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An Assessment of the Risk of Transporting Plutonium Dioxide and Liquid Plutonium Nitrate by Train

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PREFACE

This document is the second in a series of risk assessments dealing with the shipment of potentially hazardous energy materials. Work done on the initial study, An Assessment of the Risk of Transporting Plutonium Oxide and Liquid Plutonium Nitrate by Truck, (BNWL-1846), forms the basis for the series. This study, being an extension of the first, relies heavily on that work. The authors and technical contributors of the first study, therefore, deserve credit for much of the material that was used in this risk assessment.

This study was initially issued in draft form and released on a limited basis for comments. Comments received from reviewers were evaluated and wherever possible revisions were made in the draft document to increase clarity and technical credibility. Some comments were not included because it was determined that the changes suggested, although technically valid, would not significantly increase the accuracy or credibility of the results. We thank all of those who took time to review the document and respond.

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1.0 INTRODUCTION

This report is the second in a series of studies to assess the risks associated with the transportation of energy materials. The initial study[1] dealt with the risk in transporting plutonium by truck. The introduction to that study serves as an introduction to the series and therefore it is quoted below.

"Radioactive materials, in a variety of physical and chemical forms, are routinely transported between nuclear facilities. 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. In the interest of continuing to insure the health and safety of the general public, the nuclear industry and government regulatory agencies are continually improving their level of understanding of the safety-related aspects of transporting radioactive materials.

Research programs are one method of improving the level of understanding. Such a research program is being conducted by Battelle-Northwest for the Transportation Branch of the ERDA Division of Environmental Control Technology. The objective of this continuing program is to develop a methodology for quantitatively assessing the safety of transporting radioactive materials and 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 radioactive material 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 magnitude of a possible loss and the expected frequency of occurrence of the loss. There are two measures of the risk that are of importance in a risk assessment. The first is the total risk, obtained by summing the risk associated with each particular loss. In order to perform the summation, all risks have to 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 discernible. 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 truly similar only if they have the same total risk (risk magnitude) and the same risk spectrum. Both risk measures are used in this report."

This report provides an assessment of the risk in rail shipment of plutonium in two forms: liquid nitrate packaged in L-10 containers and dioxide powder in 6M containers. A comparison with the risk of truck shipment for these materials is also made.

The study encompasses only the risk of adverse health effects from possible release of plutonium during an accident. Other measures of risk, e.g., cost of clean-up of a spill, and the benefits from the transport and use of plutonium are not addressed.

REFERENCE

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.

2.0 SUMMARY

This report presents the results of an assessment of the accident risk in the shipment of plutonium by rail.

The risk assessment methodology is described in Section 3 of this report. The methodology is manifested in a model that relates the functional steps in the assessment. Data needs and analysis procedures are explicitly defined in the model. The model is constructed for ease of periodic updating of the data base to maintain the risk assessment current as additional data become available.

The remainder of the report treats the application of the model to the assessment of the risk in train shipment of plutonium in two forms - liquid nitrate [$(Pu(NO_3)_4$] and oxide powder (PuO_2). The scope of the assessment encompasses the risk of plutonium releases due to transportation accidents and package misclosure and degradation.

The report is sectioned to correspond to specific analysis steps identified in the model. The transport system and accident environment are described in Sections 4 through 7. Release sequences are postulated in Section 8 and evaluated in Sections 9 through 11 to determine both the likelihood and the possible consequences of a release. Supportive data and analyses are given in the appendices.

The risk assessment results have been related to a future time - the early 1980s - when plutonium shipments are expected to be more frequent. To conduct the risk assessments, certain assumptions about the nuclear economy and transport system in the early 1980s were required. The assumptions used for the analysis are:

- An annual total of 18 metric tons of plutonium is shipped by rail (exclusive use boxcar).
- The average shipment distance is 1530 miles.
- Shipping systems and regulations are the same as in 1974.

- PuO_2 is shipped in 6M containers (15-gallon size) and liquid $Pu(NO_3)_4$ in L-10 containers.
- 230 kg of plutonium are transported in a 6M shipment (90 containers) and 136 kg of plutonium are transported in an L-10 shipment (68 containers).

Other shipping conditions (e.g., different shipping regulations, different quantities per shipment) could result in different risks than reported herein. However, the developed methodology can be used to analyze the risks under any shipping conditions.

Based on the shipping assumptions, the likelihood that railcars containing plutonium shipments will be involved in an accident is estimated to be about once in 6 years for PuO_2 shipment and once in 3 1/2 years for the $Pu(NO_3)_4$ shipment. Most accidents will have only minor consequences. The consequences of postulated accidents were estimated based on the amount, if any, of plutonium released to the environs, the probable weather conditions at the time of the accident, and the population density downwind from the accident scene. The likelihood and the consequences of these postulated releases have been coupled and expressed as risk spectra.

Risk spectra for rail shipment of the two plutonium forms are shown in Figure 2.1 for the plutonium shipments projected for the United States in the early 1980s. These curves can be compared to similar risk curves which are presented in the Reactor Safety Study.[1] Inspection of the curves indicates that the risks of shipping plutonium by rail are small relative to other societal risks. For example, the risk curve for transporting chlorine is several orders of magnitude greater than that of transporting liquid plutonium nitrate. The risk curve for the liquid nitrate shipment is similar to the risk curve for being killed by meteorites. The curves also indicate that the likelihood of a plutonium release resulting in cancer death is one in 3,000 years for the rail shipment of liquid plutonium nitrate in L-10 containers and one in 800,000 years for rail shipments of PuO_2 in 6M containers.

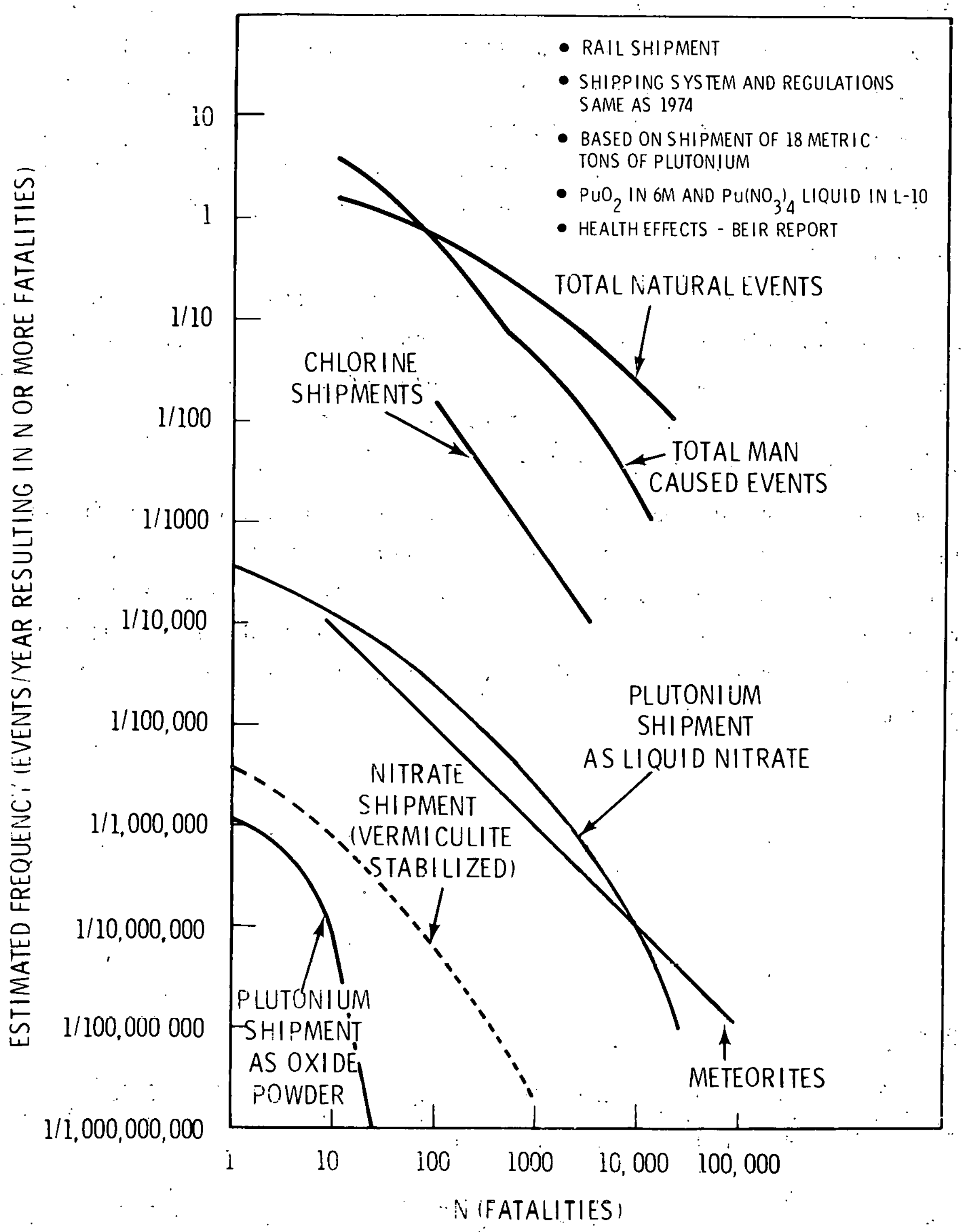


FIGURE 2.1. Risk Spectra for Plutonium Shipments by Rail in the Early 1980s for the Entire U.S.

Sensitivity studies were performed to determine the most important contributors to the risk. These studies are described in Section 11. Loss of the thermal insulation followed by exposure to a fire was found to be the most significant risk contributor for the liquid plutonium nitrate shipments. A risk curve developed assuming stabilized vermiculite insulation is included in Figure 2.1 to show the importance of the insulation.

The sensitivity studies also served another purpose. In some instances the data used in this analysis were quite conservative. The sensitivity studies served to determine the effect of this conservatism on the calculated risk. Those areas where the conservative assumptions significantly affect the calculated risk were noted as areas for further study.

The risk in the shipment of plutonium by rail was found to be similar to the previously determined risk in the shipment by truck.[2] However, for the liquid plutonium nitrate shipments, there is a difference in the importance of the various factors contributing to the risk (e.g., inertial crush is more important as a failure mechanism in rail shipment than in truck shipment).

REFERENCES

1. Reactor Safety Study - An Assessment of the Accident Risks in U.S. Commercial Nuclear Power Plants, WASH-1400 (DRAFT) U.S. Atomic Energy Commission, Washington, D.C., August 1974.

2. 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.

3.0 RISK ANALYSIS MODEL

The model used in assessing the risk of plutonium shipments by rail is briefly described in this section. Information called for by the various model components and the application of the model are further discussed in following sections. A more detailed discussion of the individual model components is given in the truck shipment report.(1) The model, still undergoing evolution, is applicable to the shipment of all radioactive materials and, with changes in component designations, could also be applied to shipments of hazardous materials in general.

3.1 RISK MODEL DESCRIPTION

The risk assessment model used in this study is shown schematically in Figure 3.1. It provides a systematic method for handling the data germane to analysis of the safety of the transport environment. The model uses one fundamental equation:

$$R = \sum_i R_i . \qquad (3\text{-}1)$$

The total system risk R is the sum of the risks of all individual releases 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. This equation could be expanded into a single, long, complex equation. In the current formulation of the model, each term in Equation 3-1 is expanded into two expressions which have more physical significance. The expanded equation for R_i is:

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

The first factor, $A\ F_{R_i}$, is the product of the amount of material present in a shipment times the fraction of that material lost to the environment in the i^{th} release sequence. This factor can be thought of as a source term for the i^{th} chain of events or failures which end with a release of

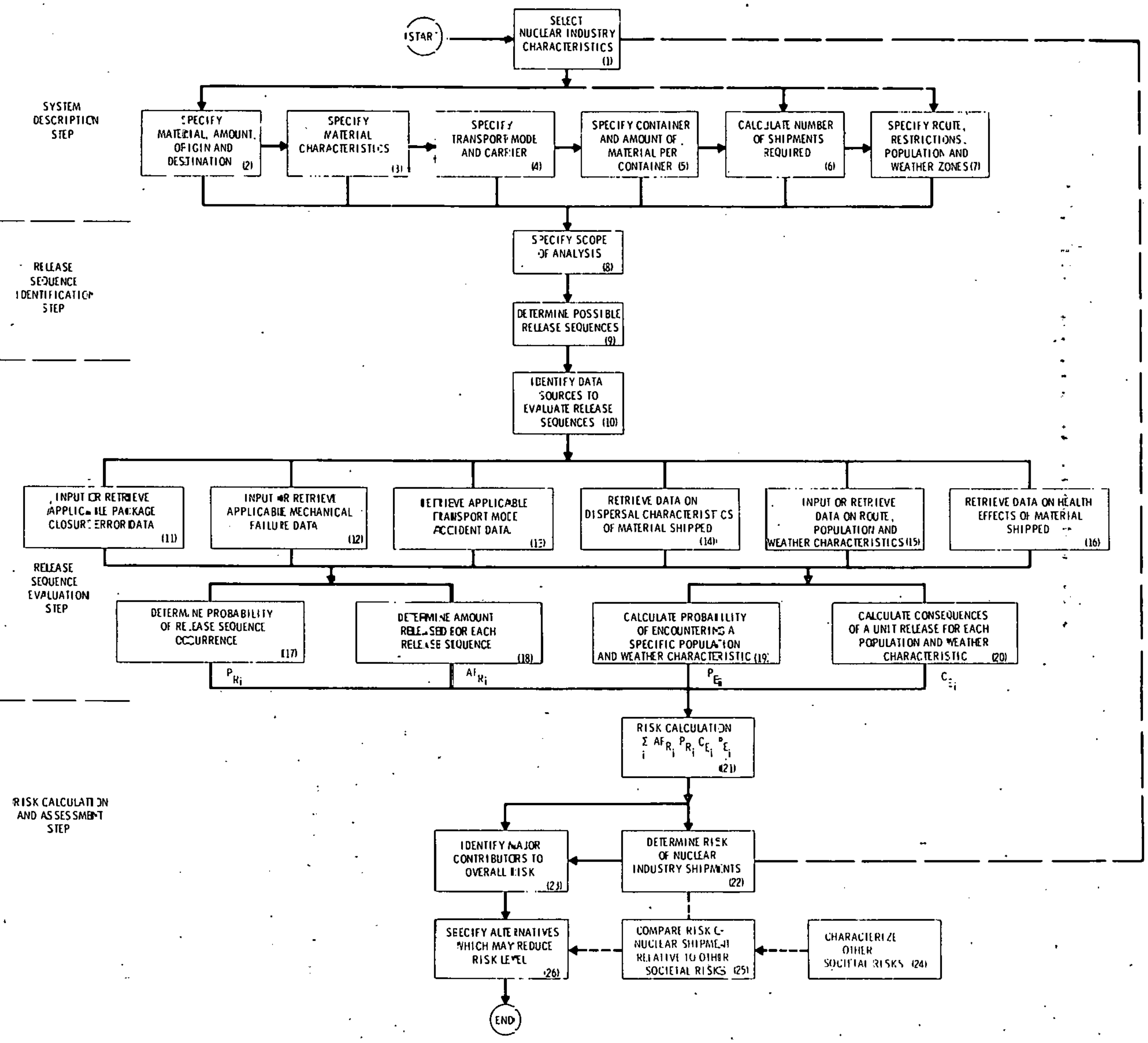


FIGURE 3.1. Model to Calculate the Risk of Shipping Nuclear Material

radioactive material. The second factor, P_{R_i}, is the probability that the release sequence will happen during transport. The first expression, $A\,F_{R_i} \times P_{R_i}$, can be thought of as a probabilistic source term for each identified.

The factor $C_{E_{i,q}}$ in the second part of Equation 3-2 is the consequences of a unit release. The subscript q is added to show that the factor is a function of the specific weather conditions existing at the time of the release and the population exposed to the release. The factor represents the effect of a unit release on the exposed population in terms of either a whole body dose to man or to a specific organ. The final factor, P_{E_q} is the probability of encountering a particular set of weather conditions within a specific population zone. The expression $\sum_q (C_{E_{i,q}} \times P_{E_q})$ can be thought of as the consequences of a unit release of radioactive material (unit source term) under probabilistically weighted weather conditions and population distributions.

Equation 3-2 is the pivotal equation in the risk model. Two preparatory steps are needed before the terms can be evaluated. These are the system description and the release sequence identification steps. Following these two steps is the release sequence evaluation step which utilizes Equations 3-1 and 3-2. The final step is to evaluate or assess the significance of the risk level determined for the transport system being evaluated. The relationship between these four steps is shown in Figure 3.1. The steps are briefly discussed in the following four subsections.

3.1.1 System Description

As shown in Figure 3.1, the system description step has seven components:

1) Select Nuclear Industry Characteristics
2) Specify Material, Amount, Origin and Destination
3) Specify Material Characteristics
4) Specify Transport Mode and Carrier
5) Specify Container and Amount of Material per Container
6) Calculate Number of Shipments Required
7) Specify Route, Restrictions, Population and Weather Zones.

Figure 3.2 shows examples of the types of information called for by these components. The seven components completely describe the system being evaluated.

3.1.2 Release Sequence Identification

The second step in the risk assessment is identification of release sequences. This requires, first, component 8, Specify Scope of Analysis, which completes the information required to initiate work in component 9, Determine Possible Release Sequences. The relationship of these two components to the rest of the model is shown in Figure 3.1. Component 8 sets the scope of the risk assessment by selecting the factors that will be considered in the analysis. For the present analysis the risks from failure sequences involving both accident conditions and substandard packaging conditions are considered. The possible release sequences within the scope of the assessment are identified in component 9 by use of fault tree analysis; a method that works backwards from a postulated release through the chains of events or failures required to breach the barriers between the material and man's environment.

3.1.3 Release Sequence Evaluation

The release sequence evaluation step considers each release sequence identified in the previous step and determines the factors in Equation 3-2. The assembly of these data will be described in the following subsections entitled Source Term Evaluation and Environmental Consequences Evaluation.

Source Term Evaluation - The release sequence factors in Equation 3-2, denoted by the subscript "R," represent the probability that a source of material will be released, the type of release, and the amount of material released. The evaluation of these factors requires the input of four data bases, shown in Figure 3.1 as components 11-14. These data bases are:

- Input or Retrieve Applicable Package Closure Error Data (11)
- Input or Retrieve Applicable Mechanical Failure Data (12)
- Retrieve Applicable Transport Mode Accident Data (13)
- Retrieve Data on Dispersal Characteristics of Material Shipped (14)

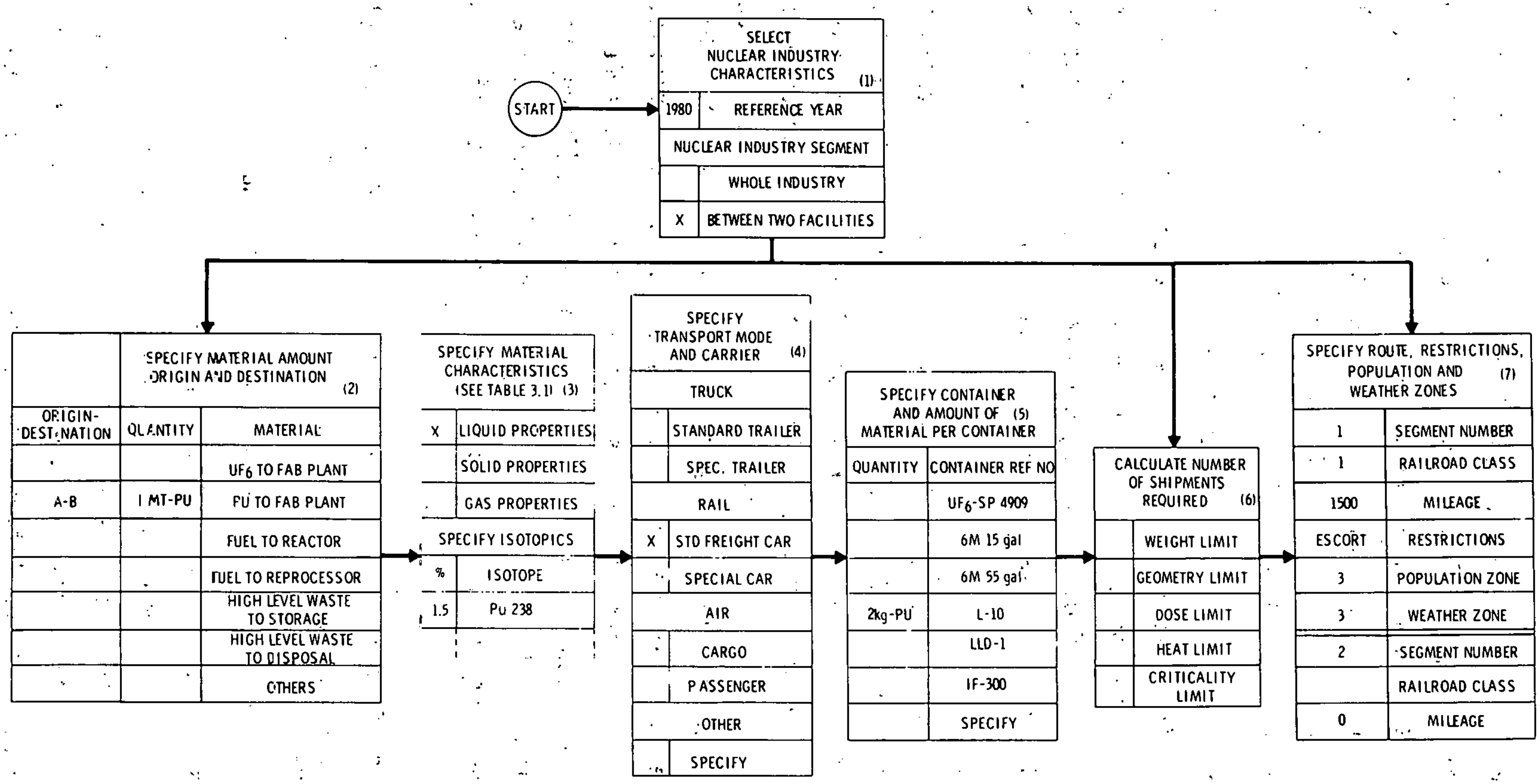


FIGURE 3.2. Information Required to Describe Transport System (Plutonium nitrate by rail shown as example.)

With the information from components 11 to 14, the model is used to evaluate the probability of a release and the source term, shown as components 17 and 18 in Figure 3.1. The source term must be expressed in equation form so that the source can be related to environmental conditions. The FR_i factors of source term expression used for various release sequences and environmental conditions are discussed in Section 9.

The "A" factor in Equation 3-2 includes terms which relate the total amount of material shipped to the fraction that is potentially dispersible. The fraction is a function of the number of containers damaged and the amount of material spilled from the damaged containers. When these terms have been evaluated for each release sequence, this part of the analysis is complete.

Environmental Consequences Evaluation - The environmental terms in Equation 3-2 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. The factor C_{E_i} represents the consequences of a unit release from an accident when it occurs in the region characterized by the weather and population density used to determine P_E. The consequences of the unit release are initially calculated as a population dose expressed in units of man-rem to a selected organ of reference. The population dose is then converted to health effects using BEIR report data. The evaluation of the two factors in Equation 3-2 requires the input from three data bases, shown in Figure 3.1 as components 14 to 16. These data bases are:

- Retrieve Data on Dispersal Characteristics of Material Shipped (14)
- Input or Retrieve Data on Route, Population and Weather Characteristics (15)
- Retrieve Data on Health Effects of Material Shipped (16)

The model uses relevant information from components 14 to 16 to evaluate the probability of experiencing a given set of weather conditions and population characteristics. These evaluations are shown as components 19 and 20 in Figure 3.1. The P_E term in Equation 3-2 is the probability associated with the weather and population characteristics. The expanded form of this term is given:

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

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

These data complete the description of the four terms in the risk equation. Once all of these variables are specified, the risk calculation and assessment step, the final step, can be completed.

3.1.4 Risk Calculation and Assessment

The final step in the risk assessment is to sum and evaluate the risks associated with all the applicable release sequences. As shown in Figure 3.1, this final step consists of six components numbered 21 to 26:

- Risk Calculation (21)
- Determine Risk of Nuclear Industry Shipments (22)
- Identify Major Contributors to Overall Risk (23)
- Characterize Other Accepted Societal Risks (24)
- Assess Risk of Nuclear Shipments Relative to Other Societal Risks (25)
- Specify Alternatives Which May Reduce Risk Level (26)

The major contribution from each of these components is summarized below.

Risk Calculation (21) - The overall risk calculation is described by Equations 3-1 and 3-2.

Determine Risk of Nuclear Industry Shipments (22) - The overall risk from the entire nuclear industry is the summation of the risks from individual routes weighted by the amount of material shipped along those routes.

Identify Major Contributors to Overall Risk (23) - The major contributors are obtained during the summation operations described by components 21 and 22. Changes which will greatly reduce the risk are those that modify the major contributors which head the list.

Characterize Other Accepted Societal Risks (24) - A comparison of the risk levels obtained in components 21 and 22 with the accepted risk levels imposed either by other technologies or by our natural environment places the calculated risk levels in perspective. Component 24 provides the data on the other accepted risk levels.

Compare Risk of Nuclear Shipment Relative to Other Societal Risks (25) - This operation is a comparative procedure. Risks not associated with the nuclear shipments are placed on the list to put the overall risk level determined in components 21 and 22 in perspective.

Specify Alternatives Which May Reduce Risk Level (26) - Based on the list of major risk contributors generated by component 23, the controlling variables are evident. If, for example, the top ten risk contributors have all occurred in the same population zone on one route, then the analysis suggests that the selection of an alternate route might be warranted. If one component failure is in each element in the list of contributors, then a design change eliminating that variable from the list may be worthwhile. Such decisions can be based on information provided from evaluations carried out under this last component in the model.

The application of this model to assessment of the risks in rail shipment of solid plutonium dioxide and liquid plutonium nitrate is demonstrated in the remainder of this report.

REFERENCE

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.

4.0 PLUTONIUM SHIPPING REQUIREMENTS

As discussed in Section 3, the risk assessment model is designed to use a plutonium shipping requirements model which projects the amount, number, origin and destination of plutonium shipments to future years. Using such a shipping requirements model, all that is required in the shipping requirements input specification is the year or the conditions of interest. However, current conditions (energy crisis, plant financing problems, administrative and regulatory process changes, etc.) make it difficult to predict the plutonium shipment scheduling which is needed to develop the shipping requirements model. Because of these uncertainties the plutonium shipping requirements model used for the present evaluation is related to the number of operating power reactors rather than the year.

4.1 NUCLEAR INDUSTRY ASSUMPTIONS

The present evaluation is based on the plutonium shipping requirements for an industry of 100 power reactors. It is felt that this assumption is reasonably representative of the stage of growth that will be reached in the early 1980s. It is assumed that plutonium recycle will be used in the industry. The industry characteristics assumptions used in the evaluation are given in Table 4.1.

TABLE 4.1. Assumed Industry Characteristics (One Year Period)

Number of Operating Power Reactors	100
Power Level per Reactor	1000 MW(e)
Number Shipping Spent Fuel to Reprocessors	75[a]
Fuel Reprocessed	30 MT per reactor
	2250 MT total
Total Pu Recovered and Shipped to Fabricators	18 MT

a. The other 25 have not begun to discharge fuel.

It is assumed that each fuel fabricator will receive an equal amount of the plutonium recovered by each of the reprocessors. Assumptions on the number and location of fuel reprocessors are given in the following paragraphs.

4.2 FUEL REPROCESSORS

It is assumed that there will be two fuel reprocessors operating at the reference time when the 100 nuclear power plants will be on line. These reprocessors are assumed to be AGNS at Barnwell, South Carolina, and NFS at West Valley, New York. It is assumed that the Barnwell plant will have a capacity to reprocess 1500 MT fuel/year; the West Valley plant, a capacity of 750 MT fuel/year. This results in a total capacity of 2250 MT fuel. It is assumed that the plants will recover and ship 18 MT plutonium/year.

4.3 FUEL FABRICATORS

It is assumed that at the reference time there will be five fabricators receiving plutonium for the production of mixed oxide fuel. The locations of these facilities are given in Table 4.2.

TABLE 4.2. Assumed Fuel Fabrication Facilities

Company	Location
Exxon	Richland, WA
General Electric	Pleasanton, CA
Kerr-McGee	Crescent, OK
Westinghouse	Cheswick, PA
NUMEC	Apollo, PA

Each of the fabricators will receive during a 1-year period, 3.6 MT of Pu; 2.4 MT from Barnwell, SC, and 1.2 MT from West Valley, NY.

4.4 PLUTONIUM SHIPPING DISTANCES

It is assumed that a fuel reprocessor will ship plutonium equally to each of the five fuel fabricators. Estimated shipping distances between the locations are shown in Table 4.3.

TABLE 4.3. Estimated Rail Distances Between Fuel Reprocessors and Fuel Fabricators (mi)

Fuel Fabricator Location	Fuel Reprocessor Location	
	1. Barnwell, SC	2. West Valley, NY
1. Richland, WA	2746	2537
2. Pleasanton, CA	2875	2893
3. Crescent, OK	1184	1407
4. Cheswick, PA	644	188
5. Apollo, PA	654	176

Mileages in Table 4.3 were obtained in the following manner. Plants were located by latitude and longitude and distances were calculated as the great circle distances multiplied by a factor of 1.26. The great circle distance correction factor was developed by comparison with several actual rail distances in different sectors of the country.[1] The mileages given are considered sufficiently accurate for the purposes of this study.

It is felt that this plutonium shipment model will result in some over-estimation of the expected frequency of a transport accident. The expected frequency is closely proportional to shipment distance. It is expected that, in general, more plutonium will be shipped to fabricators located fairly close to reprocessors than to those located a significantly further distance away. This would reduce the average shipment distance and thus the likelihood of an accident.

REFERENCE

1. Harold Harty, et al., Nuclear Energy Center Special Study - Fuel Cycle Considerations, BNWL-B-456, Battelle, Pacific Northwest Laboratories, Richland, WA, 1976.

5.0 TRANSPORTATION ACCIDENT ENVIRONMENT

Failure of a shipping container in an accident occurs only when the magnitude of insult to the container (applied forces and/or thermal radiation) exceeds a threshold of container failure. This section discusses the forces or stresses which may be generated in a rail accident environment and their likelihood of occurrence. Section 6 discusses the estimated mechanical strength of the L-10 and 6M containers. The use of the results from Sections 5 and 6 to estimate the likelihood of container failure in an accident is demonstrated in Section 9.

The train accident environment described in this section was derived from reports published by Sandia Laboratories and personal communications with Sandia personnel. The Sandia work related to train accidents is primarily presented and summarized in one report.[(1)] The report contains the most comprehensive information on the train accident environment that is currently available.

Sandia divides train accidents into five environments:[(1)] impact, crush, puncture, fire and immersion. Fire and immersion are self-explanatory. Impact involves the container striking or being struck by an object which has no sharp projections. Impact forces are applied in one area or on one side of the container. Crush forces are distinguished from impact forces in that the forces are simultaneously applied from more than one direction and the rate of application is slower. Puncture involves a localized area of the container striking or being struck by a probe which penetrates the protective structure of the container.

Of the five rail accident stresses evaluated by Sandia, expected immersion and impact stresses were found to be several times less severe than those specified in the package qualification criteria. Because the 6M and L-10 container designs meet the qualification criteria, which are more severe, these stresses were not included in the evaluation. Consideration of criticality during immersion is handled in Appendix C. Following is a summary of the remaining three--crush, puncture and fire:

Crush. Crush forces on small containers can be of two general types: inertial crush and static crush. Inertial crush can result from severe decelerations. The inertial crush force on a container is dependent on the mass lined up behind the container and the level of deceleration. Therefore, the force on a container in an array depends on the location of the container with respect to the point of railcar impact. The probability that specific levels of deceleration will exist in a train accident is shown in Figure 5.1. The deceleration curve was developed from the distribution of the effective relative acceleration between containers and the railcar in an accident, given in the Sandia report.[1] The relationship of the crush force on a particular container to the deceleration is developed in Appendix F.

