53.0	92
III	Urban	0.8	1537
	Suburban ^(a)	17.3	87
	Rural	81.9	7
IV	Urban	0.5	1695
	Suburban ^(a)	15.0	51
	Rural	84.5	10

^(a) SMSA minus cities

A map with the population zones and the locations of the facilities shipping and receiving UF₆ are shown in Figure 10.1. The designations E-1, F-1, P-1, etc., refer to the enrichment, fuel fabrication and production facilities listed in Table 10.9.^(a) Distances between shipping and receiving facilities were obtained from Rand McNalley maps.⁽¹¹⁾ For each shipping route, the fraction of the route in each population zone was determined by drawing arcs of a great circle route between each shipping and receiving point and determining the fraction of the arc in each zone. This data is summarized in Table 10.10. A listing of the fractional mileage for each individual route is included in Appendix D.

(a) All material imported from or exported to foreign sources was assumed to enter the country through Baltimore or Norfolk.

TABLE 10.9. UF_6 Shipping and Receiving Facilities

Production Plants

P-1 Metropolis, IL
P-2 Sequoyah, OK
P-3 Foreign Sources (Baltimore, MD)
P-4 Foreign Sources (Norfolk, VA)

Enrichment Plants

E-1 Paducah, KY
E-2 Oak Ridge, TN
E-3 Portsmouth, OH

Fuel Fabrication Plants

F-1 Wilmington, NC
F-2 Apollo, PA
F-3 Richland, WA
F-4 Erwin, TN
F-5 Columbia, SC
F-6 Hematite, MO
F-7 Foreign Receivers (Baltimore, MD)
F-8 Foreign Receivers (Norfolk, VA)

TABLE 10.10. Fractional Mileage of Shipping Routes
by Population Zone

<u>Zone</u>	<u>I</u>	<u>II</u>	<u>III</u>	<u>IV</u>
% of all Shipping Routes in Zone	5	12	80	3

10.4 ATMOSPHERIC DISPERSION MODEL

The products of a UF_6 release must reach man via some pathway in his environment to present any danger to human life. For the purpose of this study, only the air pathway was considered. Although material can also reach man via food chain and aquatic pathways, the amount of material following these pathways has been found to be insignificant when compared to the air pathway.⁽¹²⁾

The products of the UF_6 release, HF and UO_2F_2 , were assumed to be neutrally buoyant when airborne. In releases involving fire, the products were assumed to be carried aloft and released from the fire plume (elevated release). In instances where solid chunks of UF_6 laid on the ground and slowly hydrolyzed over a period of time (4 hours), it was assumed that only the HF became airborne; all UO_2F_2 was assumed to remain on the ground.

For releases of short duration (less than a day), the time integrated air concentration at ground level was evaluated by the bivariate normal diffusion model using Pasquill diffusion parameters.⁽¹²⁾ In equation form:

$$E = \frac{Q}{\pi \sigma_y \sigma_z \bar{u}_h} \exp \left(-y^2 / 2\sigma_y^2 \right) - (h^2 / 2\sigma_z^2) \quad (10-1)$$

where:

E is ground level time-integrated air concentration at point
x, y, gm sec/m³

x is downwind distance measured from point of release, m

y is crosswind distance measured horizontally from centerline of
cloud, m

Q is total release from source, g

σ_y is crosswind lateral standard deviation of cloud concentration, m

σ_z is crosswind vertical standard deviation of cloud concentration, m

$\bar{U}_h$ is average wind speed at the height of release in direction of travel, m/sec

h is height of release, m.

The values of σ_y and σ_z are a function of the downwind distance x and the Pasquill Stability Category existing at the time of the accident. These values are shown in Tables 10.11 and 10.12, respectively.

TABLE 10.11. Values of σ_y for Pasquill Stability Categories

Downwind Distance (meters)	σ_y for Pasquill Type					
	A	B	C	D	E	F
100	21	16	12	8.0	6.0	3.9
250	54	40	28	20	14	9.8
500	100	76	55	37	28	18
1,000	200	150	110	72	52	36
2,500	450	340	240	160	120	81
5,000	830	630	450	310	220	150
10,000	1,600	1,200	850	570	410	280
25,000	3,400	2,600	1,800	1,200	880	610
50,000	6,200	4,700	3,400	2,300	1,600	1,100
100,000	11,000	8,500	6,300	4,100	2,800	2,000

TABLE 10.12. Values of σ_z for Pasquill Stability Categories

Downwind Distance (meters)	σ_z for Pasquill Type					
	A	B	C	D	E	F
100	15	10	7.8	4.7	3.0	1.4
250	43	26	18	10	7.1	4.0
500	140	57	34	19	13	7.6
1,000	670	140	64	33	22	14
2,500	2,000	580	140	62	41	25
5,000	2,000	2,000	260	95	61	35
10,000	2,000	2,000	440	140	84	47
25,000	2,000	2,000	880	220	120	64
50,000	2,000	2,000	1,400	320	140	79
100,000	2,000	2,000	2,000	450	170	94

The concentration received by an individual at point (x,y) can now be obtained by specifying the wind speed, height of release, and Pasquill Stability Category. For these conditions, values of σ_y and σ_z at the downwind distance, x, can be obtained from Tables 10.11 and 10.12 by interpolation. The quantity E/Q can then be calculated at point (x,y) using Equation 10-1.

Amounts received by the entire population could, in theory, be calculated by locating every individual or groups of individuals and going through the above procedure until all individuals exposed to the release were included in the calculation. For this study, however, it was much simpler to determine the number of people affected by a certain level, namely that limit of concentration causing fatality. This was done by calculating isopleths at constant time-integrated air concentration using Equation 10-1. Then, by integration, the area enclosed by such an isopleth was determined (curves similar to those shown in Figure 10.2 can also be used to determine areas). A key assumption was that all individuals located within the isopleth representing a fatal concentration would be killed.

FIGURE 10.2. Area Within Isopleths for a Ground-Level Source (From Reference 13)

In the case of a release of UF_6 resulting from a transportation accident, the assumption of no evacuation near the release site would be overly conservative. HF gas generated during the release causes extreme irritation to eyes and nose at concentrations well below those assumed fatal. Thus, most of the population in the area of the release would be motivated to leave that region. Only those who are hurt or otherwise physically unable to evacuate themselves from the area would be in danger.

A study by the U.S. Environmental Protection Agency (EPA)⁽¹⁴⁾ indicates that, even when faced with threatening situations, people often refuse to evacuate. Curiosity regarding the accident may override fear, and people may not leave the danger area promptly. Results of the EPA study indicate that approximately six percent of the total population affected refuses to evacuate. Other reports indicate this figure to run as high as 50%.⁽¹⁴⁾

The physical effects of the HF gas would cause most of the population to evacuate. Thus, the low figure of 6% remaining is used here. It is also assumed that another 4% of the population is physically unable to leave the danger zone. On the average, a 90% evacuation level was assumed to prevail in this study. This is believed to be a conservative estimate since the irritation caused by the HF gas would probably cause a greater number of people to evacuate than otherwise.

10.5 ESTIMATED EXPOSURE FREQUENCY

The information presented in the previous subsections can be used as conversion factors to modify the release sequence probabilities and release fractions developed in Section 9. The remainder of this section will show how these factors are applied in the risk calculation. The risk calculation proceeds along two parallel and interrelated paths. One path characterizes the consequences of an accidental release, and the other path determines the frequency of occurrence for each event in the consequence analysis.

As briefly discussed in Section 3, risk is expressed by the equation:

$$R_i = AF_{R_i} \times P_{R_i} \times \sum_q C_{E_i,q} \times P_{E_q} \quad (10-2)$$

where q represents a number of indices as indicated below.

The terms inside the first set of parentheses represent the product of the amount of material present in a shipment (A) times the fraction of that material which is lost to the environment in the i^{th} release sequence (F_{R_i}) times the expected frequency of occurrence of the release sequence (P_{R_i}). All the information needed to evaluate these terms was developed in Section 9. The two terms in the second set of parentheses represent the consequences of a unit release (E_i, q) and the expected frequency of encountering a given set of environmental conditions (PE_q). The primary purpose of previous parts of this section has been to determine the factors required to evaluate the consequences of a release. The information required to determine the expected frequency of a given environmental consequence has also been presented; the development of the frequency of occurrence term is shown below.

The analysis presented in this section treated the wind speed, weather stability class and population class as distributed variables. The expected frequency of encountering a given set of environmental conditions can be expressed as:

$$P_{E_{j,k,\ell,m}} = P_{j/k} P_k P_{\ell/m} P_m \quad (10-3)$$

where:

- j is the atmospheric stability classification index
- k is the wind speed index
- ℓ is the population density index in zone m of the U.S.
- m is the zone index for the shipping routes

The notation j/k indicates that the expected frequency of encountering the j^{th} stability class is a function of the wind speed existing at the time of release. Similarly, the expected frequency of encountering the ℓ^{th} population density is dependent on the expected frequency that a shipment will pass through zone m .

The values for the "P" in Equation (10-3) are obtained from the following tables in this section:

P_k - Table 10.7, column 3

$P_{j/k}$ - Table 10.7, columns 4-7

$P_{\ell/m}$ - Table 10.8

P_m - Table 10.10

By specifying a value for j , k , ℓ , and m , one can obtain the expected frequency that an environmental condition will be experienced during a shipment. Associated with that frequency is a corresponding value for the environmental consequences. The relationship is best summarized by the following equation for the environmental term in the risk equation:

$$\sum_q C_{E_{i,q}} \times P_{E_q} = \sum_{j,k,\ell,m,n} A_{n,j,k} (\overline{E/Q})_{n,j,k} N_{\ell/m} P_{j/k} P_k P_{\ell/m} P_m \quad (10-4)$$

where:

$A_{n,j,k}$ is the area within the isopleth of concentration $(E/Q)_{n,j,k}$

$(\overline{E/Q})_{n,j,k}$ is the time integrated air concentration received in $A_{n,j,k}$ per gram released.

$N_{\ell/m}$ is the population density in the release plume (Table 10.8).

The subscripts and the values for P in Equation 10-4 have been defined following Equation 10-3. The product $(C_{E_{i,q}} \times P_{E_q})$ has units of population health effects per gram of material released.

Equation 10-4 summarizes the information presented in this section. In Section 11, these results will be used in conjunction with the release sequences developed in Section 9 to obtain the risk of shipping UF_6 in the United States.

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11.0 THE RISK OF SHIPPING URANIUM HEXAFLUORIDE BY TRUCK AND RAIL

In this section, the risk of shipping UF_6 by truck and rail will be discussed. The risk was calculated using the methodology presented in Section 3. The probability of an accidental release occurring during transport was determined in Section 9, and the consequences of such a release were discussed in Section 10. Section 11.1 presents the risk of shipping UF_6 in the reference year, based on the shipping system model given in Section 4. Major contributors to the overall risk are discussed in Section 11.2 and the results of sensitivity studies will be presented in Section 11.3. A discussion of multiple container failures will be presented in Section 11.4.

11.1 RISK EVALUATION OF UF_6 SHIPMENTS

Because of the complex nature of the shipping system model, the risk analysis was divided into five parts, each part corresponding to one of the five shipping package configurations. The figures which were used for calculations in the analysis are shown in Table 11.1 for each cylinder configuration. The risk involved with shipping each of the five cylinder configurations was determined; these risks were then summed to determine the overall transportation system risk.

Based on the information presented in Table 11.1, accidents involving truck shipments of UF_6 (in any of the four cylinder types) would be expected to occur at a rate of three every year. Train accidents involving UF_6 shipments (in 14-ton cylinders) would be expected to occur approximately twice every year. Based on the release sequence probabilities determined in Section 9, truck accidents resulting in a release (of any amount of material) are expected once every 33 years. Train accidents resulting in a release would occur once every 100 years. Accidents releasing sufficient UF_6 to create a hazard (a significant release) can be expected once every 1430 years for truck shipments and once every 710 years for rail shipments. These results are summarized in Table 11.2 for each cylinder configuration.

TABLE 11.1. Simplified UF₆ Shipping System Model

Shipping Container	Transport Mode	Amount/ Container (MT)	Containers/ Shipment	Shipment Origin/ Destination	Material Shipped/ Year (MT)	Number of Ship- ments/Year	Average Shipment Distance (km)	Accident/km
2.5-ton (30B) With Overpack	Truck	2.28	5	Enrichment/ Fabrication Enrichment/ Exports	7,460	653	1,050	1.55×10^{-6}
10-ton (48X)	Truck	9.54	2	Conversion/ Enrichment	9,000	472	1,040	1.55×10^{-6}
10-ton (48X) With Overpack	Truck	9.54	1	Enrichment/ Enrichment	1,340	141	420	1.55×10^{-6}
14-ton (48Y)	Truck	12.5	1	Conversion/ Enrichment	21,820	1,746	375	1.55×10^{-6}
14-ton (48Y)	Rail	12.5	4	Import/ Enrichment Enrichment/ Enrichment	12,000	420	800	6.21×10^{-6}

TABLE 11.2. Summary of UF₆ Shipping System Risks

Shipping Container	Transport Mode	Probability of Accident (events/year)	Probability of Release (events/year)	Probability of Significant Release (events/year)	Probability of Release Resulting In ≥ 1 Death
2.5-ton (30B) With Overpack	Truck	1.06	4.6×10^{-4}	3.1×10^{-4}	1.4×10^{-7}
10-ton (48X)	Truck	7.6×10^{-1}	1.0×10^{-2}	1.6×10^{-4}	3.4×10^{-6}
10-ton (48X) With Overpack	Truck	9.2×10^{-2}	3.1×10^{-5}	1.9×10^{-5}	4.1×10^{-7}
14-ton (48Y)	Truck	1.01	2.0×10^{-2}	2.1×10^{-4}	4.5×10^{-6}
14-ton (48Y)	Rail	2.09	1.0×10^{-2}	1.4×10^{-3}	9.7×10^{-5}