Static crush could occur if the container were ejected from the boxcar during an accident and a railcar or some other heavy object in the

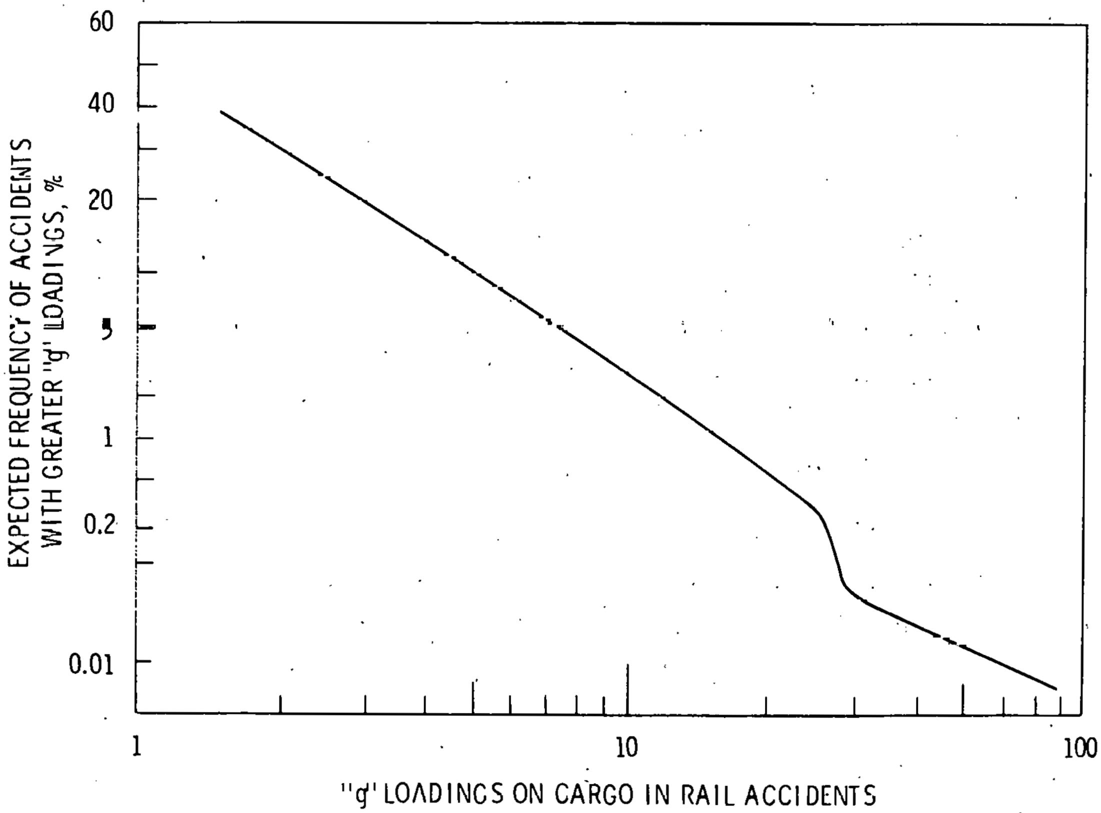


FIGURE 5.1. Expected Severity of Cargo Decelerations in the Rail Accident Environment

train subsequently came to rest on top of it. Sandia estimates the probability of a container being subjected to a static crush load is 7.1×10^{-5} per car accident.[1] The severity distribution of the static crush forces is shown in Figure 5.2.

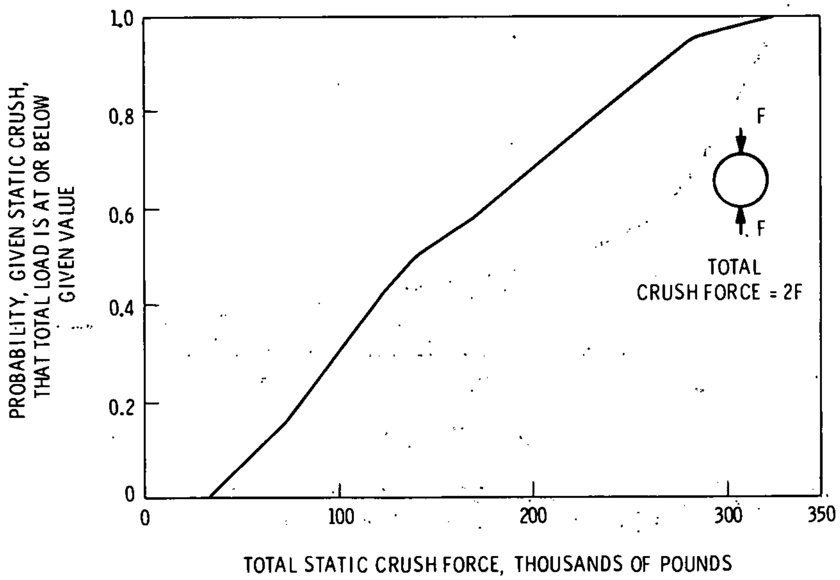


FIGURE 5.2. Cumulative Distribution of Total Crush Load, Given Static Crush

Fire. Sandia data indicate that approximately 1% of the collision and derailment accidents involving freight trains resulted in fires.[1] It was further determined by Sandia that the average fire temperature is approximately 1850°F. Fire durations range from minutes to hours. Sandia combined train accident rates with the frequency of various categories of accidents and the probable type and number of cars involved to derive the probability per car mile of exceeding any specified fire-environment level. The curve, given in Figure 5.3, shows the likelihood that should a fire occur, its duration would exceed a time T. This curve was developed from the Sandia results[1] by assuming a fire temperature of 1850°F and appropriate normalization. Since it was assumed for purposes of this analysis that in the event of a fire the container will be exposed to the full fire environment, the curve is conservative. In actuality, the railcar

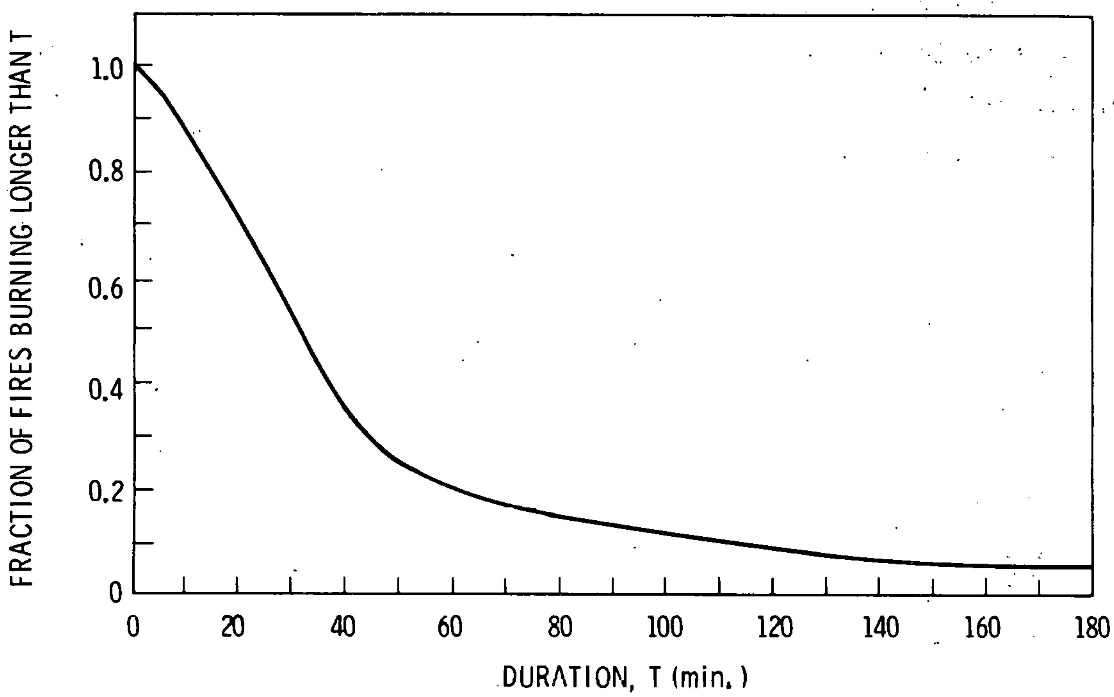


FIGURE 5.3. Expected Duration of Fires in the Rail Accident Environment

containing the plutonium shipment has a very low combustible loading, and fuel for a full fire environment would have to come from other cars.

Puncture. Sandia indicates that puncture occurs in 55% of the rail accidents and that the likelihood of packages similar in size to the L-10 or 6M being struck by a puncture probe is 2.3%.[1] Sandia determined that the likelihood of container puncture, if struck by a puncture probe, is related to the ratio of the relative velocity of the probe and container to the probe radius (V/R). The rather complex derivation and justification for choosing the parameter V/R is given in Reference 1. The reader is referred to this document for details. The likelihood of experiencing a puncture environment more severe than the parameter V/R, given that the container is struck by a puncture probe, is shown in Figure 5.4.[1] Sandia[1] developed three estimates of the V/R distribution in an accident. The curve selected for this study is the intermediate one.

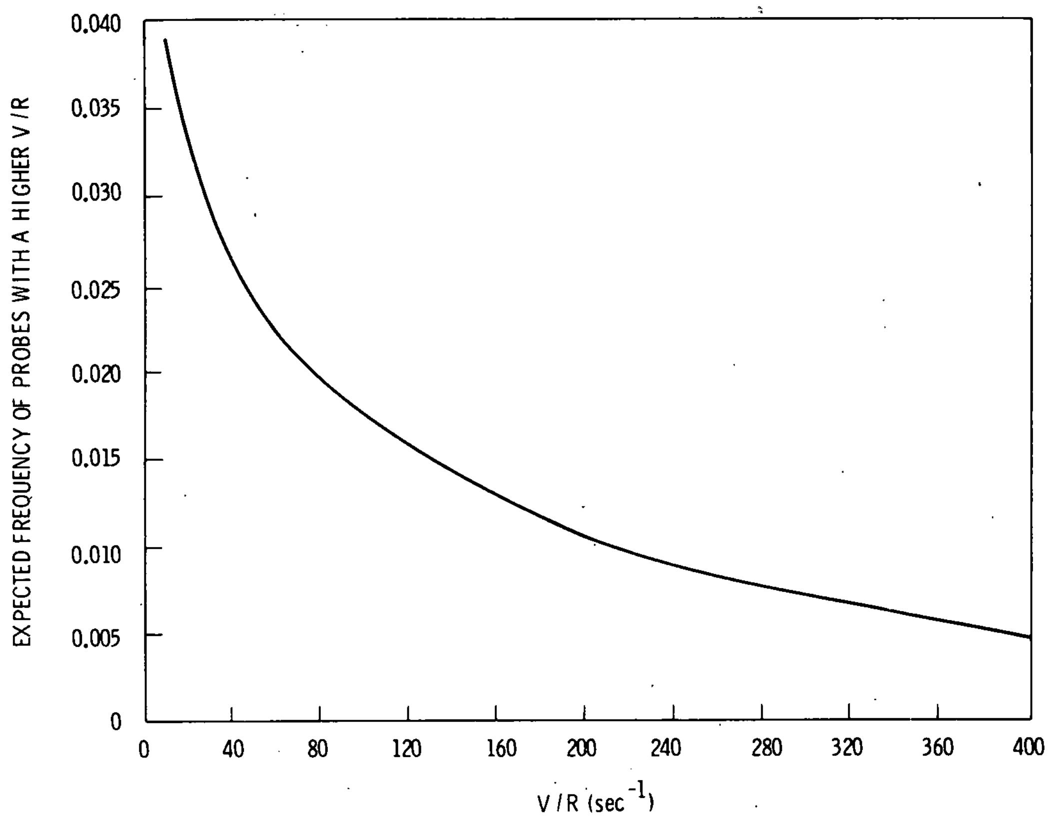


FIGURE 5.4. Expected Severity of Puncture Forces in the Rail Accident Environment

REFERENCE

1. R. K. Clarke, T. J. Foley, W. F. Hartman and D. W. Larson, Severities of Transport Accidents, Volume IV - Trains, SLA-74-001, Sandia Laboratories, Albuquerque, NM, (To be published).

6.0 PACKAGE FAILURE THRESHOLDS

The previous section described the environment imposed on containers during railroad accidents. A summary of the failure thresholds for the 6M and L-10 containers is 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. There is a most probable stress 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. However, 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 failure thresholds. The results of this section must be used in conjunction with estimates of the severity of insult resulting from accidents 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 thresholds reported here were not obtained by destructive testing. Experimental tests were beyond the scope of this evaluation. The results represent estimates of failure thresholds obtained in using the elastic theory of structure behavior and comparison with tests conducted by others. The analysis is 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 is assumed to be the predominant orientation in an accident environment. The failure points obtained using elastic theory are also believed to be less than the actual strength of the container. The degree of conservatism is unknown.

The 6M and L-10 containers are shown schematically in Figures A.2 and A.1, respectively. The detailed calculations performed on these containers are given in Appendix D (Mechanical Analysis of L-10 and 6M Containers) and in Appendix E (Thermal Analysis of L-10 Container). The pertinent results of these analyses are summarized in this section.

The analyses enable the direct evaluation of the following accident sequences:

L-10	6M
• Side impact followed by fire	• Side impact
• Puncture	• Puncture

The results from analysis of these accident sequences can be applied to other conditions. For example, analyzing container impact using elastic theory neglects the time variable. This means that the results of crushing can be inferred from the impact results. This can be accomplished by equating the energy in the container prior to impact to the work performed on the container in deformation. Thus:

$$E = 1/2\ mV_2^2 = mgh_1 = Fd \qquad (6\text{-}1)$$

where

m is the mass of the container

V_2 is the velocity of the container at impact

h_1 is the initial drop height

d is the deformation of the container after impact

F is the force representing an equivalent crush force.

The kinetic energy just before impact, $1/2\ mV_2^2$, was initially potential energy represented by the term "mgh_1." This energy is dissipated by deforming the container an amount "d" using a force "F." The force in this equation represents a crush force. In the case of crushing, the force can come from many directions whereas the impact is imposed on one side. This represents the major distinction between crush and impact analyses.

6.1 ANALYSIS OF L-10 CONTAINER

The L-10 container was evaluated for two accident sequences: impact followed by fire and puncture. Results of the analyses are shown below.

6.1.1 Impact Plus Fire

The mechanical analysis of the L-10 container is presented in Appendix D. The first accident scenario was the impact failure of the outer container of the L-10 followed by a fire which pressurized and ruptured the inner pressure vessel. The first step in the analysis was to determine the drop height (or impacting velocity) that could result in loss of the vermiculite insulation located between the inner and outer containers. It was assumed that the L-10 container was subjected to a side drop onto an unyielding surface, with all the energy absorbed by the vermiculite. The analysis assumed that loss of vermiculite would occur when the lid comes off. A further assumption was made that the lid would come off when the perimeter of the lid in the deformed state was smaller than the undeformed inside circumference of the clamp ring.* Based on this assumption, the drop height that could cause loss of vermiculite material was calculated to be approximately 47 feet in a side drop.

The rupture of the inner pressure vessel, which is a 5-in. Schedule 80 stainless steel 304 pipe, was determined under fire conditions from two sets of calculations: (a) rupture pressure versus temperature (which reflects the decrease in the rupture strength of the vessel as a function of temperature) and (b) vessel internal pressure versus temperature when it contains 10 liters of plutonium nitrate. Threshold failure temperature was determined from the intersections of the curve resulting from these calculations. This temperature was found to be 610°F. Failure of the inner pressure vessel can occur as a combination of yielding of the bolts and the flange at the closure end. Failure was defined as the point where any leakage of contents of the pressure vessel takes place.

Following the determination that the pressure vessel will fail when the temperature reaches 610°F, calculations were performed to determine the time needed to heat the inner container to this point for a range of conditions. If the pressure vessel were exposed directly to a 1475°F fire, rupture was calculated to occur 6 min after exposure to the fire.** If all the insulation is present, the pressure vessel can maintain its integrity for 240 min. If the container remains upright and part of the insulation is missing, then the rate of heat up can be calculated by considering the insulated path and the direct radiant path in parallel. Thus for a container which is upright and has lost half its insulation,

* For a discussion of these assumptions see Appendix D.
** For a discussion of these results see Appendix E.

the heat up time is 12 min instead of 6 for no insulation. Calculations were also performed on the effectiveness of vermiculite with the container deformed or on its side and some of the vermiculite lost. A 0.38 in. vermiculite thickness was found to be sufficient to prevent pressure vessel failure for 30-min exposure to the postulated fire. The conclusion reached from this calculation is that vermiculite is effective as long as the pressure vessel is covered.

6.1.2 Puncture

The next analysis carried out was the theoretical determination of the drop height onto a 6-in. diameter pin required to puncture both the inner and outer shells of the L-10 container. The drop height required to puncture the outer shell was shown to be approximately 42 in.

The minimum drop height required to cause puncture of the inner vessel alone when dropped on a 6-in. diameter pin was calculated as approximately 4000 in. This failure mode, which takes no cognizance of the energy absorption properties of the outer container and vermiculite material, is one which for the conditions described cannot occur; the vessel would fail in some other mode long before the energy required for puncture could be generated. The most likely mode would be that of the inner vessel bending over the pin upon impact, resulting in the skin of the vessel being stretched until cracking occurs. If one considers the inner vessel alone, with no support from the outer container or space frame or energy absorbing properties of the vermiculite, then incipient cracking could occur in the inner vessel wall at a minimum drop height of 58 in. This figure was used in subsequent evaluations and represents a lower bound of the drop height; the actual drop height would be much higher due to the reinforcing effect of the neglected structural components of the L-10 container.

6.2 ANALYSIS OF 6M CONTAINER

The 6M container was analyzed for both impact and puncture accident sequences. The results of these two analyses are presented on the following page.

6.2.1 Impact

An analysis was made on a 15-gal 6M container to determine the drop height which would result in rupture of the outer container. Again a side drop onto an unyielding surface was assumed. The drop height required to pop the lid off the outer container was 194 ft. Again failure or loss of the lid was assumed to occur when the perimeter of the lid in the deformed state was smaller than the undeformed inside circumference of the clamp ring.

An attempt was made to determine the drop height which would cause rupture of the inner container of the 6M. It was assumed that the inner pressure vessel would not deform until the outer shell and inner shell came into contact. The drop height required to cause this contact was calculated to be approximately 260 ft. Inner container deformation would occur from drop heights greater than this. The point at which rupture would occur due to such deformation cannot be readily calculated. The solution could best be found by physical tests. Therefore for this study the threshold failure point for the inner container was conservatively assumed to be 260 ft.

Recent tests at Sandia have shown that the inner container of the 6M assembly retains integrity at drop height equivalents exceeding 1000 ft.[1]

6.2.2. Puncture

Calculations for the 15-gal 6M showed the total drop height required to puncture both the inner and outer containers is 170 in. Just as with the L-10, the inner container of the 6M would fail in bending rather than by puncture. Failure thresholds are summarized in Table 6.1.

6.3 DISCUSSION OF ANALYTICAL TECHNIQUES

The stress analysis used in this study was based on elastic behavior of the materials. It did not include the effects of larger deformation and plastic behavior. Inclusion of such effects would give calculated results as drop heights greater than those calculated and shown in

TABLE 6.1. Calculated Failure Thresholds[a] for L-10 and 6M Shipping Containers

L-10 CONTAINER

Failure Mode	Barrier: Outer	Inner	Inner & Outer
Impact[b]	47 ft	--	>130 ft[d]
Puncture[c]	42 in.	58 in.	100 in.[e]

Fire After Impact

Container Condition	Time to Failure
i) no insulation	6 min
ii) 0.4-in. insulation (Vermiculite)	30 min
iii) container crushed, no loss of insulating material	$\geq$240 min

6M CONTAINER

Failure Mode	Barrier: Outer	Inner	Inner & Outer
Impact[b]	190 ft	--	>260 ft
Puncture[c]	133 in.	37 in.	170 in.

(a) Numbers indicated are drop height equivalents.
(b) Side drop.
(c) 6-in. diameter probe.
(d) Based on results in Reference 2.
(e) Inner vessel fails in bending.

Table 6.1. Elementary mechanics show that a structure of ductile material, such as most grades of steel, absorbs so much energy that it undergoes large plastic deformations many times greater than that absorbed by the same structure in a purely elastic mode. Though some of the equations applied in this study are empirical in nature, being based on model tests, the basic mathematical theory employed was still that of linear elasticity.

Although limiting the analysis to linear elasticity gives inherently conservative results for the cases analyzed, the characteristics of a particular accident could be such as to result in failure at somewhat lower applied force levels. However, the reasonable agreement with test results indicates that this is not the case.

To assess the transportation risks the failure thresholds reported here must be correlated to forces generated by the accident environment.

REFERENCES

1. Personal communication - Lloyd Bonzon of Sandia Laboratories to Palmer Peterson of Pacific Northwest Laboratory.
2. L. D. Stravasnik, Special Tests for Plutonium Shipping Containers 6M, SP5795, and L-10, AEC R&D Report TID-4500, Sandia Report SC-DR-72 0587, September 1972.

7.0 CONDITIONS OF PACKAGES DURING TRANSPORT

A data bank of package conditions during transport was developed for the truck shipment risk report.(1) The data were obtained by a survey of companies and laboratories that routinely received plutonium. The scope and results of the survey are given in this section. More detailed discussion of the survey is given in Reference 1.

7.1 SURVEY SCOPE

The packaging condition questions used in the survey were developed from fault trees which traced each step of package loading and closure and identified all known conditions that could possibly affect package containment integrity. The conditions of particular interest, however, were those involving the primary containment vessel.

The survey covered shipments in the time period 1970-1974.

7.1.1 Packages Included in Survey

The risk assessment in this report compares $Pu(NO_3)_4$ solution transport in L-10 packages and PuO_2 powder transport in 6M packages. Since most of the packages used in plutonium transport have similar components, the survey was extended to also include L-3 and LLD type packages. By doing do, a broader data bank was obtained. See Reference 2 for a description of these containers.

The L-3 model is used for $Pu(NO_3)_4$ solution shipment and is basically the same design as the L-10. The main difference between the two is that the L-3 is a 55-gal drum with a 3-liter capacity inner bottle, whereas the L-10 consists of two end-connected 55-gal drums with a 10-liter capacity inner bottle.

The LLD model represents a basic type used for PuO_2 powder and plutonium metal shipments. It has the same type of 2R containment vessel as the 6M.

Descriptions of the L-10 and 6M packages are given in Appendix A.

7.2 RESULTS OF SURVEY

After completion of the survey, the data were assembled and tabulated. the results are presented below.

7.2.1 Number of Shipments and Packages

A summary of the number of packages covered by the survey is given in Table 7.1. The total is about 775 shipments, which includes 2130 L-3 and L-10 type packages and about 4100 LLD and 6M type packages. Several shipments of ^{233}U in L-10 packages are included with the results for liquid $Pu(NO_3)_4$, and several shipments of plutonium metal in LLD and 6M packages are included with the PuO_2 results. These additions were felt to be justified since the primary objective of this study was to obtain information on package closure which generally is not dependent on content.

7.2.2 Final Data Compiled for Use in Risk Assessment Model

A summary of observations made by those contacted in the survey is presented in Table 7.2. It should be emphasized that, in the extensive experience sampled by the survey, a complete loss of packaging integrity has never been observed.

7.2.3 Limitations of Survey

Even though the information obtained in the survey (Table 7.2) provides a reasonably good base for the risk assessment model, certain limitations should be recognized. First, for the most part, observations were made by personnel recollections. Consequently, the time periods in which particular abnormal conditions occurred and the number of occurrences were not certain.

Second, nearly all of the sites visited indicated that they now use a check-off sheet to help assure that packages are properly and securely closed. Some of these sheets have been in use for as long as 10 years while others have been implemented more recently. The implementation of quality assurance (QA) requirements by the USAEC and quality control (QC) procedures by shippers during 1972 and 1973 would have a significant effect on any package closure information obtained. Most packaging faults occurred prior to 1972. All those interviewed pointed out that very few package closure deficiencies have been observed since about 1972.

TABLE 7.1. Estimated Number of Shipments and Packages Included in Survey

(Period covered: 1970 - 1974)

	Number
SHIPMENTS	
(All package types)	775
PACKAGES SHIPPED	
$Pu(NO_3)_4$ Solution Packages (L-3 and L-10)	2130[a]
PuO_2 Packages	
LLD-1	2700-3000[b]
6M	1243[c]
Total Packages	∿ 6200

(a) Includes several ^{233}U packages that were shipped in L-3's and L-10's in the same manner as liquid plutonium nitrate.
(b) Includes several plutonium metal packages which were shipped in the same manner as plutonium dioxide.
(c) There were 806 packages in storage not included in this survey which were all unpacked by July 1975.

TABLE 7.2. Data Bank - Package Closure Experience Obtained by Survey (For Period 1970-1974)

Occurrence	Number of Occurrence	Occurrence Frequency (per container received)	Remarks
Part I - PLUTONIUM NITRATE SOLUTION SHIPMENTS (L-3 and L-10 Packages)			
Outside Primary Containment Vessel			
1. Bolt ring on outer drum turned upward	47	2.2×10^{-2}	The bolt ring closure is designed to be attached so that the bolt is down against the drum rather than upward, although not a requirement.
2. Vermiculite level low	200	9.4×10^{-2}	Vermiculite is normally 6 in. above top of containment vessel lid. If too low, fire protection may not be adequate. In two instances the vermiculite bags around top were missing.
3. Vermiculite contaminated	4	1.9×10^{-3}	In each instance contamination is believed to have resulted at the time of closure by the shipper, not by leakage from the vessel. The amount of plutonium involved in contamination was considered negligible from viewpoints of criticality hazard.
4. Vermiculite waterlogged	1	5×10^{-4}	Source of water not certain. Could have entered as rain through vent holes in older design.
5. No cap on vent line	13	6.1×10^{-3}	
6. Vent cap loose	3	1.4×10^{-3}	
7. Valve on vent line not closed	16	7.5×10^{-3}	In no instance was the valve open and the vent line cap missing or loose at the same time.
8. Flange bolts too tight (over 80-ft lb torque)	50	2.4×10^{-2}	
9. Gasket missing	2	9.4×10^{-4}	
Inside Primary Containment Vessel			
1. Plastic bag pressurized	5	2.4×10^{-3}	Contrary to expectations before the survey, relatively few plastic bags were found to be pressurized by receivers of $Pu(NO_3)_4$.
2. Plastic bottle cap loose	1	4.7×10^{-4}	
3. Plutonium solution in plastic bag	148	7.0×10^{-2}	
4. Contamination outside plastic bag	26	1.2×10^{-2}	
5. Plutonium solution outside plastic bag	11	5.2×10^{-3}	
6. Plastic bottle gasket in "figure eight"	4	1.9×10^{-3}	Gasket twisted when tightening
7. Plastic bag broken	2	9.4×10^{-4}	

TABLE 7.2. (Contd)

Occurrence	Number of Occurrence	Occurrence Frequency (per container received)	Remarks
Part II - PLUTONIUM DIOXIDE SHIPMENTS IN 6M PACKAGES			
Outside Primary Containment Vessel			
1. Hole in outer drum	2	1.6×10^{-3}	These holes occurred during relatively minor transportation mishaps.
2. Bolt rings turned upward	66	5.3×10^{-2}	See first remark, Part I
3. Bolt ring bolt loose (finger tight)	150	1.2×10^{-1}	Although loose, wire seal prevents bolt from coming off.
4. Bolt ring bolt broke off while tightening	6 of 300	2×10^{-2}	In preparing drums for shipment bolts broke during final tightening operation.
Inside Primary Containment Vessel			
1. Can bulged due to internal pressure	2	5×10^{-4}	In these two instances, the cans were not ruptured.
2. Contamination outside of can	13		
3. Contamination of plastic bag	13		Source of contamination was evidently packaging operation, not can leak.
Part III - PLUTONIUM DIOXIDE SHIPMENTS IN (LLD-1 PACKAGES)			
Outside Primary Containment Vessel			
1. Locking cover loose	1	2.4×10^{-4}	
2. Plug in 2R containment vessel not tight	~270 6M ~525 LLD	2.2×10^{-1} 1.8×10^{-1}	These estimates are based on the recollection of those interviewed in terms of percentage of total packages received. The estimate could be conservatively high. What apparently happens is that the plug loosens due to vibration during transport. In one instance the plug had worked its way completely out of the containment vessel by the time the package reached its destination.
3. Threads damaged	1	2.4×10^{-4}	
4. Plug extremely tight	1	2.4×10^{-4}	Long handled wrench required to remove plug
5. O ring missing	11	3.9×10^{-3}	
Inside Primary Containment Vessel			
1. Can bulged due to internal pressure	2	4.9×10^{-4}	
2. Can breached or not completely sealed upon arrival	3	1.1×10^{-3}	
3. Contamination outside can but not outside containment vessel	3	1.1×10^{-3}	

Because of these factors, the results reported in Table 7.2 are considered to be conservative and not necessarily representative of current package conditions during transport.

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. Division of Waste Management and Transportation, Directory of Packagings for Transportation of Radioactive Materials, WASH-1279, United States Atomic Energy Commission, Washington, D.C., 1973.

8.0 RELEASE SEQUENCE IDENTIFICATION

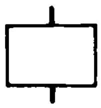
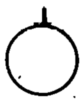
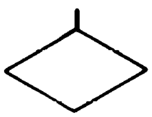
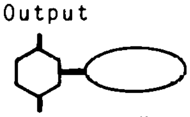
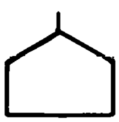
This section describes a formalized procedure for identifying combinations of conditions which could result in a release. The first step in the procedure is to develop fault trees using the techniques described in Section 8.1. Section 8.2 presents the fault trees developed for the shipment of plutonium dioxide powder in 6M containers and plutonium nitrate solution in L-10 containers. The second step in the procedure is to develop a list of release sequences from the fault tree. In Section 8.3, the release sequences will be identified for the two plutonium shipping forms using the concept of Barrier Release Sequences.

8.1 FAULT TREE CONSTRUCTION

The fault tree analysis technique was developed in the 1960s in the aerospace industry to identify design deficiencies before actual space flight of the equipment. Basically the procedure is to assume a failure and work backwards to identify component failures which could cause or contribute to the failure. The fault tree should be developed to individual components for which failure data are available. For instance, in an electronic circuit the basic failure might occur in a resistor. In practice, fault trees seldom are developed to that degree. What occurs instead is development of fault trees in terms of basic system modules. Using the electronic example, one would carry the possible failure back through the fault tree 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 plutonium involves postulation of a release of plutonium during transport and then examination of the series of events which must have occurred to cause the release. This form of reasoning is thought to be much more inclusive than beginning with an initiating event and working toward a release, (i.e., constructing accident scenarios or decision trees). At the same time, quantification

TABLE 8.1. Fault Tree Symbolism

Symbol	Meaning and Use
 output / inputs	"AND" logic gate. The simultaneous occurrence of inputs is required to cause an output.
 output / inputs	"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.
Output  Input	"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.

of the release requires specifications of an ordered sequence of events or accident scenarios. From this analysis, the tree constructed using the fault tree methodology is used as the basis for estimating the total release probability. Then the tree is broken down into all the possible known release sequences. In effect, all the known accident scenarios will be obtained from the fault tree. When properly applied, the accident scenarios obtained from using the fault tree methodology should be more complete than the 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 DIOXIDE POWDER IN THE 6M AND LIQUID NITRATE IN THE L-10

The fault trees for the plutonium dioxide shipments in the 6M and liquid nitrate shipments in the L-10 are developed for normal rail transport on primary railways in the United States. The analysis considers the combined effects of the train accident environment and packaging condition. Based on these criteria, the fault trees shown in Figures 8.1 and 8.2 were developed to determine applicable failure sequences for the 6M and L-10 shipping containers, respectively. The list of identified events or failure elements which could contribute to a release are shown in Tables 8.2 and 8.3 for the 6M and L-10, respectively.

For both the dioxide and the nitrate shipments, four barriers exist between the plutonium and man's environment. For the dioxide these were: the sample can (the primary container for the plutonium), the 2R container, the 6M drum, and the railcar. For the liquid nitrate the barriers were: the polyethylene bottle, the pressure vessel, the L-10 drum, and the railcar. Generally, in analyses, no credit is taken for the first and fourth barriers (can or bottle and the railcar). However, they can act to reduce both the probability of a release occurring and the quantity of material dispersed should a release occur. Therefore, they are included in this analysis.