Risk spectrum curves for the five individual container configurations are shown in Figure 11.1, along with the risk spectrum for the entire shipping system for the reference year. The shipment of UF₆ in 14-ton cylinders by rail contributes the greatest portion to the total system risk (especially in the high consequence portion of the spectra). The high risk for rail shipments stems primarily from the severe fire accident environment for rail. In a train accident with fire, 24% of the fires are of sufficient duration (48 min) to fail a nondefective 48Y (14-ton) UF₆ cylinder. However, only 1.3 percent of the fires in a truck accident are of this duration. Since

the explosive failure of a cylinder was found to have the most severe consequences, the rail shipments of UF_6 were found to have the highest risk. Thus, the total and 14-ton cylinder by rail risk curves are virtually identical. Figure 11.2 shows the UF_6 shipment risk spectrum in perspective with other risks, including those from previous risk assessment studies in this series.^(1,2,3)

FIGURE 11.1. Risk Spectra for Individual Transport Modes and Total for Shipping System

FIGURE 11.2. Risk Spectrum for Shipment of UF_6 and Other Risk Spectra

The results of this study indicate that the risk of shipping UF_6 by truck and rail is generally higher than the risk of shipping plutonium by truck and rail, but lower than the risk of shipping plutonium by air. At the low consequence-high probability end of the spectrum, the risks of shipping plutonium by air and UF_6 are similar, while at the high consequence-low probability end, the UF_6 risk is similar to that for shipping plutonium oxide by truck and rail. The risk of shipping UF_6 is well below the spectrum presented for man-caused events. Again, it should be noted that these spectra do not differentiate between latent (long-term) and acute (short-term) fatalities.

11.2 MAJOR CONTRIBUTORS TO OVERALL RISK

During the analysis of each of the five container configurations, the release sequences determined in Section 9 were grouped into four categories corresponding to the four release fractions described in Section 9.3. In evaluating the release sequences in each of these four groups, three effects of the released materials were addressed: the chemical effects of HF gas and the chemical and radiological effects of UO_2F_2 .

For all cylinder configurations, it was found that only release sequences in which the cylinder failed explosively in a fire presented a significant potential for producing fatalities. These release sequences correspond to the third and fourth release fraction groups described in Section 9.3. In all other release sequences, materials released were either dispersed and diluted so thoroughly that a lethal level could be found only at the source point, or the materials were not dispersed from the accident at all. Furthermore, only HF gas was found to produce fatalities. Radiation doses from UO_2F_2 were insufficient to present a chemical hazard.

The release sequence scenarios describing the explosive release of UF_6 in a fire consist of an early release of short duration (1 min) followed by a long term release (4 hr). Materials released during the short term release are elevated to a height of 230 meters by the fire. Large chunks of solid UF_6

slowly hydrolyzing on the ground characterize the long term portion of the releases. In both cases, the lethal concentrations of HF gas result from the long term release.

To summarize, all release sequences contributing significantly to the risk of shipping UF_6 include the explosive failure of the cylinder in a fire. Only the HF gas, released over a 4-hr period following the failure of the cylinder, is in sufficient concentrations to cause fatalities. All other release sequences release insufficient material to cause fatalities.

11.3 RISK SENSITIVITY STUDIES

Before discussing the sensitivity of the risk evaluation to the value of certain system parameters, it is important to point out a fundamental sensitivity of the risk evaluation. The calculated risk is a function of the shipping assumptions. Use of different shipping routes, different containers, changes in the predicted industry growth rate, etc., would result in a different risk. In general, reevaluation of the risk would be required for these changed conditions.

Risk sensitivity evaluations permit analysis of the importance of the various factors that contribute to the risk. They can be used to: 1) identify and quantify the effects of the major contributors to the risk; 2) identify ways to decrease the uncertainty in the risk evaluation, and 3) study the effects of possible design or regulatory changes on the risk. Most sensitivity studies are performed by repeating the risk calculation with a changed value for the parameter of interest. In general, the dependence of the risk on a particular parameter is complex; although in some cases, the parameter enters simply into the risk calculation and the sensitivity can be determined directly.

For this risk assessment, the area presenting the greatest uncertainty is the evacuation of people from the vicinity of the accident. Hydrogen fluoride gas is highly irritating to the eyes and nose in concentrations far below that necessary to cause physical damage. Thus, it appears that only those individuals incapable of self-evacuation (invalids or those trapped in the accident wreckage) would be in grave danger. To test the effects of

evacuation levels on the risk of shipping UF_6 , sensitivity studies assuming no evacuation, 95% evacuation, and 99% evacuation were carried out. The results of these sensitivity analyses are compared graphically with the base case (which assumed 90% evacuation) in Figure 11.3 and tabulated in Table 11.3.

In Section 5, the accident environment was described. One portion of the accident environment (the puncture environment), for both truck and rail accidents was determined using available existing accident data. The effects of using the assumed puncture rates in the risk assessment will be examined here.

FIGURE 11.3. Risk Spectra for Sensitivity Cases

TABLE 11.3. Risk Sensitivity Cases for UF₆ Shipments

<u>Description of Sensitivity Case</u>	<u>Risk Level (Estimated Annual Frequency of Occurrence of One or More Fatalities)</u>	<u>Risk Level Relative to Base Case</u>
Base Case ^(a)	1.09×10^{-4}	---
No Evacuation	5.19×10^{-4}	4.76
95% Evacuation	6.22×10^{-5}	0.57
99% Evacuation	7.59×10^{-6}	0.07
100% Exposure to Rail Fires	3.31×10^{-4}	3.04
No Packaging Defects	1.05×10^{-4}	1.00

(a) Based on Shipping Model (Section 4) and 90% Evacuation

In the previous subsection (11.2), the main contributors to the risk were discussed. In the risk analysis, it was determined that only originally intact cylinders failing explosively in a fire contributed to the risk of shipping UF₆. Cylinders punctured in the accident did not contribute to the calculated overall risk. Therefore, the risk assessment is insensitive to the puncture rate assumed in Section 5.

The sensitivity of the risk to the presence of fire in a rail accident was tested. All of the cars in a train are not expected to be exposed to the fire, because of the size of the train relative to the fire size. In Section 5, it was shown that the car carrying UF₆ cylinders would be directly exposed to the fire in 14% of all rail accidents involving fire. To test this assumption a sensitivity study was carried out in which it was assumed that the cylinders would be exposed to the fire in 100% of all rail accidents involving a shipment of UF₆ (a highly conservative assumption). The results are shown in Figure 11.3 and Table 11.3.

A final sensitivity study was carried out to determine the effects of packaging errors on the risk. The case was evaluated with the assumption of

no packaging errors present during the shipment. The results of the sensitivity analysis show that the risk is insensitive to packaging errors.

11.4 MULTIPLE CONTAINER FAILURE ANALYSIS

The evaluation presented in Section 11.2 assumed that only one container failed in an accident, but at an accident frequency multiplied by the number of containers in the shipment. The analysis did not include the possibility of multiple container failures in a single accident. Because fire is the only portion of the accident environment which can cause significant releases of UF_6 with the potential for causing fatalities, the possibility of multiple container failures must be addressed.

To determine the effects of multiple container fire failures on the risk of transporting UF_6 , a special sensitivity study was carried out. The study was based on the following assumptions:

1. All fires were assumed to be petroleum fires.
2. Fuel pools were assumed to be circular.
3. The fuel source was assumed to be located at one end of the transport vehicle.
4. Cylinders were assumed to remain in position on the transport vehicle.
5. Train tank car fuel, when involved, is spread uniformly over an area varying from 56 to 465 square meters, averaging 185 square meters with a cumulative distribution function (cdf) given by

$$1-e^{-\left[\frac{(10.76)(A)-600}{1465}\right]^{1.28}} \quad (11-1)$$

where A is the area in square meters. ⁽⁴⁾

6. When diesel fuel from locomotives is involved in the fire, it is dispersed uniformly over 46 to 93 square meters with an expected value of 65 square meters and a cdf given by

$$1-e^{-\left[\frac{(10.76)(A)-500}{252}\right]^{1.6}} \quad (11-2)$$

where A is the area in square meters. ⁽⁴⁾

7. Fuel from a truck/truck (nontanker) collision is distributed uniformly with equal probability over 4 m^2 to 19 m^2 .⁽⁴⁾
8. Fuel from a truck/tanker collision is spread uniformly and with equal probability over 5 m^2 to 47 m^2 .⁽⁴⁾
9. Cylinders were assumed to be exposed to the fire if they were completely inside the circumference of the fuel pool (see Figure 11.4).

FIGURE 11.4. Number of Cylinders Exposed to Fire as Related to Fuel Pool Size

The above assumptions were used to determine the probability of a certain number of cylinders being exposed to the fire. Analyses were made ranging from one cylinder to all cylinders in a shipment being exposed and failing. Consequences were evaluated in the same manner as for the base case.

The results of this supplemental sensitivity study are shown in Figure 11.5 along with the results of the evaluation performed in Section 11.2. The assumption of independent container failures is nonconservative by about a factor of 1.5 at the high consequence-low probability end of the

spectrum, but conservative by a factor of approximately 2.5 at the low consequence-high probability end. Based on the results of the multiple container failure analysis, the inclusion of multiple container failure data would not seriously distort the risk spectrum obtained from individual container failure analysis.

FIGURE 11.5. Risk Spectrum of Single and Multiple Container Failure Evaluations

REFERENCES

1. T. I. McSweeney, R. J. Hall et al., An Assessment of the Risk of Transporting Plutonium Oxide and Liquid Plutonium Nitrate by Truck. BNWL-1846, Battelle, Pacific Northwest Laboratories, Richland, WA, August 1975.
2. R. J. Hall et al., An Assessment of the Risk of Transporting Plutonium Dioxide and Liquid Plutonium Nitrate by Train. BNWL-1996, Battelle, Pacific Northwest Laboratories, Richland, WA, February 1977.
3. T. I. McSweeney and J. F. Johnson, An Assessment of the Risk of Transporting Plutonium Dioxide by Cargo Aircraft. BNWL-2030, Battelle, Pacific Northwest Laboratories, Richland, WA, June 1977.
4. A. W. Dennis, J. T. Foley, W. F. Hartman and D. W. Larson, Severities of Transportation Accidents Involving Large Packages. SAND 77-0001, Sandia Laboratories, Albuquerque, NM, May 1978.

APPENDIX A

UF₆ SHIPPING CONTAINER AND TRANSPORT MODE DESCRIPTION

Essentially all UF₆ shipments are currently made by either truck or rail. A third mode, piggyback (a combination of truck and rail), is sometimes used, but was not considered in this study. All shipments are made in containers meeting Department of Transportation (DOT) specifications and built to standards outlined in ANSI N14.1-1971.

UF₆ SHIPPING CYLINDERS

Although a variety of containers are available for shipping UF₆, only three were considered in this study: the 30B (2 1/2-ton) cylinder, the 48X (10-ton) cylinder, and the 48Y (14-ton) cylinder. Another 2 1/2-ton UF₆ cylinder, the 30A, is currently in use and will be described here. It was not considered as part of the study, however, for two reasons: 1) The 30B was designed to replace the 30A; this changeover should be nearly complete in the early 1980s, the reference time for the analysis, and 2) the 30A and 30B are basically similar models. The 30B was chosen as a representative 2 1/2-ton cylinder to reduce the number of cylinders analyzed.

Each cylinder is presented and described in Figures and Tables A.1 through A.4. More detailed information, including engineering drawings, can be found in Reference 1.

PROTECTIVE OVERPACKS

Except for exempt quantities of fissile material, cylinders containing UF₆ enriched to greater than 1.0 wt% ²³⁵U must be shipped in protective outer packages. Provisions to adequately separate UF₆ containers, protect against accident conditions, and assure criticality prevention have been incorporated in the designs of the protective outer packages. Protective outer packages which have been designed and tested in accordance with applicable DOE and DOT regulations for UF₆ cylinder models 30A, 30B, and 48X are shown in Figures A.5 and A.6.

FIGURE A.1. UF_6 Cylinder Model 30A

TABLE A.1. General Data for UF_6 Cylinder Model 30A Other Descriptive Terminology
Used - 2 1/2-ton UF_6 , 1-ton Chlorine

Nominal Diameter	76.2cm (30 in.)
Nominal Length	205.74cm (81 in.)
Wall Thickness	1.03cm (13/32 in.)
Head Thickness	1.91cm (3/4 in.)
Nominal Tare Weight	635kg (1,400 lb)
Maximum Net Weight	2245kg (4,950 lb)
Nominal Gross Weight	2880kg (6,350 lb)
Minimum Volume	.73m ³ (25.65 cu ft)
Basic Material of Construction	Steel
Service Pressure	$\sim 1.32 \times 10^6 \frac{\text{N}}{\text{m}^2}$ (192 psig)
Hydrostatic Test Pressure	$3.45 \times 10^6 \frac{\text{N}}{\text{m}^2}$ (500 psig)
Isotopic Content Limit	5.0% ²³⁵ U Max with Moderation Control

FIGURE A.2. UF_6 Cylinder Model 30B

TABLE A.2. General Data for UF_6 Cylinder Model 30B Other Descriptive Terminology Used - 2 1/2-ton