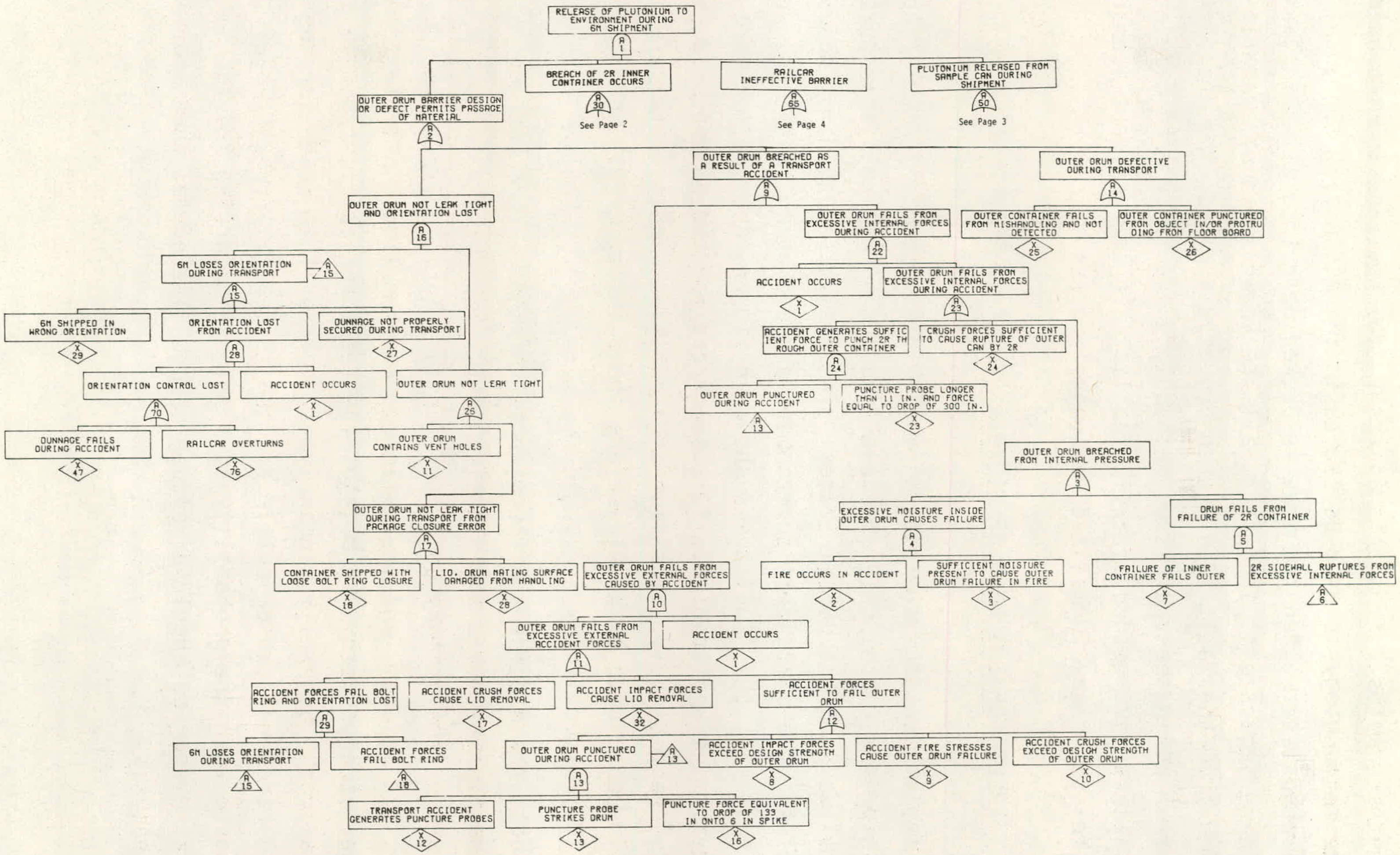


FIGURE 8.1, Page 1. Fault Tree for the Shipment of Plutonium Dioxide Powder in the 6M Container

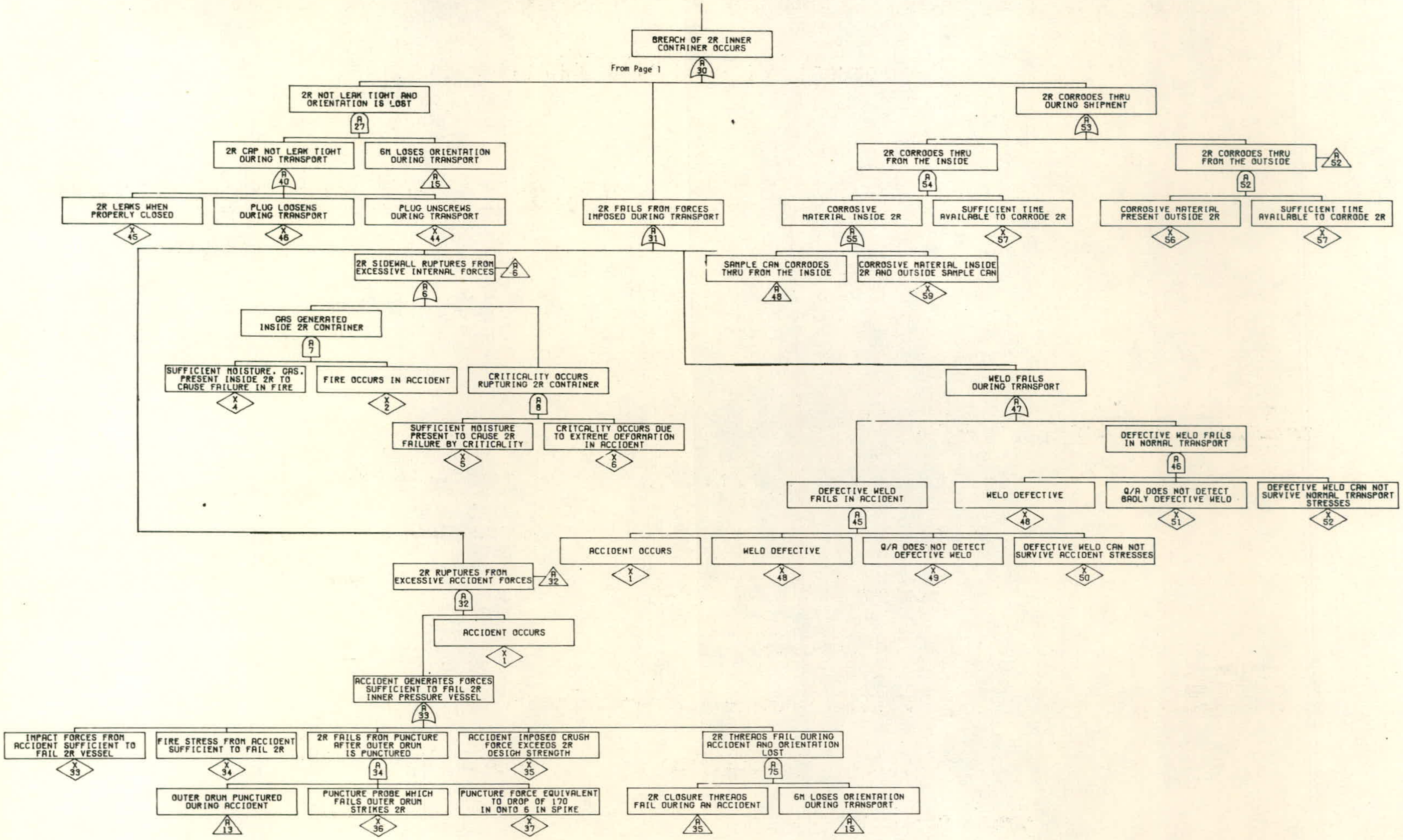


FIGURE 8.1, Page 2. (Contd)

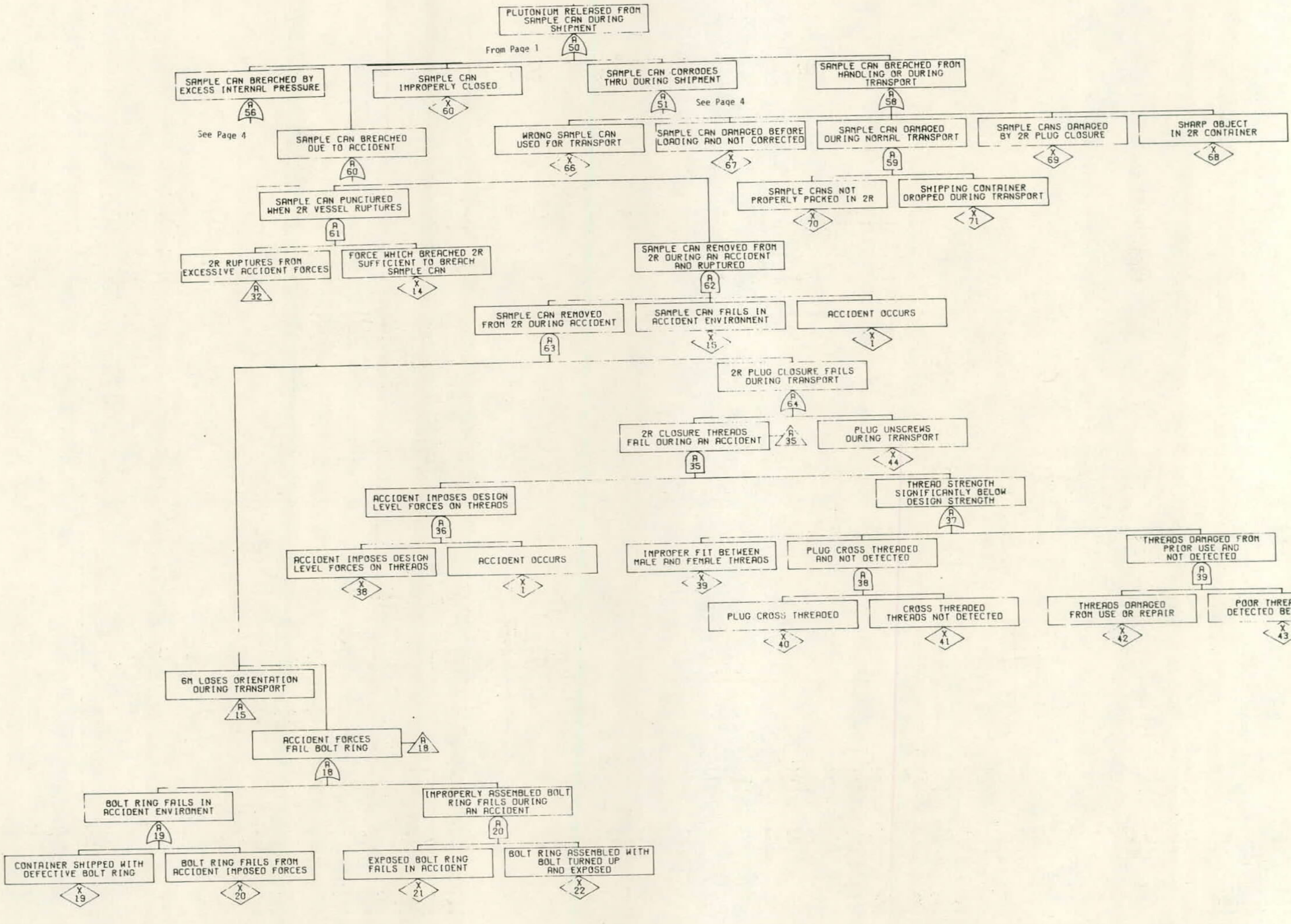


FIGURE 8.1, Page 3. (Contd)

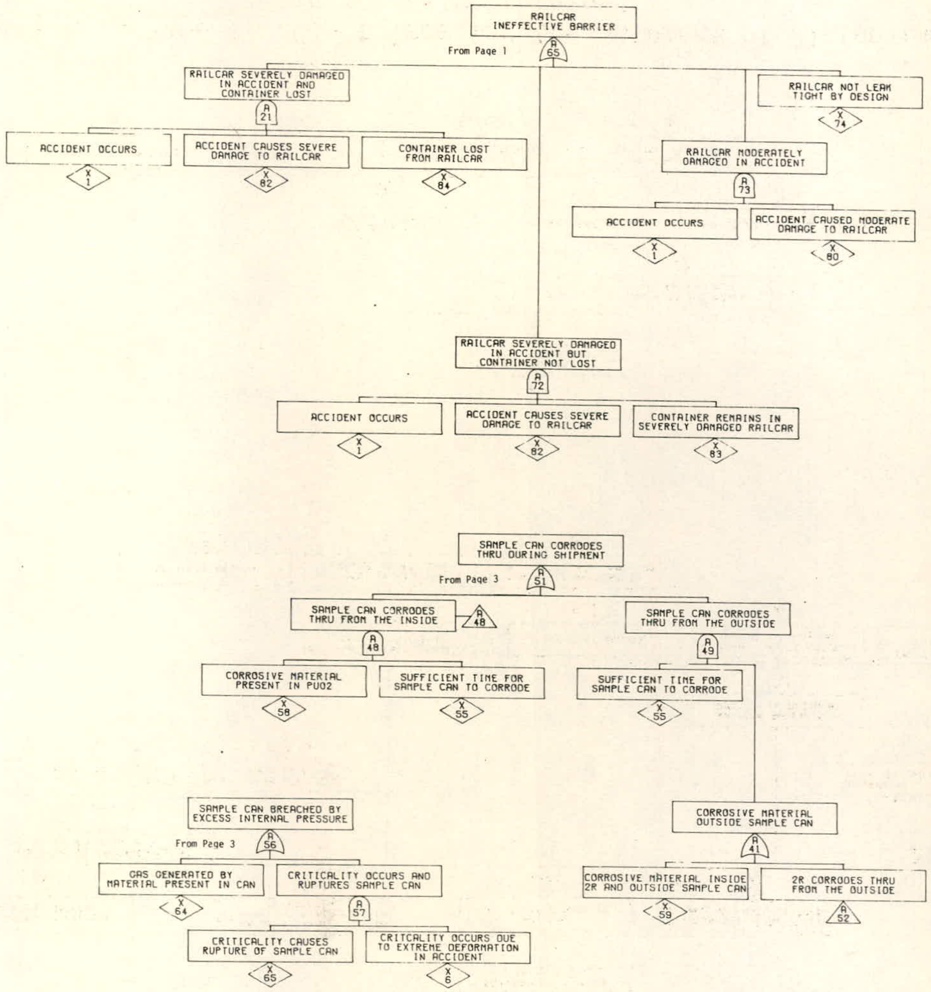


FIGURE 8.1, Page 4. (Contd)

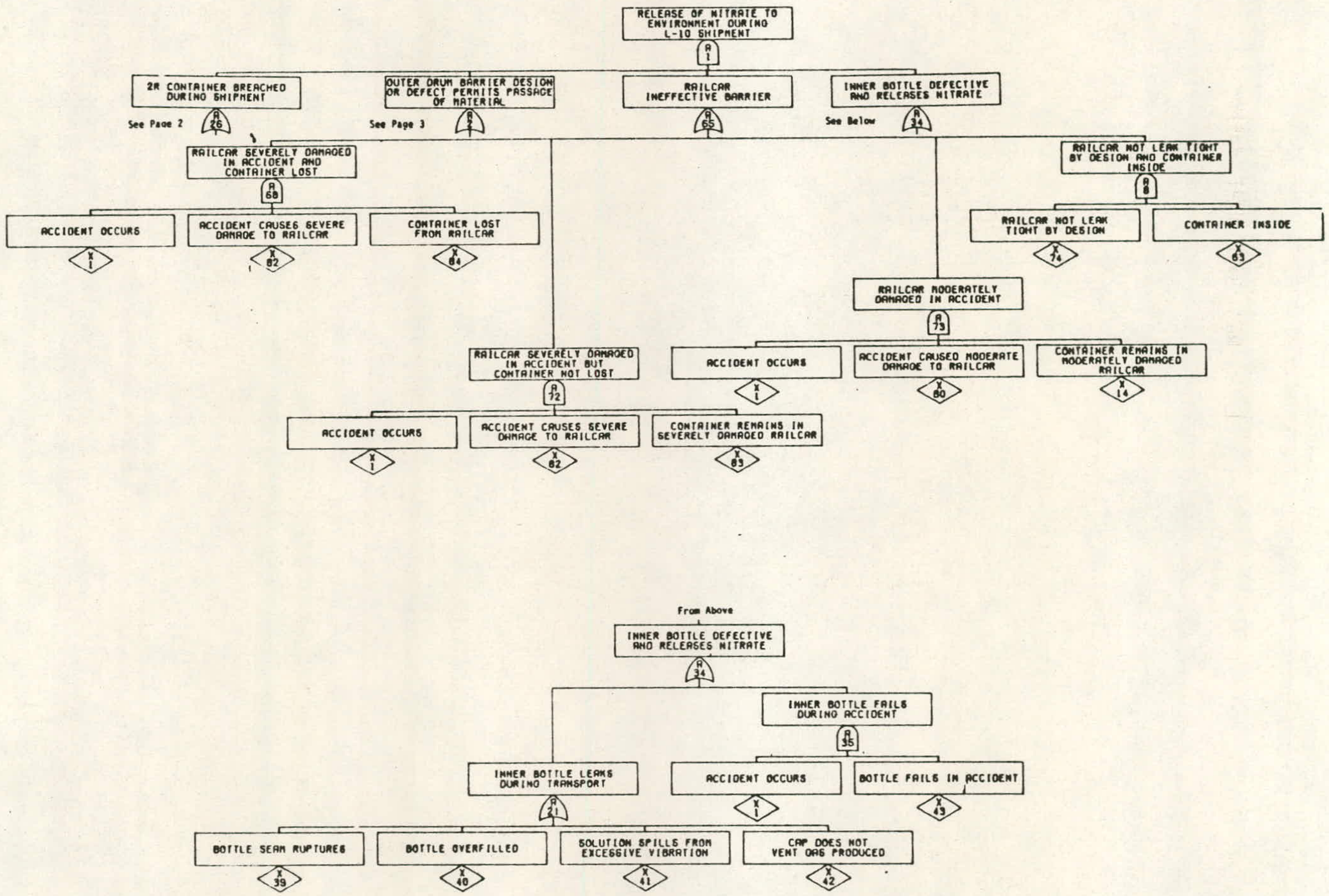


FIGURE 8.2, Page 1. Fault Tree for the Shipment of Plutonium Nitrate in the L-10 Container

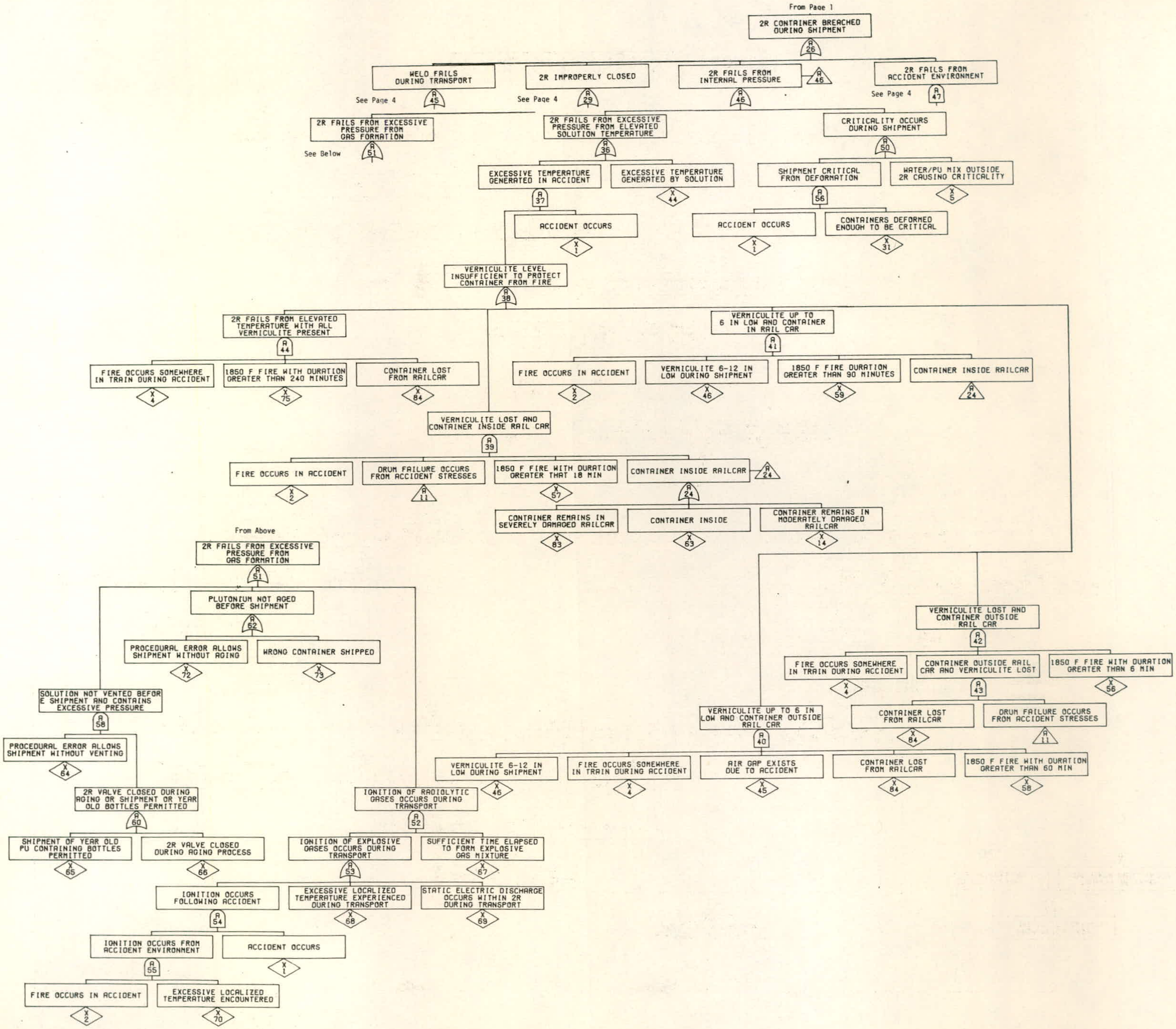


FIGURE 8.2, Page 2. (Contd)

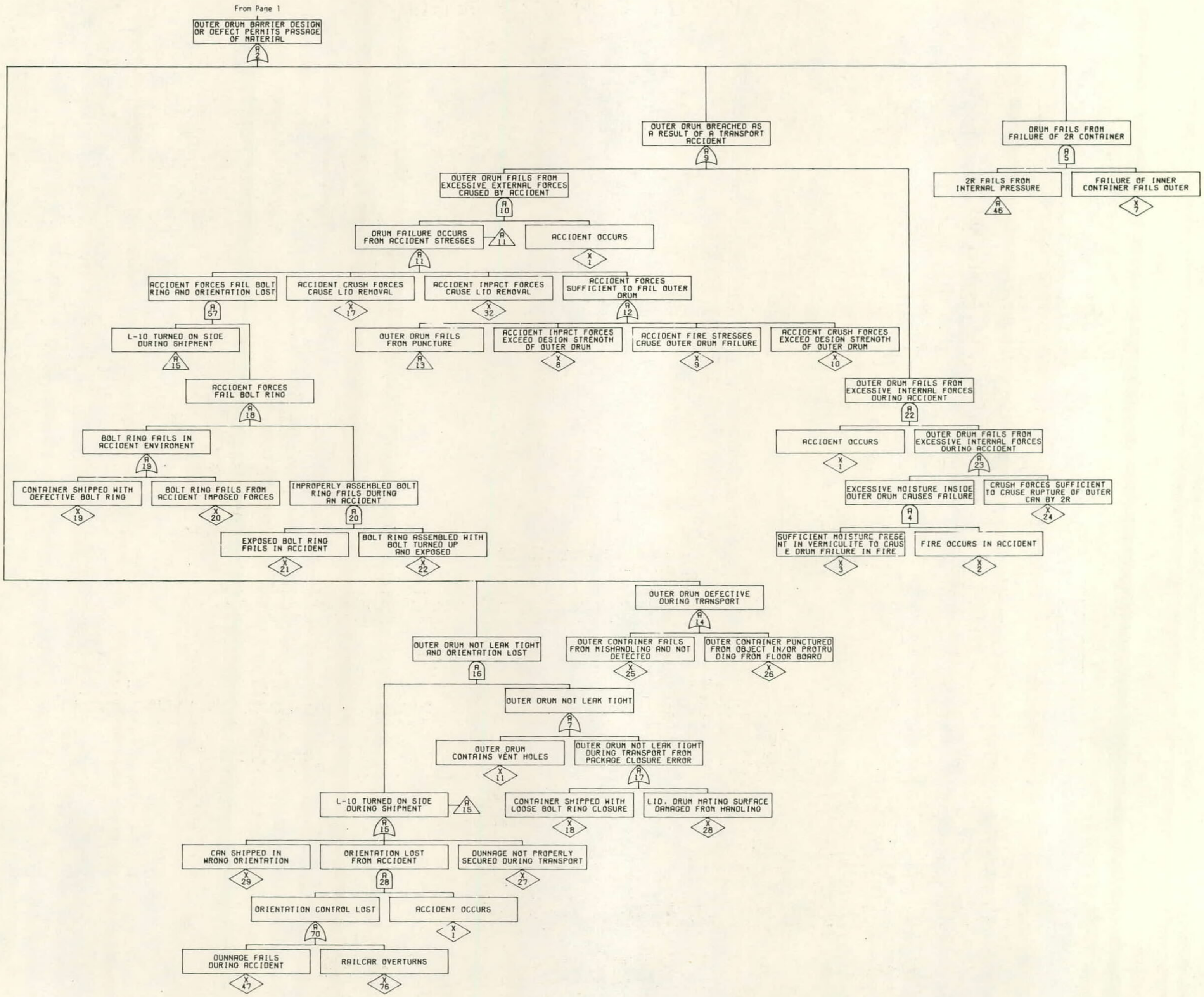


FIGURE 8.2, Page 3. (Contd)

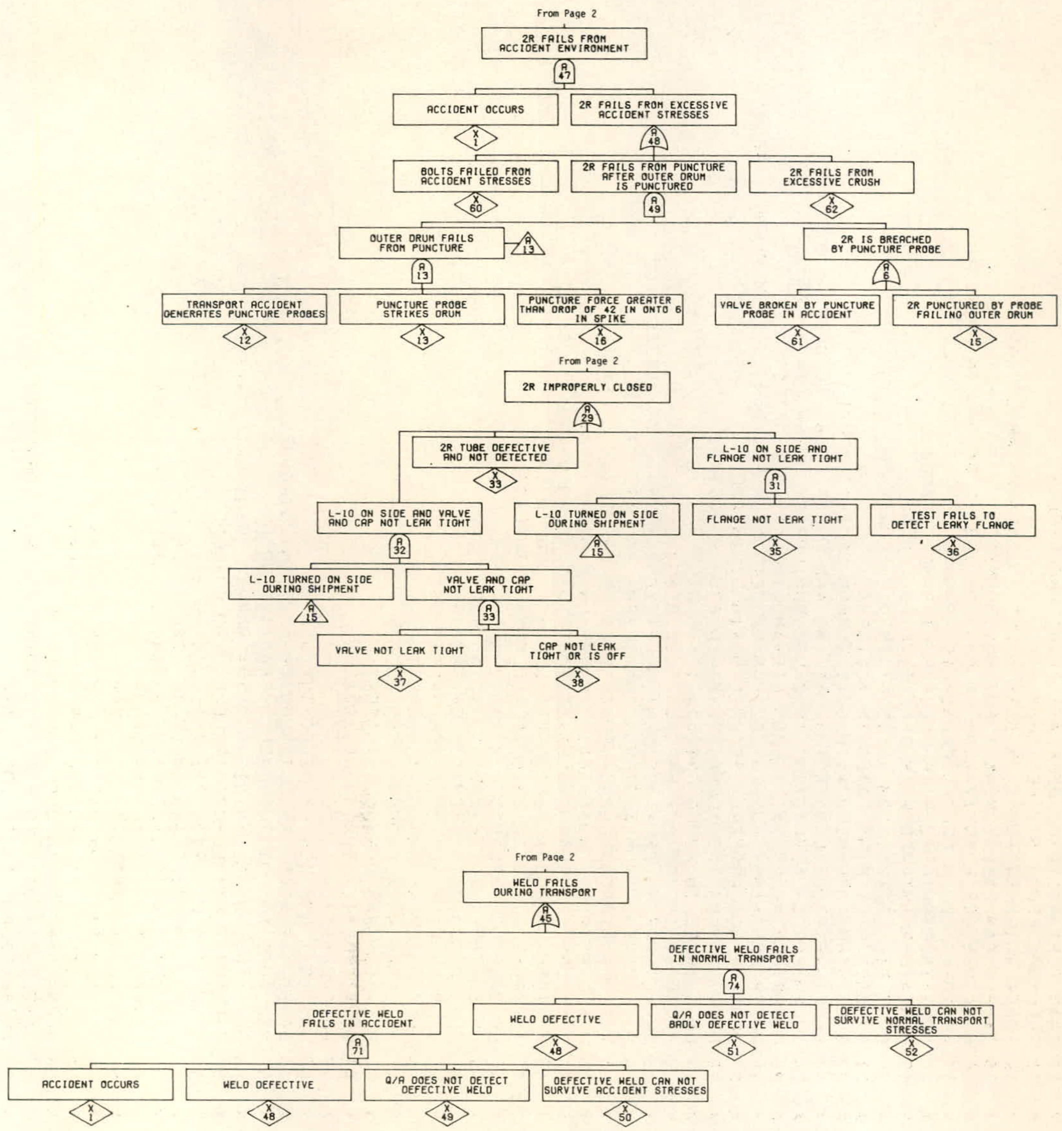


FIGURE 8.2, Page 4. (Contd)