Nominal Diameter	76.2cm (30 in.)
Nominal Length	205.74cm (81 in.)
Wall Thickness	1.27cm (1/2 in.)
Nominal Tare Weight	635kg (1,400 lb)
Maximum Net Weight	2277kg (5,020 lb)
Nominal Gross Weight	2912kg (6,420 lb)
Minimum Volume	0.74m^3 (26 cu ft)
Basic Material of Construction	Steel
Service Pressure	$\sim 1.38 \times 10^6 \frac{\text{N}}{\text{m}^2}$ (200 psig)
Hydrostatic Test Pressure	$2.76 \times 10^6 \frac{\text{N}}{\text{m}^2}$ (400 psig)
Isotopic Content Limit	5.0% ^{235}U Max With Moderation Control

FIGURE A.3. UF_6 Cylinder Model 48X

TABLE A.3. General Data for UF_6 Cylinder Model 48X Other Descriptive Terminology Used - 10-ton

Nominal Diameter	122cm (48 in.)
Nominal Length	307cm (121 in.)
Wall Thickness	1.59cm (5/8 in.)
Nominal Tare Weight	2041kg (4,500 lb)
Maximum Net Weight	9539kg (21,030 lb)
Nominal Gross Weight	11580kg (25,530 lb)
Minimum Volume	3.08m^3 (108.9 cu ft)
Basic Material of Construction	Steel
Service Pressure	$1.38 \times 10^6 \frac{\text{N}}{\text{m}^2}$ (200 psig)
Hydrostatic Test Pressure	$2.76 \times 10^6 \frac{\text{N}}{\text{m}^2}$ (400 psig)
Isotopic Content Limit	4.5% ^{235}U Max With Moderation Control

FIGURE A.4. UF_6 Cylinder Model 48Y

TABLE A.4. General Data for UF_6 Cylinder
Model 48Y Other Descriptive
Terminology Used - 14-ton

Nominal Diameter	122cm (48 in.)
Nominal Length	381cm (150 in.)
Wall Thickness	1.59cm (5/8 in.)
Nominal Tare Weight	2359kg (5,200 lb)
Maximum Net Weight	12,501kg (27,560 lb)
Nominal Gross Weight	14,860kg (32,760 lb)
Minimum Volume	4.04m^3 (142.7 cu ft)
Basic Material of Construction	Steel
Service Pressure	$1.38 \times 10^6 \frac{\text{N}}{\text{m}^2}$ (200 psig)
Hydrostatic Test Pressure	$2.76 \times 10^6 \frac{\text{N}}{\text{m}^2}$ (400 psig)
Isotopic Content Limit	4.5% ^{235}U Max With Moderation Control

AVERAGE WEIGHTS
 SHIPPING CONTAINER WEIGHT ---- 1750 LBS.
 FILLED 30" CYLINDER 6400 LBS.
 TOTAL WEIGHT 8150 LBS.

FIGURE A.5. Horizontally-Loaded Protective Outer Package for UF₆ Cylinder Models 30A and 30B (From Reference 1)

A-7

* PROJECTED OVERALL LENGTH OF FUTURE PACKAGES TO ACCOMMODATE MODEL 48X TYPE CYLINDER

APPROXIMATE WEIGHT

SHIPPING CONTAINER	10,500 LBS
FILLED CYLINDER	25,500 LBS
TOTAL	36,000 LBS

FIGURE A.6. Protective Shipping Package for UF_6 Cylinder Model 48X (From Reference 1)

TRANSPORT MODES

Most UF_6 shipments are currently made by truck or railcar. For repetitive bulk shipments, particularly of the larger cylinders, transportation safety is promoted through the use of specially designed trucks. Railcars have been designed to accommodate four Model 48X or 48Y cylinders, and up to sixteen 30A or 30B cylinders. Heavy-duty tiedown devices and saddles are utilized. Typical examples of appropriate equipment are shown in Figures A.7 through A.10. Each full cylinder must be shipped in a protective shipping package or be equipped with a valve protector. Each valve protector and each protective package containing a UF_6 cylinder is secured with a numbered seal before shipment. Uranium hexafluoride is shipped only after it has solidified and the vapor pressure of the cylinder is below one atmosphere.

FIGURE A.7. Four 10-ton Cylinders

FIGURE A.8. Two 10-ton Cylinders

FIGURE A.9. Five 2 1/2-ton Cylinders in Protective Outer Packages

FIGURE A.10. One 10-ton Cylinder in a Protective Outer Package

REFERENCES

1. Uranium Hexafluoride: Handling Procedures and Container Criteria.
ORO-651 (Rev.4), U.S. Energy Research and Development Administration
Oak Ridge Operations Office, Oak Ridge, TN, April 1977.

APPENDIX B

PROPERTIES OF UF₆

General information on the properties of uranium hexafluoride is presented below:

Sublimation Point ($1.01 \times 10^5 \text{ N/m}^2$)	56.6°C
Triple Point	$151.7 \times 10^5 \text{ N/m}^2$, 64°C
Density, Solid (20°C)	5090.67 kg/m ³
Liquid (64°C)	3647.4 kg/m ³
Liquid (121°C)	3256.55 kg/m ³
Heat of Sublimation (64°C)	135,373.22 J/kg
Heat of Fusion (64°C)	54,661.01 J/kg
Heat of Vaporization (64°C)	81,642.61 J/kg
Heat of Solution in Water (25°C)	600,573.28 J/kg
Heat Evolved	
Critical Pressure	$4.61 \times 10^6 \text{ N/m}^2$
Critical Temperature	230.22°C

At room temperature, UF₆ is a white, volatile solid. At a temperature of 64°C and a pressure of $1.52 \times 10^5 \text{ N/m}^2$, UF₆ melts to form a colorless liquid of high density. The pressure-temperature and density-temperature relations for UF₆ are presented in Figures B.1 and B.2. More detailed information on the chemical and physical properties of UF₆ can be found in References 1 and 2.

Uranium hexafluoride is a highly reactive material which reacts chemically with water, ether, and alcohol to form soluble reaction products. It reacts with most organic compounds and with many metals; however, its reactivity with most saturated fluorocarbons is low. UF₆ does not react with oxygen, nitrogen, or dry air, and it is sufficiently inert to aluminum, copper, Monel nickel, and aluminum bronze that they can be exposed to UF₆ without excessive corrosion.

FIGURE B.1. Density of Liquid UF_6 (From Reference 3)

FIGURE B.2. Phase Diagram of UF_6 (From Reference 3)

Gaseous uranium hexafluoride, when released to the atmosphere, reacts quickly with the atmospheric moisture to form HF gas and particulate UO_2F_2 , which tends to settle on surfaces. The corrosive properties of UF_6 and HF are such that exposure to a severe release can result in temporary lung impairment and skin burns. The inhalation of fumes from very large releases for more than a few breaths may result in temporary lung impairment soon after the exposure, and in some instances, mild but repairable kidney damage within a few days. Water-soluble uranium compounds such as UO_2F_2 , like most heavy metal compounds, are toxic to the kidneys when ingested or inhaled in large quantities. For uranium of ^{235}U enrichment less than 10%, the chemical toxicity is more important than the radiotoxicity ⁽³⁾. The UO_2F_2 which forms quickly during a release to the atmosphere is easily visible as a white cloud. A concentration of 1 mg of UO_2F_2 per cubic meter of air is visible; the cloud from large releases may obscure vision.