TABLE 8.2. Listing of Basic Events for 6M Analysis

X	1	ACCIDENT OCCURS
X	2	FIRE OCCURS IN ACCIDENT
X	3	SUFFICIENT MOISTURE PRESENT TO CAUSE OUTER DRUM FAILURE IN FIRE
X	4	SUFFICIENT MOISTURE, GAS, PRESENT INSIDE 2R TO CAUSE FAILURE IN FIRE
X	5	SUFFICIENT MOISTURE PRESENT TO CAUSE 2R FAILURE BY CRITICALITY
X	6	CRITCALITY OCCURS DUE TO EXTREME DEFORMATION IN ACCIDENT
X	7	FAILURE OF INNER CONTAINER FAILS OUTER
X	8	ACCIDENT IMPACT FORCES EXCEED DESIGN STRENGTH OF OUTER DRUM
X	9	ACCIDENT FIRE STRESSES CAUSE OUTER DRUM FAILURE
X	10	ACCIDENT CRUSH FORCES EXCEED DESIGH STRENGTH OF OUTER DRUM
X	11	OUTER DRUM CONTAINS VENT HOLES
X	12	TRANSPORT ACCIDENT GENERATES PUNCTURE PROBES
X	13	PUNCTURE PROBE STRIKES DRUM
X	14	FORCE WHICH BREACHED 2R SUFFICIENT TO BREACH SAMPLE CAN
X	15	SAMPLE CAN FAILS IN ACCIDENT ENVIRONMENT
X	16	PUNCTURE FORCE EQUIVALENT TO DROP OF 133 IN ONTO 6 IN SPIKE
X	17	ACCIDENT CRUSH FORCES CAUSE LID REMOVAL
X	18	CONTAINER SHIPPED WITH LOOSE BOLT RING CLOSURE
X	19	CONTAINER SHIPPED WITH DEFECTIVE BOLT RING
X	20	BOLT RING FAILS FROM ACCIDENT IMPOSED FORCES
X	21	EXPOSED BOLT RING FAILS IN ACCIDENT
X	22	BOLT RING ASSEMBLED WITH BOLT TURNED UP AND EXPOSED
X	23	PUNCTURE PROBE LONGER THAN 11 IN. AND FORCE EQUAL TO DROP OF 300 IN.
X	24	CRUSH FORCES SUFFICIENT TO CAUSE RUPTURE OF OUTER CAN BY 2R
X	25	OUTER CONTAINER FAILS FROM MISHANDLING AND NOT DETECTED
X	26	OUTER CONTAINER PUNCTURED FROM OBJECT IN/OR PROTRUDING FROM FLOOR BOARD
X	27	DUNNAGE NOT PROPERLY SECURED DURING TRANSPORT
X	28	LID, DRUM MATING SURFACE DAMAGED FROM HANDLING
X	29	6M SHIPPED IN WRONG ORIENTATION
X	32	ACCIDENT IMPACT FORCES CAUSE LID REMOVAL
X	33	IMPACT FORCES FROM ACCIDENT SUFFICIENT TO FAIL 2R VESSEL
X	34	FIRE STRESS FROM ACCIDENT SUFFICIENT TO FAIL 2R
X	35	ACCIDENT IMPOSED CRUSH FORCE EXCEEDS 2R DESIGH STRENGTH
X	36	PUNCTURE PROBE WHICH FAILS OUTER DRUM STRIKES 2R
X	37	PUNCTURE FORCE EQUIVALENT TO DROP OF 170 IN ONTO 6 IN SPIKE
X	38	ACCIDENT IMPOSES DESIGN LEVEL FORCES ON THREADS
X	39	IMPROPER FIT BETWEEN MALE AND FEMALE THREADS
X	40	PLUG CROSS THREADED
X	41	CROSS THREADED THREADS NOT DETECTED
X	42	THREADS DAMAGED FROM USE OR REPAIR
X	43	POOR THREADS NOT DETECTED BEFORE USE
X	44	PLUG UNSCREWS DURING TRANSPORT
X	45	2R LEAKS WHEN PROPERLY CLOSED
X	46	PLUG LOOSENS DURING TRANSPORT
X	47	DUNNAGE FAILS DURING ACCIDENT
X	48	WELD DEFECTIVE
X	49	Q/A DOES NOT DETECT DEFECTIVE WELD
X	50	DEFECTIVE WELD CAN NOT SURVIVE ACCIDENT STRESSES
X	51	Q/A DOES NOT DETECT BADLY DEFECTIVE WELD
X	52	DEFECTIVE WELD CAN NOT SURVIVE NORMAL TRANSPORT STRESSES
X	55	SUFFICIENT TIME FOR SAMPLE CAN TO CORRODE
X	56	CORROSIVE MATERIAL PRESENT OUTSIDE 2R
X	57	SUFFICIENT TIME AVAILABLE TO CORRODE 2R
X	58	CORROSIVE MATERIAL INSIDE 2R AND OUTSIDE SAMPLE CAN
X	59	CORROSIVE MATERIAL INSIDE 2R
X	60	SAMPLE CAN IMPROPERLY CLOSED
X	64	GAS GENERATED BY MATERIAL PRESENT IN CAN
X	65	CRITICALITY CAUSES RUPTURE OF SAMPLE CAN
X	66	WRONG SAMPLE CAN USED FOR TRANSPORT
X	67	SAMPLE CAN DAMAGED BEFORE LOADING AND NOT CORRECTED
X	68	SHARP OBJECT IN 2R CONTAINER
X	69	SAMPLE CANS DAMAGED BY 2R PLUG CLOSURE
X	70	SAMPLE CANS NOT PROPERLY PACKED IN 2R
X	71	SHIPPING CONTAINER DROPPED DURING TRANSPORT
X	74	RAILCAR NOT LEAK TIGHT BY DESIGN
X	76	RAILCAR OVERTURNS
X	80	ACCIDENT CAUSED MODERATE DAMAGE TO RAILCAR
X	82	ACCIDENT CAUSES SEVERE DAMAGE TO RAILCAR
X	83	CONTAINER REMAINS IN SEVERELY DAMAGED RAILCAR
X	84	CONTAINER LOST FROM RAILCAR

TABLE 8.3. Listing of Basic Events in L-10 Analysis

X	1	ACCIDENT OCCURS
X	2	FIRE OCCURS IN ACCIDENT
X	3	SUFFICIENT MOISTURE PRESENT IN VERMICULITE TO CAUSE DRUM FAILURE IN FIRE
X	4	FIRE OCCURS SOMEWHERE IN TRAIN DURING ACCIDENT
X	5	WATER/PU MIX OUTSIDE 2R CAUSING CRITICALITY
X	7	FAILURE OF INNER CONTAINER FAILS OUTER
X	8	ACCIDENT IMPACT FORCES EXCEED DESIGN STRENGTH OF OUTER DRUM
X	9	ACCIDENT FIRE STRESSES CAUSE OUTER DRUM FAILURE
X	10	ACCIDENT CRUSH FORCES EXCEED DESIGN STRENGTH OF OUTER DRUM
X	11	OUTER DRUM CONTAINS VENT HOLES
X	12	TRANSPORT ACCIDENT GENERATES PUNCTURE PROBES
X	13	PUNCTURE PROBE STRIKES DRUM
X	14	CONTAINER REMAINS IN MODERATELY DAMAGED RAILCAR
X	15	2R PUNCTURED BY PROBE FAILING OUTER DRUM
X	16	PUNCTURE FORCE GREATER THAN DROP OF 42 IN ONTO 6 IN SPIKE
X	17	ACCIDENT CRUSH FORCES CAUSE LID REMOVAL
X	18	CONTAINER SHIPPED WITH LOOSE BOLT RING CLOSURE
X	19	CONTAINER SHIPPED WITH DEFECTIVE BOLT RING
X	20	BOLT RING FAILS FROM ACCIDENT IMPOSED FORCES
X	21	EXPOSED BOLT RING FAILS IN ACCIDENT
X	22	BOLT RING ASSEMBLED WITH BOLT TURNED UP AND EXPOSED
X	24	CRUSH FORCES SUFFICIENT TO CAUSE RUPTURE OF OUTER CAN BY 2R
X	25	OUTER CONTAINER FAILS FROM MISHANDLING AND NOT DETECTED
X	26	OUTER CONTAINER PUNCTURED FROM OBJECT IN/OR PROTRUDING FROM FLOOR BOARD
X	27	DUNNAGE NOT PROPERLY SECURED DURING TRANSPORT
X	28	LID, DRUM MATING SURFACE DAMAGED FROM HANDLING
X	29	CAN SHIPPED IN WRONG ORIENTATION
X	31	CONTAINERS DEFORMED ENOUGH TO BE CRITICAL
X	32	ACCIDENT IMPACT FORCES CAUSE LID REMOVAL
X	33	2R TUBE DEFECTIVE AND NOT DETECTED
X	35	FLANGE NOT LEAK TIGHT
X	36	TEST FAILS TO DETECT LEAKY FLANGE
X	37	VALVE NOT LEAK TIGHT
X	38	CAP NOT LEAK TIGHT OR IS OFF
X	39	BOTTLE SEAM RUPTURES
X	40	BOTTLE OVERFILLED
X	41	SOLUTION SPILLS FROM EXCESSIVE VIBRATION
X	42	CAP DOES NOT VENT GAS PRODUCED
X	43	BOTTLE FAILS IN ACCIDENT
X	44	EXCESSIVE TEMPERATURE GENERATED BY SOLUTION
X	45	AIR GAP EXISTS DUE TO ACCIDENT
X	46	VERMICULITE 6-12 IN LOW DURING SHIPMENT
X	47	DUNNAGE FAILS DURING ACCIDENT
X	48	WELD DEFECTIVE
X	49	Q/A DOES NOT DETECT DEFECTIVE WELD
X	50	DEFECTIVE WELD CAN NOT SURVIVE ACCIDENT STRESSES
X	51	Q/A DOES NOT DETECT BADLY DEFECTIVE WELD
X	52	DEFECTIVE WELD CAN NOT SURVIVE NORMAL TRANSPORT STRESSES
X	56	1850 F FIRE WITH DURATION GREATER THAN 6 MIN
X	57	1850 F FIRE WITH DURATION GREATER THAT 18 MIN
X	58	1850 F FIRE WITH DURATION GREATER THAN 60 MIN
X	59	1850 F FIRE DURATION GREATER THAN 90 MINUTES
X	60	BOLTS FAILED FROM ACCIDENT STRESSES
X	61	VALVE BROKEN BY PUNCTURE PROBE IN ACCIDENT
X	62	2R FAILS FROM EXCESSIVE CRUSH
X	63	CONTAINER INSIDE
X	64	PROCEDURAL ERROR ALLOWS SHIPMENT WITHOUT VENTING
X	65	SHIPMENT OF YEAR OLD PU CONTAINING BOTTLES PERMITTED
X	66	2R VALVE CLOSED DURING AGING PROCESS
X	67	SUFFICIENT TIME ELAPSED TO FORM EXPLOSIVE GAS MIXTURE
X	68	EXCESSIVE LOCALIZED TEMPERATURE EXPERIENCED DURING TRANSPORT
X	69	STATIC ELECTRIC DISCHARGE OCCURS WITHIN 2R DURING TRANSPORT
X	70	EXCESSIVE LOCALIZED TEMPERATURE ENCOUNTERED
X	72	PROCEDURAL ERROR ALLOWS SHIPMENT WITHOUT AGING
X	73	WRONG CONTAINER SHIPPED
X	74	RAILCAR NOT LEAK TIGHT BY DESIGN
X	75	1850 F FIRE WITH DURATION GREATER THAN 240 MINUTES
X	76	RAILCAR OVERTURNS
X	80	ACCIDENT CAUSED MODERATE DAMAGE TO RAILCAR
X	82	ACCIDENT CAUSES SEVERE DAMAGE TO RAILCAR
X	83	CONTAINER REMAINS IN SEVERELY DAMAGED RAILCAR
X	84	CONTAINER LOST FROM RAILCAR

8.3 BARRIER RELEASE SEQUENCES

The fault tree can be thought of as a compact notation for identifying and displaying thousands of potential release sequences. There are several computer programs that can then develop lists of the release sequences from the fault tree.

These lists are frequently very long and very difficult to summarize for evaluation. To overcome these difficulties a concept of barrier release sequences has been developed. The fault trees, shown in Section 8.2, considered four barriers; the railcar, the outer drum of the package, the containment vessel. and the inner can or bottle. The concurrent failure of all four barriers is required for plutonium to be released to the atmosphere. Thus, combining a release sequence for one barrier with a release sequence for each of the other three barriers identifies a possible sequence of events which breach all the barriers. All release sequences can be obtained by combining lists of barrier release sequences.

This concept of barrier release sequences is quite powerful for understanding and analyzing the fault tree. For example, if there are four barriers and 25 release sequences for each barrier, then the more than 390,000 release sequences which would be obtained by combining the barrier sequences can be summarized in a list of 100 elements.

The barrier release sequence lists developed for the dioxide shipment are shown in Table 8.4. In the table, the items under "Sample Can" are the sample can barrier release sequences; those under "2R" are the 2R containment vessel barrier release sequences, etc. In the lists, elements are denoted by "A"s and "X"s with associated numerical designations. Elements which have further development in the fault tree are denoted with "A"s. The "X"s are basic conditions or events which are not developed further in the trees. The descriptive titles for the "X" elements were given in Table 8.2; those for the "A" elements are given in Table 8.5. Corresponding information for the liquid nitrate shipment is given in Tables 8.3, 8.6 and 8.7. Elements whose probabilities were assigned zero values were not included in the lists.

TABLE 8.4. Barrier Release Sequence Developed for the 6M Container

SAMPLE CAN				
X064				
A051				
X001	X014	X036	X037	A013
X001	X015	X029	X044	A019
X001	X015	X027	X044	A019
X001	X015	X044	X047	A019
X001	X015	X044	X076	A019
X001	X015	X029	X044	A020
X001	X015	X027	X044	A020
X001	X015	X044	X047	A020
X001	X015	X044	X076	A020
2R				
X029	X046			
X029	X044			
X027	X046			
X027	X044			
X001	X048	X049	X050	
X001	X036	X037	A013	
X001	X046	X047		
X001	X046	X076		
X001	X044	X047		
X001	X044	X076		
OUTER DRUM				
A014				
X011	X029			
A017	X029			
X011	X027			
A017	X027			
X001	A013			
X001	X008			
X001	X023	A013		
X001	X011	X047		
X001	A017	X047		
X001	X011	X076		
X001	X076	A017		
X001	X029	A019		
X001	X027	A019		
X001	X047	A019		
X001	X076	A019		
X001	X017			
X001	X029	A020		
X001	X027	A020		
X001	X047	A020		
X001	X076	A020		
RAILCAR				
X074				
X001	X082	X084		
X001	X082	X083		
X001	X080			

TABLE 8.5. Listing of Input Labels for Rectangles for 6M Container Analysis

A 1 RELEASE OF PLUTONIUM TO ENVIRONMENT DURING 6M SHIPMENT
A 2 OUTER DRUM BARRIER DESIGN OR DEFECT PERMITS PASSAGE OF MATERIAL
A 3 OUTER DRUM BREACHED FROM INTERNAL PRESSURE
A 4 EXCESSIVE MOISTURE INSIDE OUTER DRUM CAUSES FAILURE
A 5 DRUM FAILS FROM FAILURE OF 2R CONTAINER
A 6 2R SIDEWALL RUPTURES FROM EXCESSIVE INTERNAL FORCES
A 7 GAS GENERATED INSIDE 2R CONTAINER
A 8 CRITICALITY OCCURS RUPTURING 2R CONTAINER
A 9 OUTER DRUM BREACHED AS A RESULT OF A TRANSPORT ACCIDENT
A 10 OUTER DRUM FAILS FROM EXCESSIVE EXTERNAL FORCES CAUSED BY ACCIDENT
A 11 OUTER DRUM FAILS FROM EXCESSIVE EXTERNAL ACCIDENT FORCES
A 12 ACCIDENT FORCES SUFFICIENT TO FAIL OUTER DRUM
A 13 OUTER DRUM PUNCTURED DURING ACCIDENT
A 14 OUTER DRUM DEFECTIVE DURING TRANSPORT
A 15 6M LOSES ORIENTATION DURING TRANSPORT
A 16 OUTER DRUM NOT LEAK TIGHT AND ORIENTATION LOST
A 17 OUTER DRUM NOT LEAK TIGHT DURING TRANSPORT FROM PACKAGE CLOSURE ERROR
A 18 ACCIDENT FORCES FAIL BOLT RING
A 19 BOLT RING FAILS IN ACCIDENT ENVIROMENT
A 20 IMPROPERLY ASSEMBLED BOLT RING FAILS DURING AN ACCIDENT
A 21 RAILCAR SEVERELY DAMAGED IN ACCIDENT AND CONTAINER LOST
A 22 OUTER DRUM FAILS FROM EXCESSIVE INTERNAL FORCES DURING ACCIDENT
A 23 OUTER DRUM FAILS FROM EXCESSIVE INTERNAL FORCES DURING ACCIDENT
A 24 ACCIDENT GENERATES SUFFICIENT FORCE TO PUNCH 2R THROUGH OUTER CONTAINER
A 26 OUTER DRUM NOT LEAK TIGHT
A 27 2R NOT LEAK TIGHT AND ORIENTATION IS LOST
A 28 ORIENTATION LOST FROM ACCIDENT
A 29 ACCIDENT FORCES FAIL BOLT RING AND ORIENTATION LOST
A 30 BREACH OF 2R INNER CONTAINER OCCURS
A 31 2R FAILS FROM FORCES IMPOSED DURING TRANSPORT
A 32 2R RUPTURES FROM EXCESSIVE ACCIDENT FORCES
A 33 ACCIDENT GENERATES FORCES SUFFICIENT TO FAIL 2R INNER PRESSURE VESSEL
A 34 2R FAILS FROM PUNCTURE AFTER OUTER DRUM IS PUNCTURED
A 35 2R CLOSURE THREADS FAIL DURING AN ACCIDENT
A 36 ACCIDENT IMPOSES DESIGN LEVEL FORCES ON THREADS
A 37 THREAD STRENGTH SIGNIFICANTLY BELOW DESIGN STRENGTH
A 38 PLUG CROSS THREADED AND NOT DETECTED
A 39 THREADS DAMAGED FROM PRIOR USE AND NOT DETECTED
A 40 2R CAP NOT LEAK TIGHT DURING TRANSPORT
A 41 CORROSIVE MATERIAL OUTSIDE SAMPLE CAN
A 45 DEFECTIVE WELD FAILS IN ACCIDENT
A 46 DEFECTIVE WELD FAILS IN NORMAL TRANSPORT
A 47 WELD FAILS DURING TRANSPORT
A 48 SAMPLE CAN CORRODES THRU FROM THE INSIDE
A 49 SAMPLE CAN CORRODES THRU FROM THE OUTSIDE
A 50 PLUTONIUM RELEASED FROM SAMPLE CAN DURING SHIPMENT.
A 51 SAMPLE CAN CORRODES THRU DURING SHIPMENT
A 52 2R CORRODES THRU FROM THE OUTSIDE
A 53 2R CORRODES THRU DURING SHIPMENT
A 54 2R CORRODES THRU FROM THE INSIDE
A 55 CORROSIVE MATERIAL INSIDE 2R
A 56 SAMPLE CAN BREACHED BY EXCESS INTERNAL PRESSURE
A 57 CRITICALITY OCCURS AND RUPTURES SAMPLE CAN
A 58 SAMPLE CAN BREACHED FROM HANDLING OR DURING TRANSPORT
A 59 SAMPLE CAN DAMAGED DURING NORMAL TRANSPORT
A 60 SAMPLE CAN BREACHED DUE TO ACCIDENT
A 61 SAMPLE CAN PUNCTURED WHEN 2R VESSEL RUPTURES
A 62 SAMPLE CAN REMOVED FROM 2R DURING AN ACCIDENT AND RUPTURED
A 63 SAMPLE CAN REMOVED FROM 2R DURING ACCIDENT
A 64 2R PLUG CLOSURE FAILS DURING TRANSPORT
A 65 RAILCAR INEFFECTIVE BARRIER
A 70 ORIENTATION CONTROL LOST
A 72 RAILCAR SEVERELY DAMAGED IN ACCIDENT BUT CONTAINER NOT LOST
A 73 RAILCAR MODERATELY DAMAGED IN ACCIDENT
A 75 2R THREADS FAIL DURING ACCIDENT AND ORIENTATION LOST

TABLE 8.6. Barrier Release Sequence Developed for the L-10 Container

INNER
X001 X043
A021

2R
A058
A062
X001 X048 X049 X050
X048 X051 X052
X027 X035 X036
X029 X035 X036
X027 X037 X038
X029 X037 X038
X001 X015 A013
X001 X061 A013
X001 X004 X075 X084
X001 X002 X046 X059 X083
X001 X004 X045 X046 X058 X084
X001 X047 X035 X036
X001 X047 X037 X038
X001 X076 X035 X036
X001 X076 X037 X038
X001 X002 A018 X057 X083 X029
X001 X002 X017 X057 X083
X001 X002 A013 X057 X083
X001 X004 A018 X056 X084
X001 X004 X017 X056 X084
X001 X002 X008 X057 X083
X001 X004 A013 X056 X084
X001 X004 X008 X056 X084
X001 X002 A018 X057 X083 X027
X001 X002 A018 X057 X083 X076
X001 X002 A018 X057 X083 X047
X001 X002 X046 X059 X014
X001 X002 X017 X057 X014
X001 X002 A013 X057 X014
X001 X002 X008 X057 X014
X001 X002 X029 A018 X057 X014
X001 X002 X027 A018 X057 X014
X001 X002 X047 A018 X057 X014
X001 X002 X076 A018 X057 X014

OUTER DRUM
A014
X029 X011
X029 A017
X027 X011
X027 A017
X001 A018 X027
X001 X017
X001 X008
X001 X011 X047
X001 X047 A017
X001 X011 X076
X001 X076 A017
X001 A013
X001 X002 X003
X007 A058
X007 A062
X001 X004 X007 X075 X084
X001 X002 X007 X046 X059 X083
X001 X004 X007 X045 X046 X058 X084
X001 A010 X029
X001 A018 X047
X001 A018 X076
X001 X002 X046 X059 X014 X067

RAILCAR
X063 X074
X001 X082 X083
X001 X082 X084
X001 X014 X080

TABLE 8.7. Listing of Input Labels for Rectangles for L-10 Container Analysis

A	1	RELEASE OF NITRATE TO ENVIRONMENT DURING L-10 SHIPMENT
A	2	OUTER DRUM BARRIER DESIGN OR DEFECT PERMITS PASSAGE OF MATERIAL
A	3	OUTER DRUM BREACHED FROM INTERNAL PRESSURE
A	4	EXCESSIVE MOISTURE INSIDE OUTER DRUM CAUSES FAILURE
A	5	DRUM FAILS FROM FAILURE OF 2R CONTAINER
A	6	2R IS BREACHED BY PUNCTURE PROBE
A	7	OUTER DRUM NOT LEAK TIGHT
A	8	RAILCAR NOT LEAK TIGHT BY DESIGN AND CONTAINER INSIDE
A	9	OUTER DRUM BREACHED AS A RESULT OF A TRANSPORT ACCIDENT
A	10	OUTER DRUM FAILS FROM EXCESSIVE EXTERNAL FORCES CAUSED BY ACCIDENT
A	11	DRUM FAILURE OCCURS FROM ACCIDENT STRESSES
A	12	ACCIDENT FORCES SUFFICIENT TO FAIL OUTER DRUM
A	13	OUTER DRUM FAILS FROM PUNCTURE
A	14	OUTFR DRUM DEFECTIVE DURING TRANSPORT
A	15	L-10 TURNED ON SIDE DURING SHIPMENT
A	16	OUTER DRUM NOT LEAK TIGHT AND ORIENTATION LOST
A	17	OUTER DRUM NOT LEAK TIGHT DURING TRANSPORT FROM PACKAGE CLOSURE ERROR
A	18	ACCIDENT FORCES FAIL BOLT RING
A	19	BOLT RING FAILS IN ACCIDENT ENVIROMENT
A	20	IMPROPERLY ASSEMBLED BOLT RING FAILS DURING AN ACCIDENT
A	21	INNER BOTTLE LEAKS DURING TRANSPORT
A	22	OUTER DRUM FAILS FROM EXCESSIVE INTERNAL FORCES DURING ACCIDENT
A	23	OUTER DRUM FAILS FROM EXCESSIVE INTERNAL FORCES DURING ACCIDENT
A	24	CONTAINER INSIDE RAILCAR
A	26	2R CONTAINER BREACHED DURING SHIPMENT
A	28	ORIENTATION LOST FROM ACCIDENT
A	29	2R IMPROPERLY CLOSED
A	31	L-10 ON SIDE AND FLANGE NOT LEAK TIGHT
A	32	L-10 ON SIDE AND VALVE AND CAP NOT LEAK TIGHT
A	33	VALVF AND CAP NOT LEAK TIGHT
A	34	INNER BOTTLE DEFECTIVE AND RELEASES NITRATE
A	35	INNER BOTTLE FAILS DURING ACCIDENT
A	36	2R FAILS FROM EXCESSIVE PRESSURE FROM ELEVATED SOLUTION TEMPERATURE
A	37	EXCESSIVE TEMPERATURE GENERATED IN ACCIDENT
A	38	VERMICULITE LEVEL INSUFFICIENT TO PROTECT CONTAINER FROM FIRE
A	39	VERMICULITE LOST AND CONTAINER INSIDE RAIL CAR
A	40	VERMICULITE UP TO 6 IN LOW AND CONTAINER OUTSIDE RAIL CAR
A	41	VERMICULITE UP TO 6 IN LOW AND CONTAINER IN RAIL CAR
A	42	VERMICULITE LOST AND CONTAINER OUTSIDE RAIL CAR
A	43	CONTAINER OUTSIDE RAIL CAR AND VERMICULITE LOST
A	44	2R FAILS FROM ELEVATED TEMPERATURE WITH ALL VERMICULITE PRESENT
A	45	WELD FAILS DURING TRANSPORT
A	46	2R FAILS FROM INTERNAL PRESSURE
A	47	2R FAILS FROM ACCIDENT ENVIRONMENT
A	48	2R FAILS FROM EXCESSIVE ACCIDENT STRESSES
A	49	2R FAILS FROM PUNCTURE AFTER OUTER DRUM IS PUNCTURED
A	50	CRITICALITY OCCURS DURING SHIPMENT
A	51	2R FAILS FROM EXCESSIVE PRESSURE FROM GAS FORMATION
A	52	IGNITION OF RADIOLYTIC GASES OCCURS DURING TRANSPORT
A	53	IGNITION OF EXPLOSIVE GASES OCCURS DURING TRANSPORT
A	54	IGNITION OCCURS FOLLOWING ACCIDENT
A	55	IGNITION OCCURS FROM ACCIDENT ENVIRONMENT
A	56	SHIPMENT CRITICAL FROM DEFORMATION
A	57	ACCIDENT FORCES FAIL BOLT RING AND ORIENTATION LOST
A	58	SOLUTION NOT VENTED BEFORE SHIPMENT AND CONTAINS EXCESSIVE PRESSURE
A	60	2R VALVE CLOSED DURING AGING OR SHIPMENT OR YEAR OLD BOTTLES PERMITTED
A	62	PLUTONIUM NOT AGED BEFORE SHIPMENT
A	65	RAILCAR INEFFECTIVE BARRIER
A	68	RAILCAR SEVERELY DAMAGED IN ACCIDENT AND CONTAINER LOST
A	70	ORIENTATION CONTROL LOST
A	71	DEFECTIVE WELD FAILS IN ACCIDENT
A	72	RAILCAR SEVERELY DAMAGED IN ACCIDENT BUT CONTAINER NOT LOST
A	73	RAILCAR MODERATELY DAMAGED IN ACCIDENT
A	74	DEFECTIVE WELD FAILS IN NORMAL TRANSPORT

Some explanation of the evaluation method is required. In the dioxide shipment barrier release sequence lists, Table 8.4, the second element under "Sample Can" is A051 which has the title "Sample Can Corrodes Through During Shipment." In the fault tree, Figure 8.1, it can be seen that A051 is further developed into several basic elements. To shorten the barrier release sequence list, barrier release probabilities and fractions (see Section 9) were evaluated for A051 rather than for the basic elements under A051. This procedure limits the detail available from the risk assessment but does not affect the value of the risk.

The barrier release sequence lists also contain many sequences which require multiple events or conditions to occur concurrently before a barrier release can occur. In one sequence in the "Outer Drum" list, X001 entitled "Accident Occurs," is combined with X008 entitled "Accident Impact Forces Exceed Design Strength of Outer Drum." Both must occur concurrently for the outer drum to be breached by this barrier release sequence.

A release sequence is constructed by combining elements from each of the four barrier release sequence lists. Thus, as seen in Table 8.4, X064, X029, X046, A014 and X074 comprise a release sequence for a plutonium dioxide shipment.

If an element occurs more than once in a release sequence, it is not duplicated in the evaluation. For example, for the release sequence (A051) (X001, X046, X047) (X001, X008) (X001, X082, X083) it would be incorrect for X001 to enter more than once in the evaluation. If it entered more than once, this would be equivalent to saying that an accident could not simultaneously affect more than one barrier. Thus, the release sequence obtained from these four barrier release sequences is reduced to: X001, A051, X046, X047, X008, X082 and X083 for analysis.

Although the procedure for generating release sequences from the lists of barrier release sequences is relatively straightforward, care must be taken to ensure that sequences which are physically impossible cannot occur. For example, a container cannot be both inside and outside the railcar. These are quite easily sorted out through logic statements which do not allow conflicting basic failure events in a release sequence. This situation arises in the analysis of the L-10 shipment. The railcar condition enters into some of the evaluations for the integrity of inner barriers. Since a container cannot be both inside and outside the railcar, the element in the tree designated by X083 cannot coexist in the same release sequence with X084. In the combining of the barrier release sequence lists to obtain release sequences, those which contain more than one railcar condition are eliminated from the list of allowable release sequences. A final, by hand evaluation of the release sequence lists was made to ensure that duplicates release sequences, impossible sequences, etc., were not included in the analysis. This evaluation also allowed adjustments to be made for common mode and dependent failures.

9.0 RELEASE SEQUENCE EVALUATION

The previous chapter presented the fault trees for the train shipment of plutonium as either dioxide in the 6M or liquid nitrate in the L-10. From the fault trees, a long list of release sequences can be identified 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 the release fraction must be determined for each release sequence. This section presents the basic data required to evaluate all release sequences.

In some release sequence evaluations, determining the release sequence probabilities is extremely complex because components can fail and be repaired before other elements in the sequence occur. Monte Carlo techniques are frequently required to obtain release sequence probabilities for these cases. In the transportation accident environment, no repair is likely, and is assumed not to occur. Package condition during normal transport is assumed to be static and as determined by surveys of receivers. Because of these transport environment characteristics, the release sequence probability can be obtained by determining the occurrence probability for each element in the sequence and then forming the product of the element probabilities. Thus, the fundamental elements in the analysis are the basic event probabilities.

The fault trees in Section 8 were developed down to a point where data on basic events could be obtained either through analysis or survey. The estimated basic event probabilities are presented in Section 9.1. The probability data are then used to develop the information on Barrier Release Sequence Probabilities summarized in Section 9.2. Barrier Release Fractions are evaluated in 9.3, and Section 9.4 summarizes the results of the chapter by showing how release sequences are evaluated from the barrier failure release fractions and probabilities.

9.1 BASIC EVENT PROBABILITIES

The following paragraphs provide two sequential lists of failure probability estimated. The first series is for dioxide shipments in the 6M container. The second series is for the liquid nitrate shipment in the L-10. The numbering sequence corresponds to the numbering sequence shown in the fault trees. For ease of comparison, whenever possible, identical numerical designations were given to similar events in the two trees. This necessitated leaving some unused numbers in the lists. The justification for probability estimates which appear in both lists will be presented once and only referenced in the second list of failure probabilities.

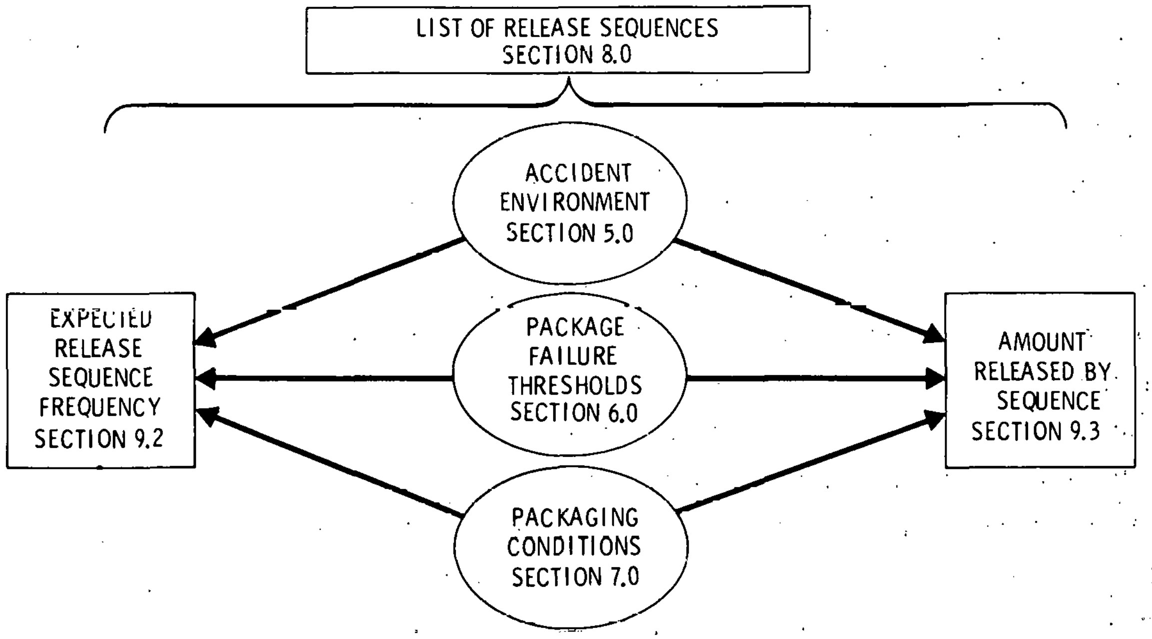


FIGURE 9.1. Release Sequence Evaluation

9.1.1 Basic Event Probabilities for PuO_2 in 6M

Accident Occurs (X1). The frequency at which an individual freight car would be expected to be involved in either a derailment or a collision railroad accident is one accident in every 730,000 miles traveled, a rate of 1.37×10^{-6} accidents per car-mile.[1] For a shipping distance of 1500 miles, the expected accident frequency is 2.05×10^{-3}/shipment.* This was used in the analysis.

* Probabilities and frequencies were estimated to two or three significant digits. Final product numbers were rounded off to only one.

Fire Occurs from Accident and Plutonium Railcar Affected (X2). Based on the Sandia Analysis,[1] an occurrence rate of 0.01 per collision or derailment accident was used for X2, the likelihood of fire affecting the packages in the railcar containing the plutonium shipment. The Sandia analysis considers involvement of flammable cargo and the railcar in the fire. The railcars used for the plutonium shipment are metal walled and have only a minimal combustible loading. Therefore, the source of any significant fire would have to be external to the car containing the plutonium packages. Thus, the value used for X2 is expected to be conservative.

Sufficient Moisture Present to Cause Outer Drum Failure in Fire (X3). The plutonium receivers survey indicated no instances where water was present in the 6M containers. Even if water were present, the outer drum would not fail in a fire due to the limited free volume and the presence of vent holes. Therefore, the value of X3 was assumed to be zero for the 6M evaluation.

Sufficient Moisture, Gas, Present Inside 2R to Cause Failure in Fire (X4). Moisture present inside the 2R could cause the 2R to fail in a fire from excessive pressure buildup. However, there would have to be the equivalent of several hundred grams of water present for creation of sufficient pressure to fail the 2R should it be involved in a fire. Since safeguard procedures require weighings and accountability during the loading operation, the accidental addition of several hundred grams of water could not go undetected. Thus, X4 was set at zero.

Sufficient Moisture Present to Cause 2R Failure by Criticality (X5). The results presented in Appendix C show that no amount of water inside or outside the 2R will make the shipping array critical. Therefore, the value for this element was set at zero.

Criticality Occurs Due to Extreme Deformation in Accident (X6). The conservative analysis reported in Appendix C shows that the array of containers in successive rows are in contact. The data in Appendix D show that the forces required to deform a container to this extent are equivalent to a 260-ft drop onto an unyielding surface. Based on Equation 1 in Section 6, a 260-ft drop is equivalent to a one million pound crush force. As shown in Appendix F, the crush forces produced under the most severe decelerations do not exceed 330,000 lb in any row of containers. Since the accident forces are not sufficient to produce the deformations required for a shipment to become critical, this element was set at zero.

Failure of Inner Container Fails Outer (X7). This element was conservatively set at 1.0 because of its common mode nature.

Accident Impact Forces Exceed Design Strength of Outer Drum (X8). Based on data from Sandia on the impact forces expected in an accident and the threshold failure value for impact, the probability that a container will experience impact forces exceeding its design strength is estimated to be less than 10^{-5} per train accident. A value of 10^{-5} per train accident was used for X8.

Accident Fire Stresses Cause Outer Drum Failure (X9). Fire stresses acting alone cannot fail the outer drum. No conditions which could cause failure, such as moisture in the Celotex[R], were found in the plutonium receivers survey, implying an extremely low probability. A value of zero was assumed for this element.

Accident Crush Forces Exceed Design Strength of Outer Drum (X10). The crush forces required to fail the outer drum exceed those required to remove the drum lid. Therefore, because the drum lid removal event (X17) will occur prior to X10, the value of X10 was set to zero.

Outer Drum Contains Vent Holes (X11). All outer drums contain vent holes to permit gas dissipation. Therefore, this element was set at 1.0.

Transport Accident Generates Puncture Probes (X12). Not all accidents generate puncture probes. Based on data from Sandia,[1] 54.6% of the accidents generate probes. Therefore, the value for X12 is 0.546/accident.

Puncture Probe Strikes Drum (X13). Based on data from Sandia on the puncture environment during an accident,[1] the likelihood that a puncture probe will strike a drum is estimated to be 0.023 per accident in which puncture probes are generated.

Force Which Breached 2R Sufficient to Breach Sample Can (X14). Very high forces are required to breach the 0.25-in. thick 2R container. The additional force required to rupture a sample can is very small in comparison. Thus, a value of 1.0 was used for this element.

Sample Can Fails in Accident Environment (X15). Based on data from Sandia,[(1)] the probability that a sample can will fail if it is not protected from the accident environment by the 2R is estimated to be 0.02 per container exposed to the accident environment.

Puncture Force Equivalent to Drop of ≥133 in. onto a 6-in. Spike (X16). In Appendix D, it is shown that a drop from at least 133 in. onto a 6-in. spike is required to breach the outer drum of the 6M. The drop height is equivalent to a V/R of 106 sec^{-1}. Based on the Sandia results,[(1)] of the puncture probes which strike a container, those with a V/R ≥ 106 sec^{-1} can be expected with a frequency of 0.017 per puncture probe.

Accident Crush Forces Cause Lid Removal (X17). Lid removal requires a total crush force of 72,000 lb. This amount of force will allow sufficient deformation to the 6M to cause the bolt ring to slip off. By using the equation in X10, a value of 9.85 g was found to be the minimum deceleration that would supply 72,000 lb. By use of Figure 5.1, it is found this deceleration or one higher will occur 0.0275 of the time. In Appendix F, it was found that the probability that a certain 6M will be crushed is 0.1339. Combining the probability of occurrence of sufficient deceleration and the probability that the container in question is crushed, the value of X17 is 3.68×10^{-3}/accident.

Container Shipped with Loose Bolt Ring Closure (X18). Based on the survey data presented in Section 7, 12% of all containers had bolt rings which were finger tight upon receipt. A tenth of an inch slack in the bolt ring is enough to make it loose. When this is compared with the 0.23-in. expansion required to remove the bolt ring, the loose ring is not a significant failure mechanism which is likely to remove the lid. However, it could make it easier to dislodge the lid during an accident and would provide an additional pathway for release if the material were free inside the drum. Thus, the value used for X18 was 0.12/container.

Container Shipped with Defective Bolt Ring (X19). Survey results indicate that 2% of the bolt rings fail when they are being tightened. This indicates that some bolt rings will be close to their failure point during a shipment. In this analysis, X19 was set at 0.02 failures/container involved in an accident.

Bolt Ring Fails from Accident Imposed Forces (X20). This element was included in X19. Therefore, it was set at zero here.

Exposed Bolt Ring Fails in Accident (X21). The value of this element was estimated to be 4×10^{-3} bolt ring failures per container involved in an accident. It was estimated on the basis of the solid angle in which a probe must strike a protruding bolt to cause failure.

Bolt Ring Assembled with Bolt Turned Up and Exposed (X22). Based on the plutonium receivers survey, the occurrence rate of the bolt ring turned up during transport is estimated to be 0.05 per container.

Puncture Probe Longer than 11 in. and Force Equal to Drop of 300 in. (X23). Calculations indicate that a drop of greater than 300 in. into a 6-in. diam spike is required to punch the 2R container through the outer drum. This drop is equivalent to a V/R of 160 sec^{-1}. In addition, the probe must be at least 11 in. long and it must strike the outer drum in an area where penetration will result in striking the bottom or top of the 2R vessel. Based on the data presented in Figure 5.4, of the probes with V/R greater than 106 sec^{-1}, 0.76 can be expected to have a V/R greater than 160 sec^{-1}. Use of this factor for X23 would be very conservative because the probes must have both the energy and the length needed to punch the 2R out through the outer drum. Based on the theory of barrier penetration described in the Sandia report,[1] two probes with the same V/R striking the container at the same angle of attack but having different lengths do not have the same puncture capability. The longer probe is more likely to strike the container and ricochet off, converting much of the energy associated with the strike into angular momentum. The theory developed by Sandia states that the acceptance angle of the probe (the angle, between the probe and the normal vector of the surface, below which penetration occurs) is inversely proportional to the length of the probe. The data presented in Figure 5.4 was obtained using a probe with a mean length of 4 in. Since the probe needed to push the 2R through the drum must be at least 11 in. long, the expected frequency of such probes is conservatively assumed to be 4/11 of the frequency of probes used in generating Figure 5.4. Thus, the 0.64 value for meeting the V/R criterion must be reduced by 4/11. The fraction of probes striking the bottom or top of the drum and then striking the 2R is proportional to their relative cross sections = 0.11. Thus, the expected frequency for punching the 2R through the outer drum was set at 0.76 x 4/11 x 0.11, which equals 0.030 per puncture of the outer drum. A value of 0.030 was used for X23.

Crush Forces Sufficient to Cause Rupture of Outer Can by 2R (X24). The characteristics and strengths of crush forces in the accident environment are not such as to force the 2R container through the outer can. Therefore, this element was set at zero.

Outer Container Fails from Mishandling and Not Detected (X25). Based on the plutonium receivers survey, the probability that a container will have an undetected breach during transport is estimated to be 2×10^{-3} per container.

Outer Container Punctured from Object in/or Protruding from Floorboard (X26). No distinction could be made between X25 and X26 from the survey results. Therefore, both events were included under X25 and this element was set at zero.

Dunnage Not Properly Secured During Transport (X27). Of the 775 shipments covered in the plutonium receivers survey, none had improperly secured dunnage. However, because of the limited number of shipments, this does not necessarily mean that the probability of failure in future shipments is zero. Assuming a constant probability of failure, no failures in 775 shipments indicates a failure rate of less than 9×10^{-4} per shipments at the 50% confidence level. The plutonium receivers survey obtained information about shipment mode; however, it is thought that most shipments were made by truck. In the absence of any information to the contrary, it was assumed that improperly secured dunnage would be equally likely in shipment by truck or railcar. A value of 9×10^{-4} per shipment was used for X27.

Lid, Drum Mating Surface Damaged from Handling (X28). The plutonium receivers survey indicated that although some containers showed visible surface damage, no defects were noted in the lid, drum mating surface of approximately 3400 drum-type containers. Assuming a constant probability of damage, no defects in 3400 containers indicates a damage rate of less than 2×10^{-4} per container at the 50% confidence level. A value of 2×10^{-4} per container was used for X28.

6M Shipped in Wrong Orientation (X29). The plutonium receivers survey indicated that of approximately 6200 packages received, none had been shipped in the wrong orientation. Assuming a constant probability of misorientation, no wrong orientations of 6200 containers indicates a misorientation rate of less than 10^{-4} per container at the 50% confidence level. A value of 10^{-4} per container was used for X29.

(X30) and (X31). Not used.

Accident Impact Forces Cause Lid Removal (X32). This element was included in X19. Therefore, it was set at zero here.

Impact Forces from Accident Sufficient to Fail 2R Vessel (X33). As indicated in X8, the probability of failure of the 6M outer drum by impact in an accident is less than 10^{-5} per accident. A significantly greater force level would be required to also fail the 2R vessel by impact. Thus, the probability of 2R vessel failure from impact is essentially zero. This element was set at zero.

Fire Stress from Accident Sufficient to Fail 2R (X34). The material being shipped is stable at high temperatures. Thus, there is insufficient stress generated in a fire to cause failure. For this reason, X34 was set at zero.

Accident Imposed Crush Force Exceeds 2R Design Strength (X35). The maximum crush force experienced by a container will not exceed 330,000 lb (see Appendix F) which will not cause buckling failure of the 2R container. Therefore, X35 was set at zero.

Puncture Probe Strikes 2R Container During an Accident (X36). The evaluation of X36 and X37 parallels the evaluation performed in X23. Only nonbending probes at least 8 in. long can strike the 2R container. Furthermore, the 2R container does not extend the full height of the outer drum of the 6M container. The fraction of the centerline of the outer drum occupied by the 2R is 12.3 in./21.5 in. = 0.57. Since the acceptance angle of the probe decreases linearly with probe length and the puncture data presented in Section 5 is based on a mean probe length of 4 in., half the probes used in generating the data presented in Section 5 cannot be included in an evaluation of 2R puncture. Thus, of the probes failing the outer drum, the expected frequency of strikes at the proper angle for penetration of the 2R (X36) was set at 0.57 x 0.5 = 0.29 per puncture of the outer drum.

Puncture Force Equivalent to Drop of ≥170 in. onto a 6-in. Spike (X37). Based on the data shown in Figure 5.4 of the probes capable of piercing the outer drum (≥ 133 in. drop onto a 6-in. spike, which is equivalent to a V/R = 106 sec^{-1}), 0.92 will have sufficient additional energy to breach the 2R (≥ 170 in. drop onto a 6-in. spike, which is equivalent to a V/R = 121 sec^{-1}). Thus, the expected frequency for X37 was set at 0.92 2R failures per strike of the 2R by a puncture probe.

Accident Imposes Design Level Forces on Threads (X38). Forces on threads are expected to be inward acting and would tend to jam the plug on more tightly rather than remove it. Therefore, this element was set at zero.

Improper Fit Between Male and Female Threads (X39). This element was set at zero. It is included in X42.

Plug Cross Threaded (X40). This element is one possible cause of thread damage. Statistics from the survey are included in X42. This element was set at zero.

Cross Threaded Threads Not Detected (X41). This element was set at zero. It is included in X42.

Threads Damaged from Use or Repair (X42). Based on the plutonium receivers survey and LLD statistics, the occurrence rate of the container having damaged threads during shipment is estimated to be 2×10^{-4} per container.

Poor Threads Not Detected Before Use (X43). The value of this element was set at 1.0 since the value for X42 is based on use of 2R vessels with damaged threads.

Plug Unscrews During Transport (X44). Based on the plutonium receivers survey including LLD statistics, the occurrence rate of the 2R plug unscrewing during transport is estimated to be 4×10^{-4} per container.

2R Leaks When Properly Closed (X45). This event is included in the X46 value. Therefore, its value was set at zero here.

Plug Loosens During Transport (X46). Based on the plutonium receivers survey, the occurrence rate of 2R plugs being loose during transport is 0.2 per container.

Dunnage Fails During Accident (X47). According to the Sandia data,[1] approximately 14% of all accidents result in decelerations greater than five times normal gravity. Since the dunnage is designed only to secure the cargo during normal transport, these decelerations are assumed to cause the dunnage to fail. Thus, the value of 0.14/accident is assigned to this failure element.

Weld Defective (X48). Experience at Battelle-Northwest indicates that about 2 ft of every 100 ft of weld requires repair to meet the quality standards for this type of equipment. Since close to 2 ft of weld is required to attach the bottom to the 2R pipe, a value of 0.04 per container was used for this element.

Q/A Does Not Detect Defective Weld (X49). Inspection, testing and record keeping requirements should make the likelihood of missing a defective weld in quality assurance procedures essentially zero. However, because of limited experience, a conservative value of 10^{-3} per container with defective weld was used for this element.

Defective Weld Cannot Survive Accident Stresses (X50). The 2R vessel is protected from all but the very severe accident stresses by the outer drum and the Celotex[R] insulation. Therefore, the weld should survive accidents less severe than, e.g., puncture of the outer drum (likelihood of less than 10^{-3} per accident). A value of 10^{-3} per defective weld-accident was used for X50.

Q/A Does Not Detect Badly Defective Weld (X51). This element is used in the analysis in combination with element X52, Defective Weld Cannot Survive Normal Transport Stresses. The only normal transport stresses that might affect the weld are minor jostling and vibration. Almost any weld so defective that it would not be able to withstand normal tranport stresses would show obvious defects and could not escape detection by quality assurance procedures. In addition, 10 CFR Part 71, subpart D requires shippers to determine, prior to initial use and each subsequent use, that the packaging has no significant defects. Based on these considerations, a value of zero was assumed for X51.

Defective Weld Cannot Survive Normal Transport Stresses (X52). It was conservatively assumed that the probability of a badly defective weld failing under normal transport stresses was 1.0 per badly defective weld.

(X53) and (X54). Not used.

Sufficient Time for Sample Can to Corrode (X55). The sample can is thin walled. Therefore, it was conservatively assumed that if corrosive material were present, there would be sufficient time during transport for it to corrode through the sample can. A value of 1.0 was used for X55.

Corrosive Material Present Outside 2R (X56). The plutonium receivers survey indicated that of approximately 6200 packages received, none had any significant corrosive material present outside the 2R vessel. Assuming a constant probability for the presence of corrosive material, no occurrences in the shipment of 6200 containers indicates an occurrence rate of less than 10^{-4} per container at the 50% confidence level. A value of 10^{-4} per container was used for X56.

Sufficient Time Available to Corrode 2R (X57). Although there has been some failure of sample cans, possibly due to corrosion, time in transit and material are inadequate to fail the 2R. Therefore, this element was set at zero.

Corrosive Material Present in PuO_2 (X58). The plutonium receivers survey did not specifically indicate any instances where corrosive material was present in the PuO_2. However, it did reveal three instances in the receipt of about 4000 6M and LLD-1 packages in which the sample can was breached or not completely sealed. The cause of the breaches was not determined. Although improper closure is considered the most likely cause of breach, the breaches could have been caused by corrosion. Since in time corrosion could potentially lead to greater consequences (failure of the 2R container) than improper closure of the sample can, for this analysis, the breaches were all assumed to be due to corrosion. Therefore, a probability of 8×10^{-4} was used for X58.

Corrosive Material Inside 2R and Outside Sample Can (X59). In the analysis, it is assumed that there is sufficient time during transport for the thin-walled sample can to corrode through if corrosive material is present. Thus, it makes essentially no difference whether the corrosive material is initially in the PuO_2 or inside the 2R container. The sample can breaches referred to in X58 could have resulted from either internal or external corrosive action. The occurrence probability for this element is included in X58. Therefore, it was set at zero here.

Sample Can Improperly Closed (X60). The sample can failures indicated in the plutonium receivers survey could have been caused by improper closure or corrosion. The occurrence probability for this element is included in X58. Therefore, it was set at zero here.

(X61), (X62) and (X63). Not used.

Gas Generated by Material Present in Can (X64). Based on the plutonium receivers survey using both 6M and LLD statistics, the occurrence rate of excess gas generation in the sample can during transport is estimated to be 5×10^{-4} per container.

Criticality Causes Rupture of Sample Can (X65). If criticality occurs, the sample is assumed to rupture. Therefore, this element was set at 1.0.

Wrong Sample Can Used for Transport (X66). Cans which are too large or too small could be more susceptible to damage during transport. In the survey results, the cause of the sample can damage included under X58 in this evaluation was not ascertained. One reason could have been use of the wrong cans. In this evaluation, the failure data were included under X58 and set at zero here.

Sample Can Damaged Before Loading and Not Corrected (X67). The survey results could not determine the cause of sample can failure. Therefore, the element was included in X58 statistics, and a value of zero was assigned here.

Sharp Object in 2R Container (X68). This event is included in the X58 value. Therefore, its value was set at zero here.

Sample Cans Damaged by 2R Plug Closure (X69). This event is included in the X58 value. Therefore, its value was set at zero here.

Sample Cans Not Properly Packed in 2R (X70). This event is included in the X58 value. Therefore, its value was set at zero here.

Shipping Container Dropped During Transport (X71). This event is included in the X25 value. Therefore, its value was set at zero here.

(X72) and (X73). Not used.

Railcar Not Leak Tight by Design (X74). Most railcars are not designed to be leak tight. Small gaps exist; e.g., at the corners and sides of the doors. The value of X74 is therefore 1.0.

(X75). Not used.

Railcar Overturns (X76). A railcar can only be overturned if derailment occurs in an accident. Based on Sandia's data,[1] 0.969 of rail accidents produce derailment and the likelihood that a derailed railcar will be overturned is about one in four. Therefore, a value of (0.969)(1/4) = 0.242 was used for X76.

(X77), (X78) and (X79). Not used.

Accident Causes Moderate Damage to Railcar (X80). For this study, moderate damage is defined as accident damage which does not result in an opening in the railcar large enough for a container to be thrown out. This event is the complement of event X82, Accident Causes Severe Damage to Railcar. Therefore, a value of 0.955 per accident was used for X82, the likelihood of a particular railcar involved in an accident suffering only moderate damage. The discussion of accident damage to the railcar is given under X82.

(X81). Not used.

Accident Causes Severe Damage to Railcar (X82). For this study, severe damage to the railcar is defined as accident damage which results in an opening in the railcar large enough to permit a container to be thrown out. Sandia[1] presents data on the likelihood of a car being involved in a train accident and the likelihood of a container sized breach, given car involvement in the accident. Since both of these distributed variables are a function of the accident class and the train speed, the mean of the distribution expressing the likelihood of a container sized breach, given car involvement in the accident, cannot be used for X82. Instead the two distributed variables must be multiplied together for each individual accident and velocity class and the results summed. The sum can then be divided by the mean of the distribution describing the likelihood of a railcar being involved in a train accident. The resultant value for the likelihood of a container sized breach in a railcar, given car involvement in the accident, is 0.045. This value has been used for X82. It should be pointed out that the Sandia evaluation of external puncture[1] uses a value of 0.015 for the likelihood that a container will be lost from a railcar given car involvement in an accident. Both values are in agreement since 1/3 of the containers are assumed to be lost given a breach of the railcar.

Container Remains in Severely Damaged Railcar (X83). Sandia's analysis[1] indicates that about two thirds of the containers will remain in a railcar that is severely damaged in an accident. Therefore, a value of 0.667 was used for X83.

Container Loss From Railcar (X84). Sandia's analysis[1] indicates that about one third of the containers will be thrown out of a railcar that is severely damaged in an accident. Therefore, a value of 0.333 was used for X84.

9.1.2 Basic Event Probability for Liquid $Pu(NO_3)_4$ in L-10 Containers

The analysis of the L-10 parallels the 6M evaluation detailed in Section 9.1.1. The list of basic events is shown in Table 8.2. Wherever possible the events have been numbered and titled to be the same as the identical events for the 6M. Rather than repeat the justification for the use of an identical event probability, the reader will be referred to the 6M evaluation.

Accident Occurs (X1). A value of 2.05×10^{-3}/shipment was used for X1. This corresponds to the value used in the 6M analysis.

Fire Occurs in Accident (X2). As in the 6M analysis, a value of 10^{-2} per accident was used for X2, the likelihood that a fire affecting the railcar containing the plutonium shipment will occur.

Sufficient Moisture Present in Vermiculite to Cause Drum Failure in Fire (X3). Vaporization of water in the L-10 outer drum resulting from a fire could cause overpressurization and failure of the drum. The plutonium receivers survey results indicate that the probability of the presence of water is 5×10^{-4} per container. This value was used for X3.

Fire Occurs Somewhere in Train During Accident (X4). A value of 6.57×10^{-2} fires per car involved in a collision or derailment accident was used for X4, fire occurs somewhere in the train during an accident. This value was obtained by multiplying the value for X2 by the ratio of accidents per train mile to accidents per car mile obtained from the Sandia report.[1]

Water/Pu Mix Outside 2R Causing Criticality (X5). Criticality is not possible in a dry L-10 container in which the solution inside the 2R leaks into the outer drum. Criticality is not possible by adding water to the outer drum of the L-10 container as long as plutonium remains in the 2R vessel. However, a narrow envelope of conditions does exist wherein criticality is possible. The conditions require both the addition of some water to the outer drum and the leakage or the presence of plutonium solution out of the 2R vessel. The survey of packaging conditions during transport indicates that the probability of water in the outer drum is 5×10^{-4} per container. Instances of plutonium contamination in the vermiculite have been reported but these involved only trace levels of material. In 2130 plutonium nitrate solution packages received there have been no instances of critically significant quantities of plutonium present in the outer drum. Assuming a constant probability of pressure vessel leakage, no occurrences in 2130 containers received indicates an occurrence rate of less than 3×10^{-4} per container at the 50% confidence level. Therefore, the probability of plutonium and water mixing in the outer drum is less than 2×10^{-7}. Even if it did occur, the probability of such a mixture being in the right proportions to cause criticality is also extremely small. Hence the probability that plutonium and water will mix in the outer drum in the right proportions to cause criticality is essentially zero. For this analysis, X5 was set to zero.

(X6). Not used.

Failure of Inner Container Fails Outer (X7). A value of 1.0 was conservatively used for this element.

Accident Impact Forces Exceed Design Strength of Outer Drum (X8). Based on data from Sandia on the impact forces expected in an accident and the threshold failure value for impact, the probability that a container will experience impact forces exceeding its design strength is estimated to be 10^{-5} per train accident. A value of 10^{-5} per train accident was used for X8.

Accident Fire Stresses Cause Outer Drum Failure (X9). Fire stresses, acting alone, cannot fail the outer drum. Thus, this element was set at zero.

Accident Crush Forces Exceed Design Strength of Outer Drum (X10). The crush forces required to fail the outer drum exceed those required to remove the drum lid. Therefore, since the drum lid removal event, X17, will occur prior to X10, the value of X10 was set to zero.

Outer Drum Contains Vent Holes (X11). Vent holes are provided in all containers to aid in moisture removal. Thus, this element was set at 1.0.

Transport Accident Generates Puncture Probes (X12). As in the 6M analysis, the expected frequency of having puncture probes present is 0.546/accident.

Puncture Probe Strikes Drum (X13). As in the 6M analysis, the expected frequency with which a puncture probe will strike a container is 0.023/accident involving a puncture environment.

Container Remains in Moderately Damaged Railcar (X14). This element is used in the fault tree in combination with element X80, Accident Causes Moderate Damage to Railcar. For this analysis moderate damage was defined as damage not severe enough to permit loss of a container from the railcar. Therefore, a value of 1.0 was used for X14.

2R Punctured by Probe Failing Outer Drum (X15). Based on the results presented in Appendix D, a drop of 100 in. onto a 6-in. diameter spike could potentially fail the 2R container in the L-10. This corresponds to a V/R of 92 sec^{-1}. Based on the results shown in Figure 5.4, of the probes breaching the outer drum (V/R = 60 sec^{-1}) the expected frequency of probes with V/R $\geq$ 92 sec^{-1} is 0.83. Two additional factors must be included in the analysis. First, the probe must be long enough to breach the outer drum and strike the 2R container. Second, the probe must pierce that fraction of the centerline of the outer drum cylinder which is occupied by the 2R.

Based on the penetration theory developed by Sandia,(1) two probes with the same V/R striking the container at the same angle of incidence but having different lengths do not have the same puncture capability. The longer probe is more likely to strike the container and ricochet off, converting much of the energy associated with the strike into angular momentum. The Sandia theory states that the acceptance angle of a probe (the angle, between the probe and the normal vector to the surface, below which penetration occurs) is inversely proportional to the length of the probe. The data presented in Figure 5.4 was obtained using a probe with a mean length of 4 in. To strike the centerline it must be 12 in. long. The 12-in. long probe with a V/R in excess of 60 sec^{-1}, striking the outer drum, will penetrate with a frequency 1/3 that of the probes used in generating Figure 5.4. Thus, the 0.83 value for meeting the V/R criterion must be reduced by 1/3. The fraction of probes piercing the centerline of the drum in the region occupied by the 2R pressure vessel is proportional to their relative heights; i.e., 52 in./69 in. When this factor is included, the expected frequency of 2R failure by puncture is 0.21 per puncture of the outer drum.

Puncture Force Equivalent to Drop of $\geq$ 42 in. onto 6-in. Spike (X16). Based on the analysis in Appendix D, the outer drum of the L-10 could be punctured by a drop of 42 in. onto a 6-in. spike. This corresponds to a V/R of 60 sec^{-1}. Based on puncture probe data shown in Figure 5.4, failure of the outer drum will occur with an expected frequency of 0.022 per container struck with a puncture probe.

Accident Crush Forces Cause Lid Removal (X17). The amount of crush force needed to remove the lid is 53,100 lb total force. The minimum deceleration that will produce this level of force, given a fully loaded railcar, is 8.51 g. From Figure 5.1 the probability of occurrence of a deceleration of 8.51 or higher is 0.036. The likelihood that a particular container will fail in crush is shown, in Appendix F, to be 0.150. Therefore, the value for X17 used in the analysis is 5.4×10^{-3}/accident.

Container Shipped with Loose Bolt Ring Closure (X18). The plutonium receivers survey indicated no instances in the receipt of 2130 L-3 and L-10 containers where the bolt ring closure was loose. Assuming a constant probability of occurrence, no loose bolt ring closures in the shipment of 2130 containers indicates an occurrence rate of less than 3×10^{-4} per container at the 50% confidence level. A value of 3×10^{-4} per container was used for X18.

Container Shipped with Defective Bolt Ring (X19). Based on the plutonium receivers survey including the 6M statistics, the occurrence rate for a container with a defective bolt ring was estimated to be 0.02/container.

Bolt Ring Fails from Accident Imposed Forces (X20). Included in X19 for the reasons given in the 6M evaluation.

Exposed Bolt Ring Failed in Accident (X21). This value was estimated to be 3×10^{-3} bolt ring failures per container involved in an accident. It was estimated on the basis of the solid angle in which a probe must strike a protruding bolt to cause failure.

Bolt Ring Assembled with Bolt Turned Up and Exposed (X22). Based on the plutonium receivers survey, the occurrence rate for a container being assembled with an exposed bolt ring is estimated to be 2×10^{-2} per container.

(X23). Not used.

Crush Forces Sufficient to Cause Rupture of Outer Can by 2R (X24). Other failure modes, such as lid removal (X17), occur at a lower threshold than this element. Therefore, this element does not affect the analysis, and its value was set at zero.

Outer Container Fails from Mishandling and Not Detected (X25). Based on the plutonium receivers survey including the 6M statistics, the occurrence rate of shipping an L-10 container with a failed drum is estimated to be 2×10^{-3} per container.

Outer Container Punctured from Object in/or Protruding from Floor (X26). Included in X25 because the survey did not determine actual causes of failures reported under X25. Therefore, this element was set at zero.

Dunnage Not Properly Secured During Transport (X27). As in the 6M evaluation, a value of 9×10^{-4} per shipment was used for X27.

Lid, Drum Mating Surfaces Damaged from Handling (X28). Based on the survey of plutonium receivers, although some containers showed visible surface damage, no defects in the lid, drum mating surfaces were noted.

As in the 6M evaluation, because of the limited number of containers surveyed, a value of 2×10^{-4} per container was used for X28.

Can Shipped in Wrong Orientation (X29). As in the 6M evaluation, a value of 10^{-4} per container was used for X29.

(X30). Not used.

Containers Deformed Enough to be Critical (X31). As shown in appendices C and F, forces in the rail accident environment are insufficient to deform the array of containers enough to cause criticality. Therefore, a value of zero was used for X31.

Accident Impact Forces Cause Lid Removal (X32). This element was included in X8. Therefore, it was set at zero here.

2R Tube Defective and Not Detected (X33). Shippers are required to make certain Q/A determinations on the packages prior to each use. These include determination that the containment ability of the 2R pressure vessel under the normal maximum operating pressure is adequate and determination that the package has not been significantly damaged. These checks will detect any pressure vessel so defective that it would release its contents under normal transport conditions. Therefore, a value of zero was used for X33.

(X34). Not used.

Flange Not Leak Tight (X35). Based on the plutonium receivers survey, the occurrence rate of gaskets being left out or otherwise not leak tight is estimated to be 10^{-3} per container.

Test Fails to Detect Leaky Flange (X36). This element was set at 1.0 since data in X35 is based on tested containers.

Valve Not Leak Tight (X37). Based on the plutonium receivers study, the occurrence rate of an open vent valve during shipment is estimated to be 8×10^{-3} per container.

Cap Not Leak Tight or Is Off (X38). Based on the plutonium receivers survey, the occurrence rate of the cap being left off or being loose upon receipt is estimated to be 8×10^{-3} per container.

Bottle Seam Ruptures (X39). In the experience of the plutonium receivers there were a few instances where the bottle had apparently failed during transport. These are included in the Plutonium Solution Outside Plastic Bag category in Table 7.2. However, no information was obtained on how the plutonium got outside the bottle. Therefore, this element was set at zero and all failures included in X41.

Bottle Overfilled (X40). For the reasons given under X39, this element was set at zero and all failures included in X41.

Solution Spills from Excessive Vibration (X41). Based on the survey results, the expected frequency of plutonium solution outside the plastic bag is 0.005/container. This value was used for the combination of X39 through X42.

Cap Does Not Vent Gas Produced (X42). Included in the X41 occurrence rate. Therefore, the value was set at zero here.

Bottle Fails in Accident (X43). The value for this element was conservatively assumed to be 1.0.

Excessive Temperature Generated by Solution (X44). Temperatures inside the container are nominal so long as no external heat source is added. Therefore, this element was set at zero.

Air Gap Exists Due to Accident (X45). Based on the plutonium receivers survey, the occurrence rate of an air gap existing above the 2R during shipment as a result of the vermiculite bags being left out is estimated to be 10^{-3} per container. This void space is enough to uncover the 2R after an accident has changed the orientation of the drum.

Vermiculite 6-12 in. Low During Shipment (X46). Based on the plutonium receivers study, the occurrence rate of containers being transported with vermiculite low in the drum is estimated to be 0.09 per container.