REFERENCES

1. J. J. Katy, and E. Rabinowitch, The Chemistry of Uranium. New York, McGraw Hill, 1951.
2. D. R. Llewellyn, "Some Physical Properties of Uranium Hexafluorides" J. Chem. Soc. 28-36, 1953.
3. Uranium Hexafluoride: Handling Procedures and Container Criteria, ORO-651 (Rev. 3), U.S. Atomic Energy Commission, Oak Ridge Operations Office, Oak Ridge, TN, August 1972.

APPENDIX C

FAILURE THRESHOLD DETERMINATION FOR UF₆ CONTAINERS

This appendix describes the methods used to estimate the UF₆ container failure thresholds presented in Section 6.0 of the text of this report. Since a number of physical tests have been conducted on these containers,^(1,2,3,4) the failure thresholds were largely estimated based on the results of these tests. For accident environments where the tests did not approach the failure levels of the containers, analytical methods were used to estimate failure thresholds.

Four containers were considered in this study:

- 30B (2 1/2-ton) cylinder with overpack
- 48X (10-ton) cylinder with overpack
- 48X (10-ton) cylinder without overpack
- 48Y (14-ton) cylinder without overpack

A complete description of these cylinders and overpacks is presented in Appendix A. Values of physical properties of UF₆ used in this appendix were taken from Appendix B.

As was explained in Section 5.0 of the text, only three accident forces were found to be severe enough to significantly threaten the UF₆ containers: fire, impact, and puncture. This appendix will show how the cylinder failure thresholds for each one of these forces were determined.

FIRE

Cylinder failure in the fire environment is a result of excess internal pressure caused by the large coefficient of thermal expansion of UF₆. As heat is added to UF₆ in a closed container, its temperature first rises to 64°C, the point at which it melts, and its vapor pressure increases to $151.7 \times 10^5 \text{ N/m}^2$. If heat is added slowly, as in an autoclave, the solid and liquid UF₆ will remain at 64°C until all of the solid melts, after which

time both the temperature of the liquid and its vapor pressure will again continue to rise. Since UF_6 shows such a large decrease in density upon melting, most of the void space (available because of the increase in density of UF_6 as it goes from liquid to solid during filling) in the cylinder becomes filled with liquid UF_6 at the melting point. The liquid continues to expand upon heating until it reaches about 138°C , when it will completely fill the container. The vapor pressure of UF_6 at this temperature is about $1.03 \times 10^6 \text{ N/m}^2$, well below the design pressure of the cylinders considered here. Additional increases in temperature will cause a very rapid rise in the system pressure because the liquid UF_6 has no more space in which to expand. The cylinder then ruptures as a result of hydraulic pressure.

A series of fire tests on small UF_6 -filled cylinders was conducted in 1965 at the Oak Ridge Gaseous Diffusion Plant.⁽⁴⁾ In these tests, the cylinders were exposed to flames from a pool of burning diesel fuel which provided a temperature of approximately 815°C . The largest cylinder tested was made of nickel, contained 111 kg of UF_6 , and measured 20.3 cm ID X 0.48 cm thick x 122 cm long (volume = 0.04 m^3). The cylinder exploded 8.5 min after the fire was started.

Since it was difficult to accurately model the complex transient heat flux into the cylinder and the multiphase conditions inside the cylinder, the results of the small size cylinder tests were used to estimate the failure thresholds of the larger cylinders. Analysis of the 48Y (14-ton) cylinder was carried out in Reference 5, with a resulting failure time of 48 min. Using the same method, failure times for the other cylinders without overpack protection were found to be 29 min. for the 30B (2-1/2-ton) cylinder and 46 min. for the 48X (10-ton) cylinder.

Failure times for cylinders protected by overpacks were not so easily derived. Due to the design and insulating characteristics of the overpacks, heat transferred to the cylinder much more slowly. This allows the UF_6 to slowly melt and fill the cylinder. It was conservatively assumed, for the purposes of this analysis, that the cylinder would rupture hydraulically when the UF_6 inside completely filled the container. Using cylinder specifications from Appendix A, it was determined that the density of UF_6

at rupture was 3092 kg/m^3 . Based on the physical properties of UF_6 given in Appendix B, this corresponds to a temperature of 138°C .

The amount of heat required to raise the temperature of the UF_6 to 138°C was found using the following relation:

$$Q = C_v (T_{\text{fusion}} - T_{\text{ambient}}) + Q_{\text{fusion}} + C_v (T_{\text{UF}_6} - T_{\text{fusion}}) \quad (\text{C-1})$$

where:

Q is the heat required to raise the UF_6 to T_{UF_6} (J/kg)

C_v is the heat capacity of UF_6 from Reference 6 ($4.187 \times 10^2 \text{ J/kg} \cdot \text{K}$)

T_{fusion} is the fusion temperature (337 K @ 1.52 N/m^2 - Appendix B)

T_{ambient} is the ambient temperature (assumed 294°K)

Q_{fusion} is the heat of fusion ($5.467 \times 10^4 \text{ J/kg}$ - Appendix B)

$$\begin{aligned} Q &= (4.187 \times 10^2)(337 - 294) + 5.467 \times 10^4 \\ &\quad + (4.187 \times 10^2)(411 - 337) = 1.04 \times 10^5 \text{ J/kg} \end{aligned}$$

This value is applicable for both the 30B and 48X cylinders with overpack.

The system used to model the flow of heat into the cylinder can be modeled as such:

where:

hr is radiation heat transfer coefficient ($\text{W/k} \cdot \text{m}^2$)

R_{op} is overpack thermal resistance ($\text{K} \cdot \text{m}^2/\text{W}$)(zero if no overpack)

hc is convective heat transfer coefficient ($\text{W/K} \cdot \text{m}^2$)
(cylinder wall - UF_6)

T_1 is overpack exterior temperature (K)

T_2 is cylinder wall temperature (K)

T_3 is UF_6 temperature (K)

Values for the parameters h_r and R_{op} were relatively easy to determine, using ordinary heat transfer tables. The parameter h_c was more difficult to determine due to the complex transfer of heat from the hot cylinder wall to rapidly vaporizing UF_6 . The Oak Ridge experimental data⁽⁴⁾ were used to determine a value for the coefficient. Temperatures at the time of the cylinder rupture were:

$$T_{fire} = 1075^\circ K$$

$$T_{cyl} = T_1 = T_2 = 811^\circ K$$

$$T_{UF_6} = T_3 = 450^\circ K$$

A heat balance was determined:

$$q = \delta \xi \left[(T_{fire})^4 - (T_{cyl})^4 \right] = h_c (T_{cyl} - T_{UF_6}) \quad (C-2)$$

where:

q is heat flow (W/m^2)