Dunnage Fails During Accident (X47). As in the 6M evaluation, a value of 0.14/accident was used.

Weld Defective (X48). A value of 0.02 per container was used for this element for the reasons given in the 6M evaluation.

Q/A Does Not Detect Defective Weld (X49). A value of 10^{-3} per container with defective weld was used for this element for the reasons given in the 6M evaluation.

Defective Weld Cannot Survive Accident Stresses (X50). Due to the protection of the pressure vessel by the outer drum and the low probability of a severe accident environment, a value of 10^{-3} per defective weld accident can be used for X50 as was done in the 6M evaluation.

Defective Weld Cannot Survive Normal Transport Stresses (X52). A value of 1.0 was used for this element for the reasons given in the 6M evaluation.

(X53 through X55). Not used.

1850°F Fire with Duration Greater than 6 Minutes (X56). The thermal analysis presented in Appendix E shows that a 1475°F fire, imposed directly on the 2R pressure vessel container could be expected to cause failure in 6 minutes. The 2R is attached to a bird cage inside the outer drum. Thus even in an accident in which all the vermiculite is lost the 2R sees the fire through an intermediate surface. The radiant heat flux on the 2R is reduced to about half its normal value when there is one radiative surface between the fire and the 2R. Therefore, failure would be expected in about 12 minutes when the L-10 is exposed to a 1475°F fire and the presence of the outer drum is considered. However, Sandia[1] found that the fire environment could be better represented by an 1850°F average fire temperature. The radiant heat flux from an 1850°F fire is double that from a 1475°F fire. Therefore, the factor of two gained by accounting for the intervening surface is lost due to the higher fire temperature. Hence, a 2R failure in an 1850°F fire can be expected in 6 minutes. Based on the fire duration curve described in Section 5, the frequency of occurrence of fires lasting longer than 6 minutes is 0.97 per accident involving fire.

1850°F Fire with Duration Greater than 18 Minutes (X57). Using X56 as a base point, if the container is in the railcar, then there is yet another intervening surface between the 2R and the fire. If two intervening surfaces are placed between the 2R and the fire, the heat flux is reduced by about a factor of three. Since the container is in the car, some of the vermiculite is likely to remain in the failed outer drum. When only half the vermiculite is lost, then only half the 2R sees the thermal flux. Thus, in a 1475°F fire, failure would be expected in 36 minutes. In the 1850°F fire environment, failure would be expected in 18 minutes. The Sandia curve presented in Section 5 shows that the frequency of occurrence of fires lasting longer than 18 minutes is 0.79 per accident involving fire.

1850°F Fire with Duration Greater than 60 Minutes (X58). This element considers an 1850°F fire on a container where the loose vermiculite is 6-12 in. low and the vermiculite bags have been left out of the container. When this occurs, approximately 10% of the surface area of the 2R container could see thermal radiation even when the outer drum has not been breached. Since only 10% of the 2R sees the thermal radiation, the time to failure is 10 times longer than X56. Based on the Sandia fire environment data, presented in Section 5, the likelihood of a fire lasting longer than 60 minutes is 0.21 per accident involving fire.

1850°F Fire with Duration Greater than 90 Minutes (X59). This element parallels X58 but considers the case where a container with low vermiculite remains in the railcar for the duration of the fire. In this case the 2R sees the fire through two reradiating surfaces. For X58 the outer surface was the only reradiating surface between the fire and the 2R. Since one intervening surface reduces the radiant heat flux by a factor of about two and two intervening surfaces reduce the radiant heat flux by a factor of about three, the time to failure for containers inside the railcar is 3/2 of the value for containers outside. Thus the time to failure for containers with low vermiculite, remaining in the railcar,is estimated to be about 90 minutes. Based on the Sandia fire environment data presented in Section 5, the frequency of occurrence of fires lasting longer than 90 minutes is estimated to be 0.14 per accident involving fire.

Bolts Failed from Accident Stresses (X60). Accident stresses to which the 2R container may be exposed are not severe enough to cause bolt failure. Therefore, this element was assumed to have a value of zero.

Valve Broken by Puncture Probe in Accident (X61). The valve can be broken by a puncture probe. The analysis parallels that used to obtain a value for X15. The only difference is that the valve area occupies about 3 in. of the total container height of 69 in. Valve failure by puncture can be expected to occur with a frequency of 0.012 breaks per puncture probe failing outer container.

2R Fails from Excessive Crush (X62). This element was set at zero since, as discussed in Appendix F, crush forces are insufficient to deform the drum enough to contact 2R.

Container Inside (X63). This event occurs in the fault tree in combination with event X74, Railcar Not Leak Tight by Design. It is used to identify where the container is located when the railcar is intact. Therefore, a value of 1.0 was used for X63.

Procedural Error Allows Shipment Without Venting (X64). This element and elements X65, X66, X72 and X73 are causative events which could contribute to, or result in, failure of the pressure vessel from overpressurization. Although the plutonium receivers survey indicated that no vessels have failed from overpressurization, the survey gave essentially no information on the occurrence frequency of these causative events. The packaging condition and quality verifications that are required prior to each use of an L-10 shipping container, would appear to make the possibility of occurrence of failure by overpressurization due to these events negligible. Accordingly, a zero value was used in the analysis for element X64 and for each of the elements X65, X66, X72 and X73. However, since the above reasoning is not demonstrative of the impossibility of nonzero values, sensitivity cases were run to determine the effect on the risk of non-zero values for these elements. The results of the sensitivity studies are given in Section 11.4.

Shipment of Year-Old Pu Containing Bottles Permitted (X65). This element was set at zero for the analysis. See discussion for element X64.

2R Valve Closed During Aging Process (X66). This element was set at zero for the analysis. See discussion for element X64.

Sufficient Time Elapsed to Form Explosive Gas Mixture (X67). This element was conservatively set at 1.0.

Excessive Localized Temperature Experienced During Transport (X68). There are no excessive localized temperature sources encountered during normal transport. Therefore, this element was set at zero.

9.2 BARRIER RELEASE SEQUENCE PROBABILITIES

The Basic Event Probabilities in Section 9.1 provide the data necessary to calculate the frequency of any event sequence. Only event sequences which lead to a release are of interest. In this section, attention is directed at the identification of Barrier Release Sequence Probabilities which will ultimately be used to obtain (system) release sequence probabilities. For plutonium shipping, a release can occur only after four barriers are breached. These are the railcar, the outer container, the 2R containment vessel and the bottle or sample can. The lists of basic events which breach individual barriers are formulated as discussed in Section 8. Tables 9.1 and 9.2 show the lists of barrier release sequences and associated occurrence frequencies developed for the 6M and L-10 shipments. The occurrence frequencies were obtained from Section 9.1.

The probability data shown in Tables 9.1 and 9.2 have not been multiplied together to obtain barrier failure probabilities. This is not a useful intermediate number because there are common elements which act on all the barriers simultaneously and must not be multiply-counted (see Section 8.3). Since the final goal is to evaluate release sequences, which are obtained by permuting the barrier release sequence lists, the probabilities will be calculated after the elements in a release sequence have been identified and duplicates eliminated.

TABLE 9.1. Summary of Barrier Release Sequences and Basic Element Occurrence Frequencies Used in the Evaluation of Plutonium Dioxide Shipments in the 6M Container

Barrier Release Sequences	Basic Element Frequencies						
SAMPLE CAN							
X064	5.000E-04	0.	0.	0.	0.	0.	0.
A051	8.000E-04	0.	0.	0.	0.	0.	0.
X001 X014 X036 X037 A013	2.050E-03	1.000E+00	2.900E-01	9.200E-01	2.135E-04	0.	0.
X001 X015 X029 X044 A019	2.050E-03	2.000E-02	1.000E-04	4.000E-04	2.000E-02	0.	0.
X001 X015 X027 X044 A019	2.050E-03	2.000E-02	9.000E-04	4.000E-04	2.000E-02	0.	0.
X001 X015 X044 X047 A019	2.050E-03	2.000E-02	4.000E-04	9.000E-02	2.000E-02	0.	0.
X001 X015 X044 X076 A019	2.050E-03	2.000E-02	4.000E-04	2.420E-01	2.000E-02	0.	0.
X001 X015 X029 X044 A020	2.050E-03	2.000E-02	1.000E-04	4.000E-04	2.000E-04	0.	0.
X001 X015 X027 X044 A020	2.050E-03	2.000E-02	9.000E-04	4.000E-04	2.000E-04	0.	0.
X001 X015 X044 X047 A020	2.050E-03	2.000E-02	4.000E-04	9.000E-02	2.000E-04	0.	0.
X001 X015 X044 X076 A020	2.050E-03	2.000E-02	4.000E-04	2.420E-01	4.000E-04	0.	0.
2R							
X029 X046	1.000E-04	2.000E-01	0.	0.	0.	0.	0.
X029 X044	1.000E-04	4.000E-04	0.	0.	0.	0.	0.
X027 X046	9.000E-04	2.000E-01	0.	0.	0.	0.	0.
X027 X044	9.000E-04	4.000E-04	0.	0.	0.	0.	0.
X001 X048 X049 X050	2.050E-03	2.000E-02	1.000E-03	1.000E-03	0.	0.	0.
X001 X036 X037 A013	2.050E-03	2.900E-01	9.200E-01	2.135E-04	0.	0.	0.
X001 X046 X047	2.050E-03	2.000E-01	9.000E-02	0.	0.	0.	0.
X001 X046 X076	2.050E-03	2.000E-01	2.420E-01	0.	0.	0.	0.
X001 X044 X047	2.050E-03	4.000E-04	9.000E-02	0.	0.	0.	0.
X001 X044 X076	2.050E-03	4.000E-04	2.420E-01	0.	0.	0.	0.
OUTER DRUM							
A014	2.000E-03	0.	0.	0.	0.	0.	0.
X011 X029	1.000E+00	1.000E-04	0.	0.	0.	0.	0.
A017 X029	1.202E-01	1.000E-04	0.	0.	0.	0.	0.
X011 X027	1.000E+00	9.000E-04	0.	0.	0.	0.	0.
A017 X027	1.202E-01	9.000E-04	0.	0.	0.	0.	0.
X001 A013	2.050E-03	2.135E-04	0.	0.	0.	0.	0.
X001 X008	2.050E-03	1.000E-05	0.	0.	0.	0.	0.
X001 X023 A013	2.050E-03	3.000E-02	2.135E-04	0.	0.	0.	0.
X001 X011 X047	2.050E-03	1.000E+00	9.000E-02	0.	0.	0.	0.
X001 A017 X047	2.050E-03	1.202E-01	9.000E-02	0.	0.	0.	0.
X001 X011 X076	2.050E-03	1.000E+00	2.420E-01	0.	0	0.	0.
X001 X076 A017	2.050E-03	2.420E-01	1.202E-01	0.	0.	0.	0.
X001 X029 A019	2.050E-03	1.000E-04	2.000E-02	0.	0.	0.	0.
X001 X027 A019	2.050E-03	9.000E-04	2.000E-02	0.	0.	0.	0.
X001 X047 A019	2.050E-03	9.000E-02	2.000E-02	0.	0.	0.	0.
X001 X076 A019	2.050E-03	2.420E-01	2.000E-02	0.	0.	0.	0.
X001 X017	2.050E-03	3.680E-03	0.	0.	0.	0.	0.
X001 X029 A020	2.050E-03	1.000E-04	2.000E-04	0.	0.	0.	0.
X001 X027 A020	2.050E-03	9.000E-04	2.000E-04	0.	0.	0.	0.
X001 X047 A020	2.050E-03	9.000E-02	2.000E-04	0.	0.	0.	0.
X001 X076 A020	2.050E-03	2.420E-01	2.000E-04	0.	0.	0.	0.
RAILCAR							
X074	1.000E+00	0.	0.	0.	0.	0.	0.
X001 X082 X084	2.050E-03	4.500E-02	3.330E-01	0.	0.	0.	0.
X001 X082 X083	2.050E-03	4.500E-02	6.670E-01	0.	0.	0.	0.
X001 X080	2.050E-03	9.550E-01	0.	0.	0.	0.	0.

TABLE 9.2. Summary of Barrier Release Sequences and Basic Element Occurrence Frequencies Used in Evaluation of Liquid Plutonium Nitrate Shipments in the L-10 Container

Barrier Release Sequences	Basic Element Frequencies					
INNER							
X001 X043	2.050E-03	1.000E+00	0.	0.	0.	0.	0.
A021	5.000E-03	0.	0.	0.	0.	0.	0.
2R							
A058	0.	0.	0.	0.	0.	0.	0.
A062	0.	0.	0.	0.	0.	0.	0.
X001 X048 X049 X050	2.050E-03	2.000E-02	1.000E-03	1.000E-03	0.	0.	0.
X048 X051 X052	2.000E-02	0.	1.000E+00	0.	0.	0.	0.
X027 X035 X036	9.000E-04	1.000E-03	1.000E+00	0.	0.	0.	0.
X029 X035 X036	1.000E-04	1.000E-03	1.000E+00	0.	0.	0.	0.
X027 X037 X038	9.000E-04	8.000E-03	8.000E-03	0.	0.	0.	0.
X029 X037 X038	1.000E-04	8.000E-03	8.000E-03	0.	0.	0.	0.
X001 X015 A013	2.050E-03	2.100E-01	2.760E-04	0.	0.	0.	0.
X001 X061 A013	2.050E-03	1.100E-02	2.760E-04	0.	0.	0.	0.
X001 X004 X075 X084	2.050E-03	6.570E-02	5.000E-03	3.333E-01	0.	0.	0.
X001 X002 X046 X059 X083	2.050E-03	1.000E-02	9.000E-02	1.400E-01	6.666E-01	0.	0.
X001 X004 X045 X046 X058 X084	2.050E-03	6.570E-02	1.000E-03	9.000E-02	2.100E-01	3.333E-01	0.
X001 X047 X035 X036	2.050E-03	9.000E-02	1.000E-03	1.000E+00	0.	0.	0.
X001 X047 X037 X038	2.050E-03	9.000E-02	8.000E-03	8.000E-03	0.	0.	0.
X001 X076 X035 X036	2.050E-03	2.420E-01	1.000E-03	1.000E+00	0.	0.	0.
X001 X076 X037 X038	2.050E-03	2.420E-01	8.000E-03	8.000E-03	0.	0.	0.
X001 X002 A018 X057 X083 X029	2.050E-03	1.000E-02	2.000E-02	7.900E-01	6.666E-01	1.000E-04	0.
X001 X002 X017 X057 X083	2.050E-03	1.000E-02	5.400E-03	7.900E-01	6.666E-01	0.	0.
X001 X002 A013 X057 X083	2.050E-03	1.000E-02	2.760E-04	7.900E-01	6.666E-01	0.	0.
X001 X004 A018 X056 X084	2.050E-03	6.570E-02	2.000E-02	9.700E-01	3.333E-01	0.	0.
X001 X004 X017 X056 X084	2.050E-03	6.570E-02	5.400E-03	9.700E-01	3.333E-01	0.	0.
X001 X002 X008 X057 X083	2.050E-03	1.000E-02	1.000E-05	7.900E-01	6.666E-01	0.	0.
X001 X004 A013 X056 X084	2.050E-03	6.570E-02	2.760E-04	9.700E-01	3.333E-01	0.	0.
X001 X004 X008 X056 X084	2.050E-03	6.570E-02	1.000E-05	9.700E-01	3.333E-01	0.	0.
X001 X002 A018 X057 X083 X027	2.050E-03	1.000E-02	2.000E-02	7.900E-01	6.666E-01	9.000E-04	0.
X001 X002 A018 X057 X083 X076	2.050E-03	1.000E-02	2.000E-02	7.900E-01	6.666E-01	2.420E-01	0.
X001 X002 A018 X057 X083 X047	2.050E-03	1.000E-02	2.000E-02	7.900E-01	6.666E-01	9.000E-02	0.
X001 X002 X046 X059 X014	2.050E-03	1.000E-02	9.000E-02	1.400E-01	1.000E+00	0.	0.
X001 X002 X017 X057 X014	2.050E-03	1.000E-02	5.400E-03	7.900E-01	1.000E+00	0.	0.
X001 X002 A013 X057 X014	2.050E-03	1.000E-02	2.760E-04	7.900E-01	1.000E+00	0.	0.
X001 X002 X008 X057 X014	2.050E-03	1.000E-02	1.000E-05	7.900E-01	1.000E+00	0.	0.
X001 X002 X029 A018 X057 X014	2.050E-03	1.000E-02	1.000E-04	2.000E-02	7.900E-01	1.000E+00	0.
X001 X002 X027 A018 X057 X014	2.050E-03	1.000E-02	9.000E-04	2.000E-02	7.900E-01	1.000E+00	0.
X001 X002 X047 A018 X057 X014	2.050E-03	1.000E-02	9.000E-02	2.000E-02	7.900E-01	1.000E+00	0.
X001 X002 X076 A018 X057 X014	2.050E-03	1.000E-02	2.420E-01	2.000E-02	7.900E-01	1.000E+00	0.
OUTER DRUM							
A014	2.000E-03	0.	0.	0.	0.	0.	0.
X029 X011	1.000E-04	1.000E+00	0.	0.	0.	0.	0.
X029 A017	1.000E-04	5.000E-04	0.	0.	0.	0.	0.
X027 X011	9.000E-04	1.000E+00	0.	0.	0.	0.	0.
X027 A017	9.000E-04	5.000E-04	0.	0.	0.	0.	0.
X001 A018 X027	2.050E-03	2.000E-02	9.000E-04	0.	0.	0.	0.
X001 X017	2.050E-03	5.400E-03	0.	0.	0.	0.	0.
X001 X008	2.050E-03	1.000E-05	0.	0.	0.	0.	0.
X001 X011 X047	2.050E-03	1.000E+00	9.000E-02	0.	0.	0.	0.
X001 X047 A017	2.050E-03	9.000E-02	5.000E-04	0.	0.	0.	0.
X001 X011 X076	2.050E-03	1.000E+00	2.420E-01	0.	0.	0.	0.
X001 X076 A017	2.050E-03	2.420E-01	5.000E-04	0.	0.	0.	0.
X001 A013	2.050E-03	2.760E-04	0.	0.	0.	0.	0.
X001 X002 X003	2.050E-03	1.000E-02	5.000E-04	0.	0.	0.	0.
X007 A058	1.000E+00	0.	0.	0.	0.	0.	0.
X007 A062	1.000E+00	0.	0.	0.	0.	0.	0.
X001 X004 X007 X075 X084	2.050E-03	6.570E-02	1.000E+00	5.000E-03	3.333E-01	0.	0.
X001 X002 X007 X046 X059 X083	2.050E-03	1.000E-02	1.000E+00	9.000E-02	1.400E-01	6.666E-01	0.
X001 X004 X007 X045 X046 X058 X084	2.050E-03	6.570E-02	1.000E+00	1.000E-03	9.000E-02	2.100E-01	3.333E-01
X001 A018 X029	2.050E-03	2.000E-02	1.000E-04	0.	0.	0.	0.
X001 A018 X047	2.050E-03	2.000E-02	9.000E-02	0.	0.	0.	0.
X001 A018 X076	2.050E-03	2.000E-02	2.420E-01	0.	0.	0.	0.
X001 X002 X046 X059 X014 X067	2.050E-03	1.000E-02	9.000E-02	1.400E-01	1.000E+00	1.000E+00	0.
RAILCAR							
X063 X074	1.000E+00	1.000E+00	0.	0.	0.	0.	0.
X001 X082 X083	2.050E-03	4.500E-02	6.666E-01	0.	0.	0.	0.
X001 X082 X084	2.050E-03	4.500E-02	3.333E-01	0.	0.	0.	0.
X001 X014 X080	2.050E-03	1.000E+00	9.550E-01	0.	0.	0.	0.

9.3 RELEASE FRACTIONS

The barrier release sequence concept also provides a convenient way to evaluate release fractions. In this subsection, release fractions will be selected for each event sequence capable of breaching a barrier (i.e., each barrier release sequence). The release fraction given for a barrier is developed on the basis that it is the only barrier which contains the plutonium. The (system) release fraction is then obtained as the product of barrier release fractions. (In selecting barrier release fractions for the analysis, conservatism was a major consideration.)

The following paragraphs present the release fraction used in the analysis when a given barrier is breached. A brief rationale for the estimate is also given. Release fractions for PuO_2 powder shipments are given first, followed by those for $Pu(NO_3)_4$ solution shipments.

9.3.1 Barrier Release Fractions for the 6M Containing PuO_2 Powder

The four barriers for this shipping system are the steel sample cans, the 2R inner vessel, the outer drum, and the railcar.

Sample Cans

The steel can containing the dioxide powder is not considered an effective barrier. If the can is defective, all the material in the can is potentially available for release. Since there are two cans in the 2R container, the release fraction for all can failures from closure errors or defects is conservatively assumed to be 0.5. The fraction released for failures from accident forces is assumed to be 1.0.

2R Vessel

Two types of failures of the 2R vessel can be postulated. One is the loose cap. Assuming that all material is free inside the 2R and the cap is loose, it is still necessary for the material to work its way past the cap threads. With the plug half unscrewed, there are assumed to be five full turns remaining threaded.* For this condition, a fractional release from the barrier of 10^{-6} of the total 2R contents was used in the analysis.

The second failure mode of the 2R is a failure either because the cap is completely unscrewed or because the 2R is breached in an accident. If the 2R is open and the container is on its side, or if the bottom weld fails in an accident, then the fraction released is assumed to be 1.0. Otherwise the fraction released is assumed to be 0.5.

Outer Drum

The outer drum represents a less effective barrier than the 2R. If the drum is breached by lid removal and the drum is on its side, or if it is breached by impact, all material is assumed to be released from the drum. If it is punctured, the fraction released assumed to be 0.5 through the outer drum. If the outer drum is not extensively damaged, then the powder must work its way past the Celotex[R] and through a vent hole or some other small opening in the drum. No more than a few grams of material should be released in this matter. Thus, a release fraction of 10^{-3} has been selected for this latter condition.

Railcar

Although not airtight, the railcar can be a reasonably effective containment barrier for internally released plutonium provided that it is not extensively damaged in an accident. It is assumed that material is released into the air inside the railcar. Studies indicate that 0.01 g PuO_2/m^3 (Reference 2) to 0.1 g PuO_2/m^3 (Reference 3) can remain suspended in air for several hours. For conservatism the latter value was used in the analysis. A railcar has a volume of 140 m^3. Thus it could contain up to 14 g of plutonium in the car air. Assuming that the railcar is only slightly damaged, the air in the car will very gradually exchange with the outside air. The plutonium will diffuse out with the exchanging air. Thus the presence of the railcar reduces the total fraction available for release to that in the railcar atmosphere, which is approximately 5×10^{-3} of the

* Requirements for specification 2R containers are that only five threads have to be engaged when the plug is fully tightened. However, containers examined in this study had at least ten threads engaged when the plug was fully seated.

total amount in any container. In releases not involving an accident, this release fraction is further reduced by a factor of 100 because of the absence of any strong mechanism for making the material airborne in the railcar's atmosphere.

If the container is lost from the railcar, a release fraction of 1.0 is used. A value of 1.0 is also used when a significant breach is opened in the railcar even though the container remains in the car.

9.3.2 Barrier Release Fractions for the L-10 Containing Liquid $Pu(NO_3)_4$

The four barriers for this shipping system are the polyethylene sample bottle, the 2R inner vessel, the outer drum, and the railcar.

Sample Bottle

In the accident environment the sample bottle is not considered to be an effective barrier, therefore, a release fraction of 1.0 is used for these cases. If the sample bottle is defective, or overfilled, a release fraction of 0.1 is used. This is considered to be conservative since most sample bottle leakages are through or around the cap and are much smaller than 10%.

2R Pressure Vessel

The 2R pressure vessel is considered to be the main barrier controlling the release of plutonium nitrate. The release fraction for the 2R vessel is a function of the vessel orientation relative to the location of the breach and the duration of the release. The release fraction estimates have been subdivided into fire and no-fire release categories.

Nearly all releases in the no-fire category are dependent on orientation. For sequences where the closure assembly leaks and the container is shipped upside down, a release fraction of 1.0 is used. If the bottom weld on the 2R is defective and the container is upright, a release fraction of 1.0 is also used. Internal pressurization will cause leakage through the closure which will stop when the pressure is sufficiently relieved. Whether the leakage is in the gas phase or in the liquid phase depends on the orientation of the container. A 0.1 release fraction is conservatively used for this release mechanism for any orientation. When the vessel is on its side, the release fraction is very dependent on the relationship of the leak path to the level of the liquid. The amount released varies randomly from 0 to 1.0 with a mean of 0.5. For all of the other postulated no-fire breaches of the 2R vessel, a release fraction of 0.5 is used. This includes the 2R punctured sequence.

The release fractions for the fire cases are a function of orientation and fire duration. For release sequences where the container remains upright and the solution is boiled off, the release fraction is estimated to be 2.0×10^{-3}. This value was derived from experiments summarized in Appendix C of the truck shipment report.(4) For the cases where orientation is lost, liquid is present in the flange region, the material released in a fire would be expected to be a flashing two phase liquid. For fires that last long enough to evaporate the entire contents of the 2R, the release fraction would be 1.0. However, if the fire is put out before the solution can be completely evaporated then the release fraction would be reduced accordingly.

Based on an enthalpy balance, heating the solution to 610°F under pressure represents about 45% of the energy required to cause complete vaporization of water and nitrates. Assuming that the rate of energy input to the container is approximately constant for the entire accident results in the conclusion that a container which begins releasing material after 6 minutes will have released all the material in approximately 13 minutes. Based on the fire duration curve presented in Section 5, 85% of all fires last longer that 13 minutes. These fires represent 0.85/0.967 or 88% of the fires which last long enough to cause a release. Thus, 88% of all fires which last 6 minutes will release all the material. Since fires with a duration between 6 and 13 minutes are postulated to release only part of the solution, 12% of all fires which release some material release only part. When the partial releases are included in the release fraction estimate, the mean release fraction for a fire lasting longer than 6 minutes is 0.6. Use of the same procedure yields a release fraction of about 0.3 for any releases which are initiated from fires lasting longer than 18 minutes.

Outer Drum

The effectiveness of the outer drum is mainly a function of the degree of damage incurred by this barrier. Since orientation effects were included in the 2R release fraction estimates, they are not considered again for this barrier. Two cases are considered: 1) the material does not have to pass through vermiculite in order to be released, and 2) the release path is through vermiculite. For the first case, if the drum has a major breach (e.g., lid removed) a release fraction of 1.0 is used. If the drum has a smaller breach (e.g., puncture) a release fraction of 0.5 is used.

In the second case, some credit is taken for deposition on the vermiculite in the drum. Based on experiments with vermiculite as an air filter media,[5] approximately 50% of any respirable dust particles are removed by an 8-in. vermiculite filter bed. In releases where the liquid is jetted out of the 2R as a result of a fire, at least 90% of the particles are larger than 10 μ and would quickly deposit out on any contacted surface. Thus, it is conservative to assume that the fraction of the material released from the outer drum is less than 0.05. For nonfire-driven releases the release fraction can be expected to be even smaller. A value of 0.005 was used as a release fraction for a nonfire release through vermiculite.

Railcar

The railcar was not assumed to be as effective a barrier for liquid nitrate spills as it was for oxide powder. Nitric acid solution could leak through small openings in the railcar and around the doors and potentially could eat through the metal of the railcar. Controlling factors appear to be the seams in the railcar floor that could trap liquid and the fact that a significant area must be wetted before the solution will drain from the railcar. Thus, a release fraction of 0.01 was used for cases where the railcar was not significantly damaged. For cases where the railcar was postulated to have suffered severe damage (punctured, etc.), a barrier release fraction of 1.0 was used.

9.4 SUMMARY OF RELEASE SEQUENCE EVALUATIONS

The evaluations of the risk dominant release sequences for the 6M containing PuO_2 powder and the L-10 containing liquid $Pu(NO_3)_4$ are summarized in Tables 9.3 and 9.4, respectively. Under the first heading are the event numbers which result in failure of one of the four barriers. These events were obtained from the fault tree. Under the second heading are the basic event probabilities associated with the events given in the first column. The third column summarizes the Barrier Release Fractions presented in 9.3.

Since a release sequence is made up of a single member from each of the four barrier release sequences, the fraction released for a release sequence is obtained by multiplying the barrier release fractions for each selected barrier release sequence. Release sequence probabilities must be obtained by forming a list of basic failure elements and by eliminating any duplicates before the probability multiplication is performed. Following these two operations, a release fraction can be paired with a release probability for all the release sequences. The release fraction is the AF_{R_i} term and the release probability is the P_{R_i} term in Section 3, Equation 2:

$$R_i = (AF_{R_i} \times P_{R_i}) \sum_q (C_{E_{i,q}} \times P_{E_q})$$

The environmental terms $(C_{E_{i,q}} \times P_{E_q})$ are developed in Section 10.

TABLE 9.3. Summary of Dominant Barrier Release Sequences, Basic Element Frequencies and Barrier Release Fractions for Shipping Plutonium Dioxide Powder a Distance of 1500 Miles in the 6M Container

Barrier Release Sequence	Basic Element Frequencies							Release Fractions
SAMPLE CAN								
X064	5.000E-04	0.	0.	0.	0.	0.	0.	5.000E-01
A051	8.000E-04	0.	0.	0.	0.	0.	0.	5.000E-01
X001 X014 X036 X037 A013	2.050E-03	1.000E+00	2.900E-01	9.200E-01	2.135E-04	0.	0.	1.000E+00
X001 X015 X029 X044 A019	2.050E-03	2.000E-02	1.000E-04	4.000E-04	2.000E-02	0.	0.	1.000E+00
X001 X015 X027 X044 A019	2.050E-03	2.000E-02	9.000E-04	4.000E-04	2.000E-02	0.	0.	1.000E+00
X001 X015 X044 X047 A019	2.050E-03	2.000E-02	4.000E-04	9.000E-02	2.000E-02	0.	0.	1.000E+00
X001 X015 X044 X076 A019	2.050E-03	2.000E-02	4.000E-04	2.420E-01	2.000E-02	0.	0.	1.000E+00
X001 X015 X029 X044 A020	2.050E-03	2.000E-02	1.000E-04	4.000E-04	2.000E-04	0.	0.	1.000E+00
X001 X015 X027 X044 A020	2.050E-03	2.000E-02	9.000E-04	4.000E-04	2.000E-04	0.	0.	1.000E+00
X001 X015 X044 X047 A020	2.050E-03	2.000E-02	4.000E-04	9.000E-02	2.000E-04	0.	0.	1.000E+00
X001 X015 X044 X076 A020	2.050E-03	2.000E-02	4.000E-04	2.420E-01	4.000E-04	0.	0.	1.000E+00
2R								
X029 X046	1.000E-04	2.000E-01	0.	0.	0.	0.	0.	1.000E-06
X029 X044	1.000E-04	4.000E-04	0.	0.	0.	0.	0.	1.000E+00
X027 X046	9.000E-04	2.000E-01	0.	0.	0.	0.	0.	1.000E-06
X027 X044	9.000E-04	4.000E-04	0.	0.	0.	0.	0.	1.000E+00
X001 X048 X049 X050	2.050E-03	2.000E-02	1.000E-03	1.000E-03	0.	0.	0.	1.000E+00
X001 X036 X037 A013	2.050E-03	2.900E-01	9.200E-01	2.135E-04	0.	0.	0.	5.000E-01
X001 X046 X047	2.050E-03	2.000E-01	9.000E-02	0.	0.	0.	0.	1.000E-06
X001 X046 X076	2.050E-03	2.000E-01	2.420E-01	0.	0.	0.	0.	1.000E-06
X001 X044 X047	2.050E-03	4.000E-04	9.000E-02	0.	0.	0.	0.	1.000E+00
X001 X044 X076	2.050E-03	4.000E-04	2.420E-01	0.	0.	0.	0.	1.000E+00
OUTER DRUM								
A014	2.000E-03	0.	0.	0.	0.	0.	0.	1.000E-03
X011 X029	1.000E+00	1.000E-04	0.	0.	0.	0.	0.	1.000E-03
A017 X029	1.202E-01	1.000E-04	0.	0.	0.	0.	0.	1.000E-03
X011 X027	1.000E+00	9.000E-04	0.	0.	0.	0.	0.	1.000E-03
A017 X027	1.202E-01	9.000E-04	0.	0.	0.	0.	0.	1.000E-03
X001 A013	2.050E-03	2.135E-04	0.	0.	0.	0.	0.	5.000E-01
X001 X008	2.050E-03	1.000E-05	0.	0.	0.	0.	0.	1.000E+00
X001 X023 A013	2.050E-03	3.000E-02	2.135E-04	0.	0.	0.	0.	1.000E+00
X001 X011 X047	2.050E-03	1.000E+00	9.000E-02	0.	0.	0.	0.	1.000E-03
X001 A017 X047	2.050E-03	1.202E-01	9.000E-02	0.	0.	0.	0.	1.000E-03
X001 X011 X076	2.050E-03	1.000E+00	2.420E-01	0.	0.	0.	0.	1.000E-03
X001 X076 A017	2.050E-03	2.420E-01	1.202E-01	0.	0.	0.	0.	1.000E-03
X001 X029 A019	2.050E-03	1.000E-04	2.000E-02	0.	0.	0.	0.	1.000E+00
X001 X027 A019	2.050E-03	9.000E-04	2.000E-02	0.	0.	0.	0.	1.000E+00
X001 X047 A019	2.050E-03	9.000E-02	2.000E-02	0.	0.	0.	0.	1.000E+00
X001 X076 A019	2.050E-03	2.420E-01	2.000E-02	0.	0.	0.	0.	1.000E+00
X001 X017	2.050E-03	3.680E-03	0.	0.	0.	0.	0.	1.000E+00
X001 X029 A020	2.050E-03	1.000E-04	2.000E-04	0.	0.	0.	0.	1.000E+00
X001 X027 A020	2.050E-03	9.000E-04	2.000E-04	0.	0.	0.	0.	1.000E+00
X001 X047 A020	2.050E-03	9.000E-02	2.000E-04	0.	0.	0.	0.	1.000E+00
X001 X076 A020	2.050E-03	2.420E-01	2.000E-04	0.	0.	0.	0.	1.000E+00
RAILCAR								
X074	1.000E+00	0.	0.	0.	0.	0.	0.	5.000E-05
X001 X082 X084	2.050E-03	4.500E-02	3.330E-01	0.	0.	0.	0.	1.000E+00
X001 X082 X083	2.050E-03	4.500E-02	6.670E-01	0.	0.	0.	0.	1.000E+00
X001 X080	2.050E-03	9.550E-01	0.	0.	0.	0.	0.	5.000E-03

TABLE 9.4. Summary of Dominant Barrier Release Sequences, Basic Element Frequencies and Barrier Release Fractions of Shipped Liquid Plutonium Nitrate a Distance of 1500 Miles in the L-10 Container

Barrier Release Sequences	Basic Element Frequencies							Release Fractions
INNER								
X001 X043	2.050E-03	1.000E+00	0.	0.	0.	0.	0.	1.000E+00
A021	5.000E-03	0.	0.	0.	0.	0.	0.	1.000E-01
2R								
A058	0.	0.	0.	0.	0.	0.	0.	1.000E-02
A062	0.	0.	0.	0.	0.	0.	0.	1.000E-02
X001 X048 X049 X050	2.050E-03	2.000E-02	1.000E-03	1.000E-03	0.	0.	0.	1.000E+00
X048 X051 X052	2.000E-02	0.	1.000E+00	0.	0.	0.	0.	5.000E-01
X027 X035 X036	9.000E-04	1.000E-03	1.000E+00	0.	0.	0.	0.	5.000E-01
X029 X035 X036	1.000E-04	1.000E-03	1.000E+00	0.	0.	0.	0.	1.000E+00
X027 X037 X038	9.000E-04	8.000E-03	8.000E-03	0.	0.	0.	0.	5.000E-01
X029 X037 X038	1.000E-04	8.000E-03	8.000E-03	0.	0.	0.	0.	1.000E+00
X001 X015 A013	2.050E-03	2.100E-01	2.760E-04	0.	0.	0.	0.	5.000E-01
X001 X061 A013	2.050E-03	1.100E-02	2.760E-04	0.	0.	0.	0.	5.000E-01
X001 X004 X075 X084	2.050E-03	6.570E-02	5.000E-03	3.333E-01	0.	0.	0.	3.000E-01
X001 X002 X046 X059 X083	2.050E-03	1.000E-02	9.000E-02	1.400E-01	6.666E-01	0.	0.	2.000E-03
X001 X004 X045 X046 X058 X084	2.050E-03	6.570E-02	1.000E-03	9.000E-02	2.100E-01	3.333E-01	0.	3.000E-01
X001 X047 X035 X036	2.050E-03	9.000E-02	1.000E-03	1.000E+00	0.	0.	0.	5.000E-01
X001 X047 X037 X038	2.050E-03	9.000E-02	8.000E-03	8.000E-03	0.	0.	0.	5.000E-01
X001 X076 X035 X036	2.050E-03	2.420E-01	1.000E-03	1.000E+00	0.	0.	0.	5.000E-01
X001 X076 X037 X038	2.050E-03	2.420E-01	8.000E-03	8.000E-03	0.	0.	0.	5.000E-01
X001 X002 A018 X057 X083 X029	2.050E-03	1.000E-02	2.000E-02	7.900E-01	6.666E-01	1.000E-04	0.	3.000E-01
X001 X002 X017 X057 X083	2.050E-03	1.000E-02	5.400E-03	7.900E-01	6.666E-01	0.	0.	3.000E-01
X001 X002 A013 X057 X083	2.050E-03	1.000E-02	2.760E-04	7.900E-01	6.666E-01	0.	0.	3.000E-01
X001 X004 A018 X056 X084	2.050E-03	6.570E-02	2.000E-02	9.700E-01	3.333E-01	0.	0.	6.000E-01
X001 X004 X017 X056 X084	2.050E-03	6.570E-02	5.400E-03	9.700E-01	3.333E-01	0.	0.	6.000E-01
X001 X002 X008 X057 X083	2.050E-03	1.000E-02	1.000E-05	7.900E-01	6.666E-01	0.	0.	3.000E-01
X001 X004 A013 X056 X084	2.050E-03	6.570E-02	2.760E-04	9.700E-01	3.333E-01	0.	0.	6.000E-01
X001 X004 X008 X056 X084	2.050E-03	6.570E-02	1.000E-05	9.700E-01	3.333E-01	0.	0.	6.000E-01
X001 X002 A018 X057 X083 X027	2.050E-03	1.000E-02	2.000E-02	7.900E-01	6.666E-01	9.000E-04	0.	3.000E-01
X001 X002 A018 X057 X083 X076	2.050E-03	1.000E-02	2.000E-02	7.900E-01	6.666E-01	2.420E-01	0.	3.000E-01
X001 X002 A018 X057 X083 X047	2.050E-03	1.000E-02	2.000E-02	7.900E-01	6.666E-01	9.000E-02	0.	3.000E-01
X001 X002 X046 X059 X014	2.050E-03	1.000E-02	9.000E-02	1.400E-01	1.000E+00	0.	0.	2.000E-03
X001 X002 X017 X057 X014	2.050E-03	1.000E-02	5.400E-03	7.900E-01	1.000E+00	0.	0.	3.000E-01
X001 X002 A013 X057 X014	2.050E-03	1.000E-02	2.760E-04	7.900E-01	1.000E+00	0.	0.	3.000E-01
X001 X002 X008 X057 X014	2.050E-03	1.000E-02	1.000E-05	7.900E-01	1.000E+00	0.	0.	3.000E-01
X001 X002 X029 A018 X057 X014	2.050E-03	1.000E-02	1.000E-04	2.000E-02	7.900E-01	1.000E+00	0.	3.000E-01
X001 X002 X027 A018 X057 X014	2.050E-03	1.000E-02	9.000E-04	2.000E-02	7.900E-01	1.000E+00	0.	3.000E-01
X001 X002 X047 A018 X057 X014	2.050E-03	1.000E-02	9.000E-02	2.000E-02	7.900E-01	1.000E+00	0.	3.000E-01
X001 X002 X076 A018 X057 X014	2.050E-03	1.000E-02	2.420E-01	2.000E-02	7.900E-01	1.000E+00	0.	3.000E-01
OUTER DRUM								
A014	2.000E-03	0.	0.	0.	0.	0.	0.	5.000E-03
X029 X011	1.000E-04	1.000E+00	0.	0.	0.	0.	0.	5.000E-03
X029 A017	1.000E-04	5.000E-04	0.	0.	0.	0.	0.	5.000E-03
X027 X011	9.000E-04	1.000E+00	0.	0.	0.	0.	0.	5.000E-03
X027 A017	9.000E-04	5.000E-04	0.	0.	0.	0.	0.	5.000E-03
X001 A018 X027	2.050E-03	2.000E-02	9.000E-04	0.	0.	0.	0.	1.000E+00
X001 X017	2.050E-03	5.400E-03	0.	0.	0.	0.	0.	1.000E+00
X001 X008	2.050E-03	1.000E-05	0.	0.	0.	0.	0.	1.000E+00
X001 X011 X047	2.050E-03	1.000E+00	9.000E-02	0.	0.	0.	0.	5.000E-03
X001 X047 A017	2.050E-03	9.000E-02	5.000E-04	0.	0.	0.	0.	5.000E-03
X001 X011 X076	2.050E-03	1.000E+00	2.420E-01	0.	0.	0.	0.	5.000E-03
X001 X076 A017	2.050E-03	2.420E-01	5.000E-04	0.	0.	0.	0.	5.000E-03
X001 A013	2.050E-03	2.760E-04	0.	0.	0.	0.	0.	5.000E-01
X001 X002 X003	2.050E-03	1.000E-02	5.000E-04	0.	0.	0.	0.	5.000E-01
X007 A058	1.000E+00	0.	0.	0.	0.	0.	0.	5.000E-03
X007 A062	1.000E+00	0.	0.	0.	0.	0.	0.	5.000E-03
X001 X004 X007 X075 X084	2.050E-03	6.570E-02	1.000E+00	5.000E-03	3.333E-01	0.	0.	2.000E-02
X001 X002 X007 X046 X059 X083	2.050E-03	1.000E-02	1.000E+00	9.000E-02	1.400E-01	6.666E-01	0.	5.000E-01
X001 X004 X007 X045 X046 X058 X084	2.050E-03	6.570E-02	1.000E+00	1.000E-03	9.000E-02	2.100E-01	3.333E-01	5.000E-02
X001 A018 X029	2.050E-03	2.000E-02	1.000E-04	0.	0.	0.	0.	1.000E+00
X001 A018 X047	2.050E-03	2.000E-02	9.000E-02	0.	0.	0.	0.	1.000E+00
X001 A018 X076	2.050E-03	2.000E-02	2.420E-01	0.	0.	0.	0.	1.000E+00
X001 X002 X046 X059 X014 X067	2.050E-03	1.000E-02	9.000E-02	1.400E-01	1.000E+00	1.000E+00	0.	5.000E-01
RAILCAR								
X063 X074	1.000E+00	1.000E+00	0.	0.	0.	0.	0.	1.000E-02
X001 X082 X083	2.050E-03	4.500E-02	6.666E-01	0.	0.	0.	0.	1.000E+00
X001 X082 X084	2.050E-03	4.500E-02	3.333E-01	0.	0.	0.	0.	1.000E+00
X001 X014 X080	2.050E-03	1.000E+00	9.550E-01	0.	0.	0.	0.	1.000E-02

REFERENCES

1. R. K. Clarke, T. J. Foley, W. F. Hartman and D. W. Larson, Severities of Transport Accidents, Volume IV - Trains, SLA-74-001, Sandia Laboratories, Albuquerque, NM, (To be published).

2. Siting of Fuel Reprocessing Plants and Waste Management Facilities, ORNL-4451, Oak Ridge National Laboratory, Oak Ridge, TN, July 1970.

3. J. M. Selby, et al., Considerations in the Assessment of the Consequences of Effluents from Mixed Oxide Fuel Fabrication Plants, BNWL-1697, Battelle, Pacific Northwest Laboratories, Richland, WA, June 1973.

4. R. J. Hall, T. I. McSweeney, 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.

5. W. Washington, R. Chi, R. Regan, "The Use of Vermiculite to Control Dust and Radon Daughters in Underground Uranium Mine Air," Proc. of the 12th AEC Air Cleaning Conference, CONF-720823, Oak Ridge, TN, August 1972, p. 355.

10.0 EVALUATION OF ENVIRONMENTAL CONSEQUENCES

In Section 9, release sequences were identified and evaluated by determining their expected frequency of occurrence and the associated amount of material released. A risk number could be obtained by forming the product of the expected frequency of occurrence and the amount of material released and summing over all release sequences. This number does not fit one of the criteria for a risk assessment as specified in the Introduction. Namely, the results of the assessment must be expressed in a form that permits comparison to other societal risks.

This section develops the data required to compare the plutonium transportation risk assessment to other societal risks. Factors in developing this information are: Quantity Airborne, Meteorology, Demography, Individual and Population Dose, Population Health Effects and Expected Exposure Frequency.

Analyses of these factors are summarized sequentially in separate parts of this section. These factors and their relationships to other steps in the risk assessment are shown in Figure 10.1.

Results given in this section can be thought of as conversion factors required to obtain risk values which can be compared to other societal risks.

10.1 QUANTITY AIRBORNE

Section 9.4 showed the method used to get release sequence data and summarized the data in terms of Barrier Release Sequences. The released material considered in Section 9 is in the environment at the point of release but it is not dispersed. Plutonium pathway analysis calculations presented in the truck shipment risk report[1] indicate that the airborne pathway dominates all other pathways through the environment by about four orders of magnitude. Thus, only the airborne pathway was considered in this analysis.

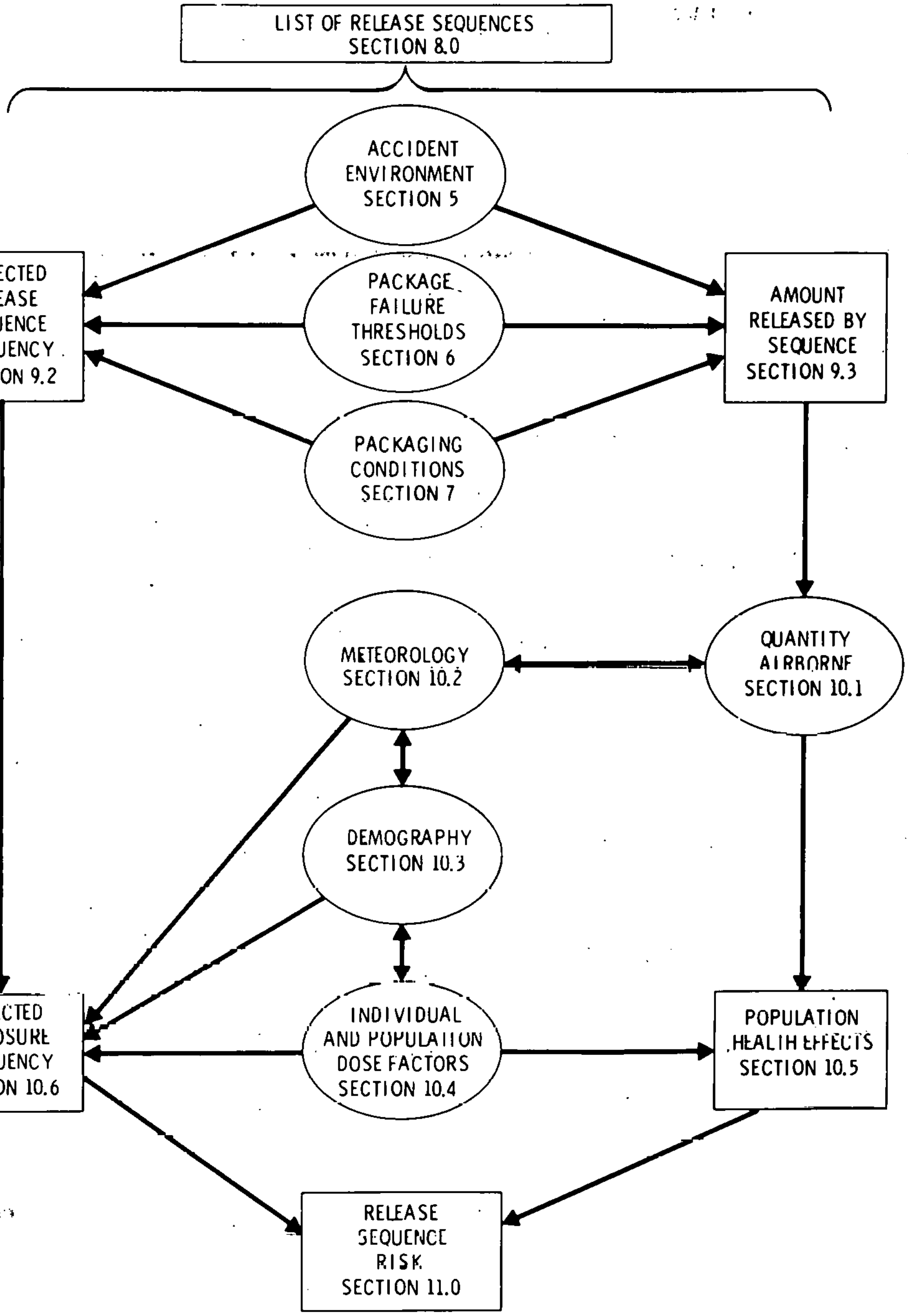


FIGURE 10.1. Release Sequence Evaluation

The airborne dispersal evaluation in this subsection will be divided into two parts: Quantity of Material Immediately Dispersed and Quantity Dispersed During Time Intervals Following the Initial Release.

10.1.1 Quantity of Material Immediately Dispersed

There have been no experiments performed which exactly simulate the breach of a container in a rail accident and the subsequent puff of material which becomes airborne and is dispersed downwind.

A relevant simulation was reported by S. Hagsgard et al.[2] They determined the quantity of material released when a Type A package* filled with a fine sand was breached by a puncture probe. Releases of sand from both plastic bottles and tin cans were studied.

The fraction of material released upon failure was found to have a mean of 0.76×10^{-3} and a standard deviation of 0.46×10^{-3}. These fractions include all the material released which could be greater than the amount airborne. However, since the PuO_2 powder is a very fine, easily entrained powder, it is conservatively assumed that when the container is breached all the material immediately released will be airborne. In this analysis a value of 10^{-3} was used for the fraction immediately airborne when a 6M container is failed in an accident.

The failure analysis of the sand-filled Type A containers gives little direct guidance in determining the airborne release fraction for liquid-filled L-10 containers. There are two basic classes of releases which are immediately airborne when an L-10 fails. The first class of releases considers the puff-dispersible material which becomes airborne when the container is initially breached. The second type of release occurs when the nitrate solution is exposed to a fire and the containment vessel is breached by the resultant pressure increase.

In the first case, the fraction instantaneously released upon failure can be expected to be nearly the same as occurred for the oxide case. However, whereas the oxide is a very fine, highly dispersible powder, the

* As defined in 10 CFR Part 71.

liquid will be dispersed in droplet form. The size of the droplets can be expected to be similar to droplets formed by slow-speed jet atomizers. They produce droplets with a mean size of approximately 280 microns.[3] The particle size distribution is log normal with only 0.1% less than 160 microns. Particles must be an order of magnitude smaller before they can be entrained for long periods of time in even rapidly moving air currents. Thus, the fraction of the plutonium solution immediately dispersed upon rupture of the L-10 is very much less than 0.1% of the 0.1% immediately released to the air when the barriers are failed. As a result, the amount immediately airborne upon spillage from the L-10 will not be included in the source term. This source term is used for accidents where no fire occurs following the accident.

Releases which result from excessive heating of the nitrate solution have characteristics which differ markedly from the previous release. First the release occurs at high temperature and at high pressure. Secondly the material released will be dried by the high temperature gases, which exist in the fire environment. Both these factors make the final particle size much smaller and much more dispersible.

The mechanical evaluations, presented in Appendix D, indicate that the 2R pressure vessel will relieve the excessive internal pressure by jetting either gas or a flashing liquid past the flange gasket. Two accident conditions must be considered. If the L-10 is upright, then a release fraction of 2×10^{-3} is used in the analysis. This release fraction is inferred from the "rolling" boil results reported by Mishima.[4] If the container is on its side, then liquid is normally present in the flange region. As the pressure is relieved it is impossible to assure separation of phases. It is therefore assumed that the escaping material is in the form of a flashing liquid jet. Based on analyses reported by Brown and York[5] and Ostrowski,[6] most of the liquid escaping is expected to be in drops less than 60 microns in diameter. Although these drops are too large to be easily carried by air currents, they are ejected into a high temperature gas stream. The arrangement parallels the conditions which exist in a spray drying operation. The Chemical Engineering Symposium Series Monograph on atomization and spray drying[7] states that: "Spray drying produces a product consisting of approximately spherical particles which are more or less hollow, depending on the material and on certain operating variables." The article goes on to state that: "It is not a simple matter to produce solid spherical particles by spray drying. Hollow particles are the rule, solid particles the exception." Thus, the most likely product from the release of material in the fire environment is hollow spherical particles with an average diameter less than 60 microns. Most of these hollow spheres are ruptured. In any case, the dried material can be expected to be as extremely buoyant and as entrainable as a very fine powder. Since conversion of the nitrate solution to the oxide is rapid above 250°F,[8] the solid is expected to be a fine oxide powder. For this reason, the material released as a result of the fire environment was assumed to be immediately airborne and 100% dispersed downwind.

10.1.2 Quantity Dispersed During Time Intervals Following Initial Release

The total amount of material which is made airborne is the sum of the fraction immediately airborne and any subsequent releases. For the plutonium dioxide powder there are two types of delayed releases. One occurs as a result of airborne entrainment of dioxide powder spilled on the ground. The other occurs as a result of the release to the atmosphere of plutonium powder which has been made airborne in an enclosure (e.g., a railcar). For plutonium nitrate solutions, the only delayed release is by entrainment from ground spills.

10.1.2.1 Aerodynamic Entrainment of Plutonium Dioxide Powder Following Spillage on the Ground

The basic data on resuspension of dioxide powder spilled on the ground are shown in Appendix C of Reference 1. Resuspension factors ranging over 10 orders of magnitude have been generated over the lifetime of the atomic energy industry.[9] Some attempts have been made to generate resuspension rates,[10-14] but none appeared to be directly applicable to model this case. Thus an empirical fit was made to data on the time-dependent removal of ball-milled uranium dioxide powder from smooth, sandy soil.[15] Plutonium dioxide is expected to act aerodynamically similar to uranium dioxide.

Based on the release fraction data in Appendix C of Reference 1 for ball-milled uranium dioxide powder from smooth, sandy soil, the fraction airborne over a 24-hr period can be correlated by the expression:

$$f = 4.6 \times 10^{-4}\ U^{1.78}. \qquad (10\text{-}1)$$

In this expression, U is the windspeed normally measured at the 50-ft level. In deriving this equation, the data in Appendix C of Reference 1 which expressed windspeeds in mph at the 1-ft level had to be corrected to an equivalent windspeed expressed in m/sec and measured at an elevation of 15-m. When a 1-mph wind is encountered at 1 ft, the windspeed measured at the 15-m elevation can be expected to be 1 m/sec; thus the data can be used as if U had been expressed in m/sec measured at 15-m.

The release fractions for times less than 24-hr are shown in Figures 10.2 and 10.3. These data were taken from Reference 15. It shows that for times longer than 24-hr, essentially all the material that is going to be dispersed will have been dispersed. Since shipment of plutonium is escorted for safeguard reasons, prompt notification of emergency personnel is possible. As a result, it should be possible to fix most released material within a half hour after the accident. A half hour release duration was used in the analysis. The effect of 2-hr release durations on the risk magnitude is considered in Section 11.4.

An empirical time-dependent term which fits the fractional release values for times under 24-hr is:

$$f = (1-e^{-0.15Ut}). \qquad (10\text{-}2)$$

Where U is the windspeed 1 ft above ground in miles/hr and t is in hours. Converting the U to m/sec at 15 m and correcting for difference in heights results in the same expression. Equations 10-1 and 10-2 can be combined with the 10^{-3} fraction immediately airborne to obtain the following source term for airborne dispersal of plutonium dioxide powder.

$$S = K\left[0.001 + 4.6 \times 10^{-4}\ (1-e^{-0.15Ut})\ U^{1.78}\right] \qquad (10\text{-}3)$$

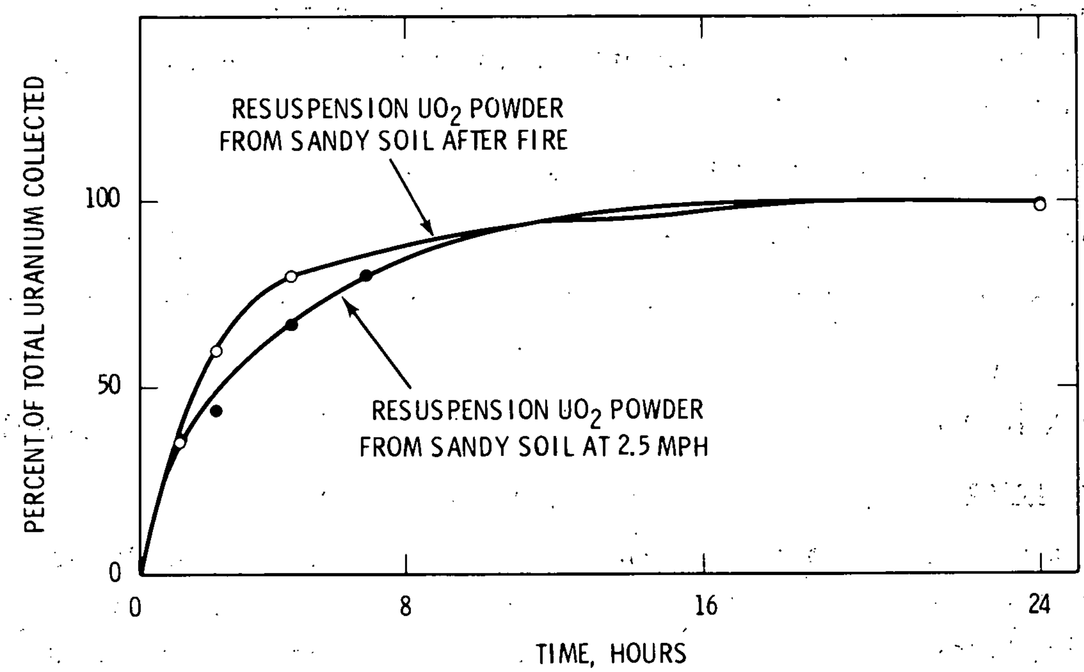


FIGURE 10.2. Aerodynamic Entrainment of Uranium Dioxide Powder from Smooth Sandy Soil at an Air Velocity of 2.5 mph

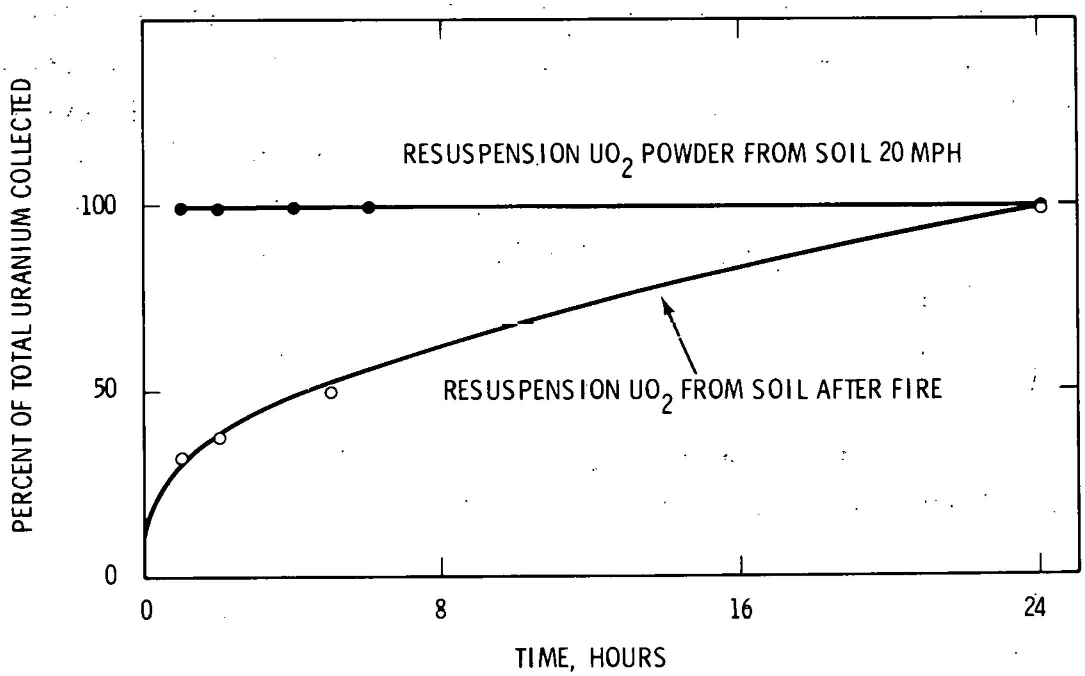


FIGURE 10.3. Aerodynamic Entrainment of Uranium Dioxide Powder from Smooth Sandy Soil at an Air Velocity of 20 mph

K is the quantity of material available for dispersal (i.e., the quantity assumed to have penetrated the barriers which contain the plutonium)

U is the windspeed at 50 ft, expressed in m/sec

t is the duration of the release, hours.

The expression used in the risk evaluation for a half hour release duration was:

$$A = K \left[0.001 + 4.6 \times 10^{-4} \ (1 - e^{-0.075U}) \ U^{1.78}\right]. \quad (10\text{-}4)$$

10.1.2.2 Release of Plutonium Dioxide Aerosols from an Enclosure

The other type of release mechanism for plutonium dioxide powder is the case where the container fails in the railcar and the railcar is the controlling barrier. The evaluation in Section 9.3 showed that a 5×10^{-3} fraction of the container inventory could be entrained in the air inside the railcar and gradually leak out following the accident.

The leak rate from the enclosure is very dependent on the extent of the damage to the railcar. In a very tight railcar, a leak rate of a few percent per day would be reasonable. However, accident forces sufficient to fail a container in all likelihood will fail the railcar. In the evaluation it was assumed that any release inside the railcar had to pass through one orifice 1 cm wide and 1 m long and the velocity through the orifice was equal to the windspeed at the 15-m level. In a well mixed volume, the release rate is then:

$$S = K(1 - e^{-0.015Ut}) \quad (10\text{-}5)$$

where the symbols are the same as those in Equation 10-3. In the half hour postulated release time, the source term is:

$$A = K(1 - e^{-0.0075U}). \quad (10\text{-}6)$$

10.1.2.3 Aerodynamic Entrainment of Plutonium Nitrate Solution Spilled on the Ground

As in Equation 10-3, an empirical fit was made to existing experimental data on the release of uranium nitrate on smooth, sandy soil at windspeeds of 2.5 and 20 mph measured 1 ft above the surface in a 2-ft square wind tunnel.[15] The equation used to model this case was:

$$S = K(10^{-4}\ U^{1.41}) \qquad (10\text{-}7)$$

where the symbols are defined the same as in Equation 10-3. Time-dependent release values were not available, and thus data for a 24-hr sampling period were used. Inasmuch as the time span assumed for the accidental releases is 0.5 hr, the value is expected to be conservative.

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 - indicates the initial direction of travel, 2) windspeed - indicates the rate of transport, and 3) atmospheric stability - indicates the rate of dilution and plume rise potential. Certain characteristics of the release (e.g., height and temperature) can also be important in the evaluation of the atmospheric pathway.

The meteorological data used in this analysis are shown in Table 10.1. The values were developed from micrometeorological data collected at 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 windspeeds 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 10.1. Average Windspeed/Stability Characteristics

Wind Speed			Pasquill Stability Classification			
U_k m/sec	k	P_k	B(j=1)	D(j=2)	E(j=3)	F(j=4)
			$P_{j/k}$			
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

The objective of this subsection is to characterize the population distribution along the plutonium shipping routes. As shown in Figure 10.1, this information is needed to determine both the expected frequency at which a given population distribution will be exposed to a release and the distribution of the resultant exposure. These data can be developed using the shipping routes together with a population distribution model.