δ is Stefan-Boltzmann constant ($5.99 \times 10^{-8} W/m^2 \cdot K^4$)

ξ is the grey body shape factor

ξ can be determined using the following relation:

$$\xi = \left[\frac{1}{\epsilon_{fire}} + \frac{1}{\epsilon_{cyl}} - 1 \right]^{-1} \quad (C-3)$$

where:

ϵ_{fire} is the emissivity of the fire (0.9 from 10CFR71)

ϵ_{cyl} is the emissivity of the cylinder (0.8 from 10CFR71)

$$\xi = 0.73$$

Substituting into (C-2)

$$q = (5.699 \times 10^{-8})(0.73) \left[(1075)^4 - (811)^4 \right] = 3.756 \times 10^4 \text{ W/m}^2$$

$$h_c = \frac{q}{(311-450)} = 1.04 \times 10^2 \frac{\text{W}}{\text{m}^2 \text{ K}}$$

This value for h_c plus a value of $1.25 \frac{\text{W}}{\text{m K}}$ for the conductivity of the overpack material (from Reference 7) were input to the heat transfer model. The overpack insulating foam thickness is 15.2 cm. A heat balance was established:

$$q = q_{1075 \rightarrow T_1} = q_{T_1 \rightarrow 450}$$

$$q_{T_1 \rightarrow 450} = (T_1 - 450) \left[\frac{0.152}{1.25} + \frac{1}{1.04 \times 10^2} \right]^{-1} = (T_1 - 450)(7.60)$$

$$\begin{aligned} q_{1075 \rightarrow T_1} &= (5.699 \times 10^{-8})(0.73) \left[(1075)^4 - (T_1)^4 \right] \\ &= (4.16 \times 10^{-8}) \left[(1075)^4 - (T_1)^4 \right] \end{aligned}$$

Solving the two equations simultaneously, a value of 1050°K was determined for T_1 . The heat flow in this case was $4839 \frac{\text{W}}{\text{m}^2}$.

The time to failure was determined using the relationship:

$$qAt = Qm \tag{C-4}$$

where:

A is the overpack surface area (m^2)

t is the time to failure (sec)

m is the mass of UF_6 (kg)

The surface area of the overpack was determined from information presented in Appendix A to be 9.8 m^2 . Likewise, the value of m was found to be 2277 kg.

$$t = \frac{Qm}{qA} = \frac{(1.04 \times 10^5)(2277)}{(4839)(9.8)} = 4993 \text{ sec} = 83 \text{ min}$$

A similar calculation was carried out for the 48X cylinder with overpack. The failure time was determined to be 156 min.

IMPACT

Impact failure threshold estimates for the various cylinders were based mainly on the results of physical tests. This was found to be necessary because of the difficulty of accurately modeling the deformation and rupture of cylinders filled with solid UF_6 . In most cases, these thresholds are felt to be conservative. The four cylinders considered in the study were considered individually and the results are presented below. Failure thresholds were calculated only for configurations corresponding to a horizontal drop.

30B (2 1/2-Ton) Cylinder with Overpack

For shipments of UF_6 at enrichment levels below 1 wt% ^{235}U , packaging need only conform to Type A standards. At enrichment levels greater than 1%, cylinders must be shipped in protective outer packages to provide adequate spacing of cylinders, protect against accident conditions and assure criticality prevention. At this level, packages must be able to pass all Type B shipping container standards. Tests on a prototype overpack similar to those in use today have been conducted.⁽³⁾ However, in no instance was the cylinder breached in these tests. Therefore, the impact failure threshold estimates for the 30B cylinder with overpack are derived from analysis.

For the purpose of this analysis, it was conservatively assumed that the cylinder fails when the overpack has been completely deformed. This condition is shown in Figure C.1. The shaded area indicates the material deformed in absorbing the impact energy.

As a first step in the analysis, the cross-sectional area of the deformed portion of the cylinder was evaluated.

$$\theta = \cos^{-1} \frac{38.1}{53.34} = 44.4^\circ$$

$$\begin{aligned} \text{AREA DEFORMED} &= (\pi R_{\text{op}}^2 \frac{2\theta}{360}) - (R_{\text{cyl}} \times R_{\text{op}} \sin 44.4^\circ) & (C-5) \\ &= \pi(53.34)^2 \frac{88.8}{360} - (38.1)(53.34)(0.70) \\ &= 782.9 \text{ cm}^2 \end{aligned}$$

FIGURE C.1. Diagram of 30B Cylinder with Overpack Parted by Impact Forces

From Figure C.1, the impact energy is absorbed by crushing the overpack material. This material consists of laminated wooden end plate and insulating foam in the annulus between the cylinder and overpack covering.

$$E_T = E_W + E_F \quad (C-6)$$

where:

E_T is the total energy absorbed (Joules)

E_W is the energy absorbed in crushing the wooden end plate

E_F is the energy absorbed in crushing the foam

$$E_W = (\text{AREA DEFORMED}) (\text{LENGTH})(2)(CR_W) \quad (C-7)$$

$$E_F = (\text{AREA DEFORMED}) (\text{LENGTH})(CR_F)$$

where:

AREA DEFORMED is the derived cross-sectional area from (C-5)

LENGTH is the length of the particular segment

CR_W is the crush strength of wood ($4.14 \times 10^7 \text{ N/m}^2$)

CR_F is the crush strength of foam ($9.65 \times 10^5 \text{ N/m}^2$ - Reference 8)

$$\begin{aligned} E_T = E_W + E_F &= (782.9)(2)(10.48)(4.14 \times 10^7) \\ &+ (782.9)(182.88)(9.65 \times 10^5) = 8.17 \times 10^5 \text{ Joules} \end{aligned}$$

Using the basic equation for potential energy

$$E = mgh$$

and information on the overpack from Appendix A, the drop height necessary to cause the deformation can be found.

$$h = \frac{E}{mg} = \frac{8.17 \times 10^5}{(3.70)(9.80665)} = 22.5 \text{ m.}$$

Therefore, the conservative impact failure threshold for the 30B UF₆ cylinder with overpack is an impact with a force equivalent to that experienced in a 22.5-m drop onto an unyielding surface.

48X (10-Ton) Cylinder Without Overpack

Impact (drop) tests have been performed on 10-ton UF₆ cylinders at Paducah, KY. In these tests, two versions of the 10-ton cylinder were evaluated, a heavy-wall version (nearly identical to the 48X cylinders) and a thin-wall design with a wall thickness one-half that of the heavy-wall cylinder.

During the tests, the thin-walled cylinders were dropped from heights of 3, 6, and 9 m without rupturing.

The heavy-walled cylinder was dropped once from a height of 6 m with no leakage. The deformation of the heavy-walled cylinder after the 6-m drop was similar to that of the thin-walled cylinder dropped from 3 m. Considering the energy required to deform the thin-walled cylinder, it is reasonable to expect the heavy-walled cylinder to survive a drop of 9 m. No further evaluations could be made and justified. Therefore, it was conservatively assumed that the impact failure threshold for the 40X cylinder without overpack was equivalent to the impact experienced by the cylinder in a 9-m fall onto an unyielding surface.

48X (10-Ton) Cylinder with Overpack

The addition of a protective overpack to the standard 48X cylinder qualifies it for use in the shipment of UF₆ to enrichment levels of 4.5 wt% ²³⁵U. In this configuration, the shipping package is designed to withstand all Type B qualification tests.

Evaluation of the additional impact protection provided by the overpack was carried out in the same manner as for the 30B cylinder with overpack. The analysis was based on a prototype of the Paducah Tiger overpack⁽⁸⁾ which is for all purposes identical to those in use today. The results of the analysis showed that the overpack added protection equivalent to an additional 3.4 m in drop height. This represents a failure threshold for a 48X cylinder with overpack equivalent to a drop from 12.4 m.

48Y (14-Ton) Cylinder Without Overpack

The 48X and 48Y cylinders are very similar except that the 48Y cylinder is 74 cm longer than the 48X. Otherwise, for this analysis they are identical. The gross weights per unit length for both cylinders are nearly equal. Since the deformed shape after impact is nearly constant along the cylinder axis, it is reasonable to assume that the 48Y could withstand a horizontal drop from the same height as the 48X cylinder. Therefore, the impact failure threshold of the bare 48Y cylinder was given a value equivalent to the impact forces experienced in a drop from 9 m.

PUNCTURE

As in the previous failure threshold analysis, results from actual tests were used to determine puncture failure thresholds wherever possible. All puncture failure thresholds were expressed in terms of an equivalent drop height onto a 15.24-cm diameter puncture probe.

30B (2-1/2-Ton) Cylinder with Overpack

Results of tests conducted at Oak Ridge, TN on a prototype overpack⁽³⁾ similar to those in use today were used as a starting point in this analysis. When dropped from a height of approximately 1 m, the overpack sustained minor damage but the cylinder inside was undamaged. To determine a drop height which would cause a cylinder failure, the bare cylinder (without overpack) was analyzed. Using equations and procedures described in Reference 9 it was possible to determine that a drop of 3.2 m onto the puncture probe was sufficient to puncture the bare cylinder. Assuming that an additional 1-m in drop height would be sufficient to rupture the overpack, an overall drop height of 4.2 m was estimated as the failure threshold of the cylinder and overpack.

48X (10-Ton) Cylinder Without Overpack

Tests conducted at Paducah, KY on cylinders nearly identical to the 48X showed that this cylinder could be breached in a puncture drop of 1 m if the probe hit the cylinder in the right orientation. During the test, a 48-in diameter heavy-wall cylinder failed when the probe struck the cylinder

immediately adjacent to a stiffening ring. A mathematical analysis of the cylinder puncture (see 30B analysis) was carried out with the results predicting survival of the cylinder in a puncture drop test of 1.4 m. This analysis, however, did not take into account the effects of the stiffening rings. The value used for puncture failure of the bare 48X in this study was a 1-m drop onto a standard puncture pin. This assumption is conservative because not every accidental puncture will occur next to a stiffening ring.

48X (10-Ton) Cylinder with Overpack

Tests on a prototype of the Paducah Tiger overpack were conducted as part of its development and certification program.⁽⁸⁾ As part of the testing, the overpack (with cylinder) was dropped from a height of 1 m onto a standard puncture probe. This test resulted in a cylinder penetration (dent) of 3.81 cm by the probe. From the results of other tests on the bare cylinder⁽¹⁾ a penetration of 10.16 cm was determined to result in a breach of the container. If we assume that no additional energy absorption due to the overpack occurs during penetration of the remaining 6.35 cm, the drop height required to breach the container in the overpack can be determined.

$$h = 100 + \frac{6.35}{10.16} (100) = 163 \text{ cm} = 1.63 \text{ m}$$

A puncture drop height of 1.63 m was estimated as the 48X with overpack puncture failure threshold.

48Y (14-Ton) Cylinder Without Overpack

Based on the results presented for the 48X cylinder, the structural similarities of the two cylinders, and the relationship of puncture energies of the different masses, a failure threshold equivalent to a 79.5 cm puncture drop was estimated.

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APPENDIX D

FRACTIONAL MILEAGE OF SHIPPING ROUTE BY POPULATION ZONE

This appendix contains a complete listing of the fractional mileage of all shipping routes considered in this study. The percentage of each route lying in each population zone is given in Table D.1. Table D.2 is a listing of the shipping and receiving facilities used in Table D.1.

**TABLE D.1. Fractional Mileage of Shipping Routes
by Population Zones (Values in Percent)**

Facilities (See Table D.2)		Population Zone			
From	To	I	II	III	IV
P-1	E-1	--	--	100	--
P-1	E-2	--	--	100	--
P-1	E-3	--	--	100	--
P-2	E-1	--	--	100	--
P-2	E-2	--	--	100	--
P-2	E-3	--	--	100	--
P-3	E-1	29	5	66	--
P-3	E-2	24	--	76	--
P-3	E-3	45	40	15	--
P-4	E-1	--	--	100	--
P-4	E-2	--	--	100	--
P-4	E-3	--	--	100	--
E-1	E-2	--	--	100	--
E-1	E-3	--	--	100	--
E-2	E-3	--	--	100	--
E-2	F-1	--	--	100	--
E-2	F-2	--	41	59	--
E-2	F-3	--	--	37	63
E-2	F-4	--	--	100	--
E-2	F-5	--	--	100	--
E-2	F-6	--	--	100	--
E-2	F-7	24	--	76	--
E-2	F-8	--	--	100	--
E-3	F-1	--	--	100	--
E-3	F-2	--	90	10	--
E-3	F-3	--	--	38	62
E-3	F-4	--	--	100	--
E-3	F-5	--	--	100	--
E-3	F-6	--	--	100	--
E-3	F-7	46	41	13	--
E-3	F-8	--	--	100	--

TABLE D.2. UF₆ Shipping and Receiving Facilities

Production Plants

- P-1 Metropolis, IL
- P-2 Sequoyah, OK
- P-3 Foreign Sources (Baltimore, MD)
- P-4 Foreign Sources (Norfolk, VA)

Enrichment Plants

- E-1 Paducah, KY
- E-2 Oak Ridge, TN
- E-3 Portsmouth, OH

Fuel Fabrication Plants

- F-1 Wilmington, NC
- F-2 Apollo, PA
- F-3 Richland, WA
- F-4 Erwin, TN
- F-5 Columbia, SC
- F-6 Hematite, MO
- F-7 Foreign Receivers (Baltimore, MD)
- F-8 Foreign Receivers (Norfolk, VA)

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