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 10.4. A representative state was chosen for each of the zones (see Table 10.2). Then for the purpose of the study, the population data of the selected states were used in forecasting population characteristics of their respective zones.

TABLE 10.2. Representative States for Population Zones

Zone	Representative State
I - High urbanization	New Jersey
II - Densely populated	Massachusetts
III - Moderately populated	Missouri
IV - Low population	Washington

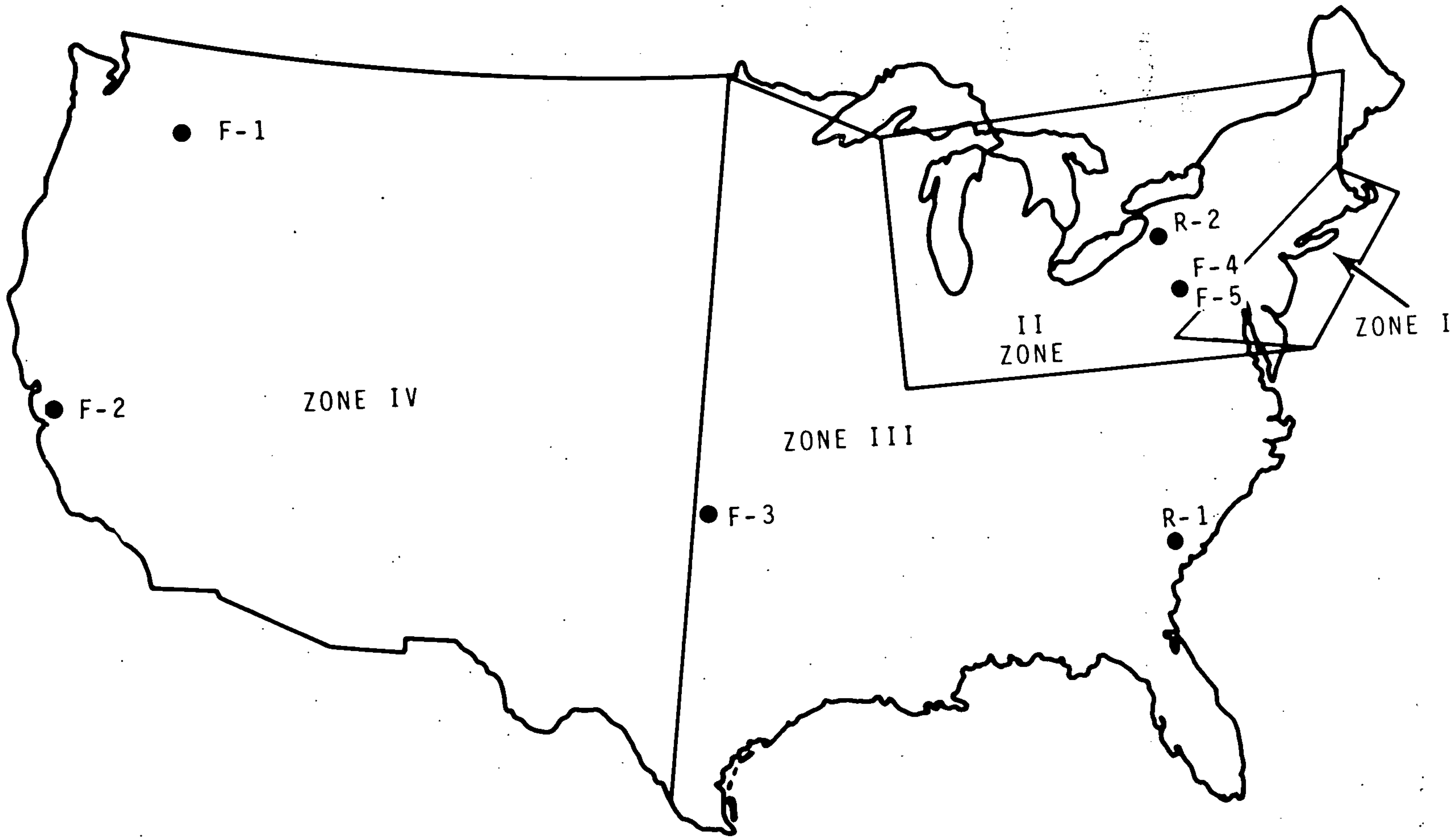


FIGURE 10.4. Fuel Reprocessing Sites, Plutonium Fuel Fabrication Facility Locations, and Population Zones

The 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 initial approach was to establish a set of population data for the representative states. Census data for 1960 and 1970 were used as a data base. Using the compound interest formula to model population growth, population projections were made for 1980. The fraction of each fuel reprocessor to plutonium fuel fabricator route in each of the population zones was identified. Using this, a 1980 route population density was calculated for each route.

Further discussion of the techniques employed in the demography model is given in the following subsections.

10.3.1 Average Size of an Urban Area

The data in Table 10.3 show that urban areas occupy a small fraction of the land area. If a release occurs in a city, it would be incorrect to assume that the release plume is confined completely to an urban area. For that reason, it is important to determine the size of a representative urban area and thereby limit the urban area included in any dose calculation. Using the representative states for each of the four zones, the average urban land area was determined. Only urban areas having a population greater than 25,000 in the year 1960 were used in the analysis. The results of this analysis are summarized in Table 10.4 for the years of interest.

10.3.2 Shipping Route Mileage by Population Zones

The second factor in the characterization of the demography is to relate the shipping routes to the population zones. Plutonium shipment routes were previously determined in Section 4. Previous parts of Section 10.3 have characterized the population distribution for the various zones of the country. This section will develop the information on the route mileage in each zone that is needed to obtain the population density along each shipping route.

TABLE 10.3. Projected 1980 Population Density and Land Area by Zone and Population Classes

Zone and Population Classes		Land Area, %	Density People/mi^2
I	Urban	3.8	9290
	Suburban	66.9	822
	Rural	29.3	612
II	Urban	11.5	3170
	Suburban	35.5	845
	Rural	53.0	238
III	Urban	0.8	3980
	Suburban	17.3	226
	Rural	81.9	17
IV	Urban	0.5	4390
	Suburban	15.0	131
	Rural	84.5	25

TABLE 10.4. Projected Land Area of Urban Areas for 1980 in the Four Zones of the U.S.

Zone	Average Urban Land Area, mi^2
I	7.92
II	25.66
III	43.92
IV	37.80

A map with the population zones and the location of the fabrication and reprocessing plants is shown in Figure 10.4. The designations F-1 through F-5 refer to the fuel fabrication facilities listed in Table 4.2. The designations R-1 and R-2 refer to the fuel reprocessing facilities identified in Section 4.2. The distance between each reprocessor and fabricator was obtained from normalized great circle distances. For each route the fraction of the route in each of the four zones was determined by drawing arcs of a great circle between each fuel fabricator and reprocessor and determining the fraction of the arc in each zone. This data is summarized in Table 10.5. The four columns under each reprocessor contain the fractioned route mileage in each zone to each fuel fabricator.

TABLE 10.5. Fractional Shipping Route Mileage by Population Zones

(values in percent)

Reprocessor Number, Name, Location	1, A-G, Barnwell, SC				2, NFS, West Valley, NY			
Population Zone Numbers	I	II	III	IV	I	II	III	IV
Fabricator Number, Name, Location	Percent of Transport Route in Zone No.							
1 Exxon, Richland, WA	-	-	42	58	-	28	16	56
2 GE, Pleasanton, CA	-	-	40	60	-	25	17	58
3 Kerr-McGee, Crescent, OK	-	-	100	-	-	42	57	-
4 NUMEC, Apollo, PA	4	26	70	-	-	100	-	-
5 Westinghouse, Cheswick, PA	2	26	72	-	-	100	-	-

- Denotes zero contribution.

Contributions less than 0.05 are neglected, i.e., added to or averaged between other zones.

Example: Route 1-1 Barnwell, SC to Richland, WA
42% of Mileage in Zone III
58% of Mileage in Zone IV

The shipping routes are completely characterized. The mileage between any reprocessor and fabricator can be determined from Table 4.3. The fraction of the route in each zone is shown in Table 10.5, and the population distribution in each zone along the route for a particular year can be determined from the data presented in Table 10.3.

10.4 INDIVIDUAL AND POPULATION DOSE FACTORS

As shown in Figure 10.1, factors from the meteorological and demographic characteristics of the shipping route are combined with the dose conversion factors developed here to determine the population doses resulting from an accidental release of plutonium. There are two parts to the calculation, discussed in the following subsections. First, Dose Conversion Factors must be developed to characterize the effect of inhaled plutonium on an individual's health. Second, using the meteorological data, an Atmospheric Dispersion Model must be developed to characterize the plutonium aerosol concentration downwind from the release point.

10.4.1 Dose Conversion Factors

The dose to an individual from inhalation of a plutonium aerosol is a function of the duration of the release, the concentration during the release period, the particle size, the isotopic content of the released plutonium, the individual's ventilation rate, the solubility of the inhaled material in body fluids and the retention time of plutonium in body organs.

The dose resulting from plutonium inhalation may be calculated using either of two lung models recommended by the International Commission on Radiological Protection (ICRP). The Initial Lung Model (ILM) recommended by ICRP differentiates soluble and insoluble inhaled material.[16,17] When the inhaled material is soluble, the uptake by other organs is assumed to be essentially instantaneous. A more sophisticated lung model (TGLM), recently suggested by ICRP, characterizes more completely the metabolic pathways of the inhaled material.[18] The derived equations for estimating the dose to organs other than the lung are considerably more complex than those for the ILM. A computer program has been developed for calculating the dose to lung and other organs using the TGLM.[19] Only results from the TGLM calculations were used in the dose conversion for the present analysis.

The inhalation dose per unit release to an individual exposed to a passing cloud is given by:

$$\frac{D_j}{Q} = K \left(\frac{E}{Q}\right) \tag{10-8}$$

where

D_j is dose to organ of interest, j, delivered over time t, rem

Q is the quantity released in curies

K is the inhalation dose conversion factor

E is time-integrated air concentration, $\mu Ci \cdot sec/cm^3$, obtained from the Atmospheric Dispersion Model discussed in Section 10.4.2.

Table 10.6 lists the plutonium isotopic mixture, assumed to be representative of that which will be shipped in the early 1980s, which was used for the dose calculations reported in this document. Using this isotopic mixture, the conversion factors for the mixture have been calculated and summarized in Table 10.7 using the TGLM conversion factors. The set of K values shown in Table 10.7 convert the amount of material inhaled, expressed in total curies of the mixture, into 50-year dose commitments to the lung and bone for both soluble and insoluble particles. The Task Group Lung Model was used in this analysis with PuO_2 metabolized as translocation class Y and all nitrate compounds as class W.

The release fractions developed in Section 10.1 are presented as fractions of the total weight of plutonium in a container based on the isotopic mixture shown in Table 10.6.

$$Q = 11.4 \times A \times F_r \tag{10-9}$$

where

11.4 is the number of curies per gram in the plutonium isotopic mixture being shipped. (See Table 10.6)

Q is the curies released

A is the amount of plutonium in a container in grams

F_r is the release fraction of plutonium dispersed during a release.

TABLE 10.6. Reference Mixture of Plutonium and Americium

	Composition[a] by Weight (%)	Activity[b] (Ci/g of Mix)
^{238}Pu	1.5	0.26
^{239}Pu	58	0.036
^{240}Pu	24	0.054
^{241}Pu	11	11
^{242}Pu	4.9	1.9×10^{-4}
^{241}Am	0	0.034

a. Initial composition, after separation from U and fission products. Note: Sum does not equal 100 because only two significant figures are used.
b. Activity of isotope in mixture 2 years after separation.

TABLE 10.7. Dose Conversion Factors for Inhalation of Reference Plutonium Mixture (Standard Man)[a]

Organ of Reference	Solubility in Body Fluids	k[b][c] (rem per Ci sec/m^3)
Lung	Insol (Y)	5.4×10^3
	Sol (W)	4.0×10^2
Bone	Insol (Y)	6.1×10^3
	Sol (W)	1.7×10^4

a. Biological parameters recommended by ICRP[17]
b. Calculated as a 50-year dose commitment per Ci sec/m^3 inhaled
c. Particle size: 1 micron (AMAD)

10.4.2 Atmospheric Dispersion Model

The atmospheric dispersion model calculates the ground level, time integrated air concentration at any downwind distance x and crosswind distance y. Based on the coefficients derived in the previous section, the dose to an individual standing at point (x,y) can be calculated. By integrating over the contaminated area, a population dose can then be determined.

10.4.2.1 Time-Integrated, Ground Level Air Concentration

For releases of short duration, less than a day, the time-integrated air concentration at ground level is evaluated by the bivariate normal diffusion model using Pasquill diffusion parameters.[20] In equation form:

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

where

- E is ground level time-integrated air concentration at point x, y, $Ci \cdot sec/m^3$
- 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, curies
- 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 windspeed 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 10.8 and 10.9, respectively.

TABLE 10.8. 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 10.9. 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 dose to an individual at point (x,y) can now be obtained by specifying the windspeed, height of release and the Pasquill Stability Category. For these conditions, values of σ_y and σ_z at the downwind distance, x, can be obtained from Tables 10.8 and 10.9 by interpolation. Then E/Q can be calculated at x,y using Equation 10-10 and D/Q obtained using Equation 10-8 and Table 10.7.

The population dose could, in theory, be calculated by locating every individual or groups of individuals and going through the above procedure until all individuals receiving a dose have been included in the calculation. In practice, however, Equations 10-8 and 10-10 are used mainly to obtain the maximum individual dose. The population dose is more easily estimated by calculating isopleths of constant dose or time-integrated air concentration. Then the differential area between isopleths and the mean dose received by individuals residing between the two isopleths is calculated.

The isopleths outside 100 m from the release are obtained using Equation 10-10. Rather than evaluate E in Equation 10-10 for every Q and every windspeed U, it is more convenient to move Q and U to the other side of the equation and determine isopleths of constant (UE/Q). The isopleths are determined by first selecting a value of UE/Q, obtaining values of σ_y and σ_z for each x beginning at 100, and then solving Equation 10-10 using the k^{th} average windspeed (see Table 10.1) to obtain the value of y for each x. The x,y coordinates for an entire isopleth of constant UE/Q can be obtained in the same way. Then by integration, the area enclosed by any isopleth can be determined. The area between two isopleths receives a dose which is intermediate between the two boundary isopleths.

Table 10.10 presents a summary of the isopleth calculations for a 1 m/sec windspeed ($U_k = U_1$), similar tables could be constructed for the other windspeeds considered. Isopleths were calculated for UE/Q values at order of magnitude intervals from 10^{-2} to 10^{-10}. Areas between adjacent isopleths were calculated and are shown as the area values for each Pasquill Stability Class. The mean value of $\overline{UE/Q}$ is set at 2.5 times the value of UE/Q at the outer isopleth. The n subscript refers to the isopleth number and the j subscript denotes the stability class. A value of j = 1 refers to

TABLE 10.10. Land Areas Within Isopleths of a Release Plume and More Than 100 m from the Release Point ($U_k = U_1 = 1$ m/sec)

n	$\overline{(UE/Q)}_{n,j,1}$ m^{-2}	Pasquill Stability Classification B	D	E	F
		$A_{n,j,1}$ (Area m^2)			
1	2.5×10^{-2}	0	0	0	4.4×10^{3}
2	2.5×10^{-3}	0	1.6×10^{4}	2.2×10^{4}	2.6×10^{4}
3	2.5×10^{-4}	4.1×10^{4}	1.4×10^{5}	3.8×10^{5}	8.0×10^{5}
4	2.5×10^{-5}	1.8×10^{5}	3.0×10^{6}	3.8×10^{6}	2.2×10^{7}
5	2.5×10^{-6}	1.4×10^{6}	7.1×10^{7}	1.9×10^{8}	2.3×10^{8}
6	2.5×10^{-7}	3.3×10^{6}	4.8×10^{8}	3.1×10^{8}	1.5×10^{8}
7	2.5×10^{-8}	2.8×10^{6}	2.9×10^{8}	1.7×10^{8}	1.1×10^{8}
8	2.5×10^{-9}	1.3×10^{7}	2.1×10^{8}	1.3×10^{8}	8.8×10^{7}
9	2.5×10^{-10}	6.0×10^{6}	1.8×10^{8}	1.1×10^{8}	7.7×10^{7}

B stability and j = 2 refers to D stability, etc. The windspeed index, k, is one in the table. In Table 10.10 some of the values of $A_{n,j,1}$ are zero. These zeros are present because the calculations indicate that for those stabilities the isopleth areas lie entirely within the 100 m evacuation distance.

As in the truck shipment risk analysis,[1] it is assumed that the people residing within 100 m of the accident can be evacuated. The model evacuates the individuals residing within the 100 m radius circle, which would be in the release plume, to a point where they receive the centerline dose at 100 m. This is conservative since it is hoped that they could be moved out of the release plume entirely. However, onlookers who happen onto the accident scene also have to be considered. It is felt that giving the centerline dose at 100 m to all evacuated individuals will more than compensate for the dose received by any onlookers. Based on this model, Table 10.11 shows the area within 100 m which would be in an isopleth for the various stability conditions. Also shown are the values of UE/Q at the centerline 100 m downwind from the release point.

TABLE 10.11. Land Area Contaminated Within 100 m of Accident Scene and Centerline Value of UE/Q at 100 m Versus Pasquill Stability Classification

Pasquill Stability Classification	UE/Q m^{-2}	Area m^2
B	2.0×10^{-3}	5.9×10^{3}
D	8.6×10^{-3}	3.3×10^{3}
E	1.9×10^{-2}	2.5×10^{3}
F	5.7×10^{-2}	1.9×10^{3}

10.5 POPULATION HEALTH EFFECTS

The health effects of plutonium are discussed in several survey articles. Bair and Thompson(21) and Bair, Richmond and Wachholz(22) summarize the major findings of over 30 years of research with plutonium. These findings indicate that exposure of humans to large quantities of plutonium (μCi range) may ultimately result in undesirable health effects; however, none have been observed to date. The few individuals who have been so exposed consist of occupational workers at nuclear facilities, and after more than 25 years of these exposures there have been no observable deleterious effects. Such findings give little guidance in estimating the health effects which may result from the exposure of large populations to small quantities of plutonium. The effects of ionizing radiation on large populations are the only applicable data source available. The number of deaths in the U.S. population which might result from continual exposure to ionizing radiation at a rate of 0.1 rem/yr has been estimated by an advisory committee of the National Academy of Science.(23) Two risk models were used to estimate the number of excess deaths due to radiation-induced cancer. The results for each model are reported here as Tables 10.12 and 10.13. Details of the models can be found in the NAS-BEIR committee report.(23)

A range of risk estimators for the present study was determined as follows. The excess deaths due to "all other cancers" for all ages were assumed to range from the lower subtotal value of the "Absolute Risk Model"

TABLE 10.12. Estimated Numbers of Deaths per Year in the U.S. Population Attributable to Continual Exposure at a Rate of 0.1 rem/yr, Based on Mortality from Leukemia and from all Other Malignancies Combined[23]

Irradiation During Period	Absolute Risk Model[a] Excess Deaths Due to: Leukemia	Absolute Risk Model[a] Excess Deaths Due to: All Other Cancer	Relative Risk Model[a] Excess Deaths Due to: Leukemia	Relative Risk Model[a] Excess Deaths Due to: All Other Cancer
In Utero	75	75	56	56
0-9 years	164	73[b] 122[c]	93	715[b] 5,869[c]
10 + years	277	1,062[b] 1,288[c]	589	1,665[b] 2,415[c]
Subtotal	516	1,210[b] 1,485[c]	738	2,436[b] 8,340[c]
TOTAL	1,726[b] = 0.6% incr. 2,001[c] = 0.6% incr.		3,174[b] = 1.0% incr. 9,078[c] = 2.9% incr.	

a. The figures shown are based on the following assumptions:
- 1967 U.S. vital statistics can be used for age specific death rates from leukemia and all other cancer and for total U.S. population.
- Values for the duration (b or c) of the latent period (the length of time after irradiation before any excess of cancer deaths occur), duration of risk ("plateau region"), and magnitude of average increase in annual mortality for each group are as shown in Table 10.13.

b. Thirty year duration of plateau (see Table 10.13).
c. Lifetime duration of plateau (see Table 10.13).

to the upper subtotal value of the "Relative Risk Model." As shown in Table 10.12, the resulting range is from 1210 to 8340 excess deaths per year due to all cancers other than leukemia. Based on a U.S. population of 200 million people and a dose rate of 0.1 rem/yr the range can be expressed as 6×10^{-5} to 4×10^{-4} in units of deaths per man-rem.

The frequency of cancer death by type of cancer was estimated from Table 10.13 to be:

Type of Cancer	Frequency
Breast	0.30
Lung	0.26
GI including stomach	0.20
Bone	0.04
All other cancer	0.20
Total	1.00

TABLE 10.13. Assumed Values Used in Calculating Estimates of Risk Shown in Table 10.12[23]

Age at Irradiation	Type of Cancer	Duration of Latent Period (years)	Duration of Plateau Region[a] (years)	Risk Estimate: Absolute Risk[b] (deaths/10^6/yr/rem)	Risk Estimate: Relative Risk (% incr. in deaths/rem)
In Utero	Leukemia	0	10	25	50
	All Other Cancer	0	10	25	50
0-9 years	Leukemia	2	25	2.0	5.0
	All Other Cancer	15	30 Life	1.0	2.0
10 + years	Leukemia	2	25	1.0	2.0
	All Other Cancer	15	30 Life	5.0	0.2

a. Plateau region is the interval following latent period during which risk remains elevated.

b. The absolute risk for those aged 10 or more at the time of irradiation for all cancer excluding leukemia can be broken down into the respective sites as follows:

Type of Cancer	Deaths/10^6/yr/rem
Breast	1.5
Lung	1.3
GI incl. Stomach	1.0
Bone	0.2
All Other Cancer	1.0
Total	5.0

These frequencies of occurrence were then applied to the range of excess deaths previously derived to estimate the range of excess deaths which might occur from plutonium releases postulated in this study. The resulting risk estimators are shown in Table 10.14.

It is noted that the risk estimators listed in Table 10.14 are based on observed health effects produced at high dose levels, primarily by low linear energy transfer (LET) radiations and a hypothesis of linearity between effect and dose. It is probable that these estimators are significantly dependent on the energy transfer (LET) of the ionizing radiation and upon the dose levels actually encountered.[24] Determination of these probable dependencies is not within the scope of this study and the dependencies have not yet been determined by others. Therefore, they have been ignored in this analysis.

Conversion of population doses in man-rem to estimated possible excess cancer deaths was based on the factors presented in Table 10.14. These conversion factors enable a comparison to be made of plutonium shipment risk estimates with other societal risks.

TABLE 10.14. Cancer Risk Estimates for Plutonium in Man

Organ of Reference	Estimated Excess Cancer Deaths Per 10^6 man-rem[a]: Range of Values	Estimated Excess Cancer Deaths Per 10^6 man-rem[a]: Value Used[b]
Lung	16-110	40
Bone	2-17	6

a. Derived from the BEIR Report
b. Geometric Mean

10.6 EXPECTED EXPOSURE FREQUENCY

As shown in Figure 10.1, 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:

$$R_i = \left(AF_{R_i} \times P_{R_i}\right) \times \sum_q \left(C_{E_{i,q}} \times P_{E_q}\right) \qquad (10\text{-}11)$$

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 times the fraction of that material which is lost to the environment in the i^{th} release sequence times the expected frequency of occurrence of the release sequence. This part of the analysis is shown as the top half of Figure 10.1 and all the information needed to evaluate these terms was developed in Section 9. The last two terms represent the consequences of a unit release and the expected frequency of encountering a given set of environmental conditions. These parts of the analysis are shown in the bottom part of Figure 10.1. The primary purpose of previous parts of this section has been to determine the factors required to evaluate the consequences of a release. Simultaneously, the information required to determine the expected frequency that a given environmental consequence will be encountered has been presented. This part of Section 10 will show the development of the frequency of occurrence term.

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

$$P_{E_{j,k,\ell,m}} = P_{j/k} P_k P_{\ell/m} P_m \qquad (10\text{-}12)$$

where

j is the atmospheric stability classification index

k is the windspeed 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 windspeed existing at the time of release. In like manner 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 of the "P" in Equation 10-12 are obtained from the following tables in this section:

P_k = Table 10.1, column 3

$P_{j/k}$ = Table 10.1, columns 4-7

$P_{\ell/m}$ = Table 10.3

P_m = Table 10.5.

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:

$$\sum_q \left(C_{E_{i,q}} \times P_{E_q} \right) = \sum_{j,k,\ell,m,n} 11.4\ K_{1,i}\ K_2\ A_{n,j,k} (\overline{E/Q})_{n,j,k} N_{\ell/m} P_{j/k} P_k P_{\ell/m} P_m \tag{10-13}$$

where

11.4 is the factor to convert grams releases to curies (Table 10.6)

$K_{1,i}$ converts curies received to organ dose (Table 10.7)

K_2 converts organ dose to health effects (Table 10.14)

$A_{n,j,k}$ is the area between two isopleths n and n-1 (Tables 10.10 and 10.11

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

$\overline{E/Q}$ = $\overline{UE/Q}$ (Tables 10.10 and 10.11) divided by $\overline{U}$ (Table 10.3).

$N_{\ell/m}$ is the population density in the release plume (Table 10.3).

The subscripts and the values for P in Equation 10-13 have been defined following Equation 10-12. The product ($C_{E_{i,q}} \times P_{E_q}$) has units of population health effects per gram of material released. If several organs receive a dose as a result of a release, then the product $K_{1,i}K_2$ for each organ receiving a dose must be summed to get the overall effect to the human body.

Equation 10-13 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 plutonium dioxide in the 6M and liquid nitrate in the L-10 by rail in the United States.

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. S. Hagsgård, S. F. Johnson, G. Jonasson, and S. Henriksson, "The Release of Radioactive Material in the Event of the Destruction of a Full Type A Package," Proc. Second International Symposium on Packaging and Transportation of Radioactive Materials, Gatlinburg, TN, October 1968.

3. W. R. Marshall, Jr., "Atomization and Spray Drying," Chemical Engineering Progress Monograph Series, no. 2, vol. 50, Amer. Inst. Chem. Engineers, p. 6, 1954.

4. J. Mishima, L. C. Schwendiman, and C. A. Radasch, Plutonium Release Studies, IV. Fractional Release from Heating Plutonium Nitrate Solutions in a Flowing Airstream, BNWL-931, Battelle, Pacific Northwest Laboratories, Richland, WA, November 1968.

5. R. Brown and J. L. York, "Sprays Formed by Flashing Liquid Jets," J. Amer. Inst. Chem. Engineers, vol. 8, no. 2, pp. 149-153, May 1962.

6. H. S. Ostrowski, Evaporation and Induced Airflows in Sprays Produced by Superheated Water Jets, Ph.D. Thesis, The University of Michigan, 1966.

7. W. R. Marshall, Jr., "Atomization and Spray Drying," Chemical Engineering Progress Monograph Series, no. 2, vol. 50, Amer. Inst. Chem. Engineers, p. 105, 1954.

8. O. J. Wick, Ed., Plutonium Handbook, Gordon and Beach Science Publishers, New York, 1967.

9. J. Mishima, A Review of Research on Plutonium Release During Overheating and Fires, HW-83668, General Electric Co., Richland, WA, August 1964.

10. A. M. Amato, A Mathematical Analysis of the Effects of Wind on Redistribution of Surface Contamination, WASH-1187, USAEC, Division of Biology and Medicine, Washington, D.C., September 1971.

11. D. E. Michels, Diagnosis of Plutonium Re-Entrainment in Air, RFP-1927, Dow Chemical Co., Rocky Flats Division, Golden, CO, April 1973.

12. G. A. Sehmel, Particle Resuspension from Asphalt Roads Caused by Car and Truck Traffic, BNWL-SA-4175, Battelle, Pacific Northwest Laboratories, Richland, WA, January 1972.

13. W. G. N. Slinn, "Initial Resuspension Model," in Pacific Northwest Laboratory Annual Report for 1972 to the USAEC Division of Biomedical and Environmental Research, Volume II: Physical Sciences, Part I, Atmospheric Sciences, BNWL-1715 Pt. 1, Battelle, Pacific Northwest Laboratories, Richland, WA, April 1973.

14. G. A. Sehmel, "Resuspension by Wind at Rocky Flats," in Pacific Northwest Laboratory Annual Report for 1972 to the USAEC Division of Biomedical and Environmental Research, Volume II: Physical Sciences, Part I, Atmospheric Sciences, BNWL-1715 Pt. 1, Battelle, Pacific Northwest Laboratories, Richland, WA, April 1973.

15. J. Mishima and L. C. Schwendiman, Some Experimental Measurements of Airborne Uranium (Representing Plutonium) in Transportation Accidents, BNWL-1732, Battelle, Pacific Northwest Laboratories, Richland, WA, March 1973.

16. Report of Committee II on Permissible Dose for Internal Radiation, ICRP Publication 2, Pergamon Press, 1959.

17. Recommendations of the International Commission on Radiological Protection, ICRP Publication 6, Pergamon Press, 1962.

18. The Metabolism of Compounds of Plutonium and Other Actinides, A Report prepared by a Task Group of Committee 2 of the International Commission on Radiological Protection, ICRP Publication 19, Pergamon Press, May 1972.

19. J. Houston, D. L. Strenge, and E. C. Watson, DACRIN Computer Program for Calculations of Organ Dose from Acute or Chronic Radionuclide Inhalation, BNWL-B-389, Battelle, Pacific Northwest Laboratories, Richland, WA, December 1974.

20. David H. Slade, Ed., Meteorology and Atomic Energy, 1968, TID 24190, Office of Information Services, U.S. Atomic Energy Commission, Washington, D.C., 1968.

21. W. J. Bair and R. C. Thompson, "Plutonium: Biomedical Research," Science, vol. 183, p. 715, February 22, 1974.

22. W. J. Bair, C. R. Richmond, and B. W. Wachholz, A Radiobiological Assessment of the Spatial Distribution of Radiation Dose from Inhaled Plutonium, WASH-1320, U.S. Atomic Energy Commission, Washington, D.C., September 1974.

23. The Effects on Populations of Exposure to Low Levels of Ionizing Radiation, Report of the Advisory Committee on the Biological Effects of Ionizing Radiations, National Academy of Science, November 1972.

24. National Council on Radiation Protection and Measurements, Review of the Current State of Radiation Protection Philosophy, NCRP Report no. 43, Washington, D.C., January 15, 1975.

11.0 THE RISK OF SHIPPING PLUTONIUM DIOXIDE AND LIQUID NITRATE BY RAIL

In this section the risk of shipping plutonium by rail is calculated using the model described in Section 3 and the data developed in Sections 9 and 10. As stated in Section 3, the first step in making the risk assessment is to develop a system description to define the extent and conditions of the assessment. Two risk assessments for plutonium nitrate and dioxide shipments were made in this study. System descriptions for the two cases are given in Section 11.1. The risk evaluations are presented in Section 11.2. Section 11.3 contains a discussion of uncertainties in the results. Major contributors to the risk and the sensitivity of the assessment to pertinent parameters are indicated in Section 11.4. Section 11.5 presents a comparison of the risk in shipment by rail with that in shipment by truck.

11.1 SYSTEM DESCRIPTION

Two cases were analyzed. The first case compares the risk of shipping plutonium dioxide powder in 6M containers with the risk of shipping plutonium nitrate solution in L-10 containers. The second case evaluates the annual U.S. risk from rail transport of plutonium at a shipping level projected for the early 1980s.

11.1.1 System Description for the Plutonium Dioxide and Liquid Nitrate Comparison

For the comparison it is assumed that there is a requirement to ship 1 metric ton of plutonium a distance of 1500 miles in either the form of dioxide or liquid nitrate; the dioxide being shipped in 6M containers and the nitrate solution in L-10 containers. It is further assumed that shipments would be made in 1980 by rail, in an exclusive use boxcar, across a region designated as Zone III (S.E. and N. Central United States). It is further assumed that the shipment will be escorted. The boxcar is assumed to be of the "Damage Free" type having impact cushioning couplers.

The number of shipments, quantity shipped, shipping arrangement and the shipping distance must be defined for each form of plutonium before the risk can be assessed. The number of shipments required to transport 1 metric ton of plutonium in both the form of oxide and the form of nitrate has been based on shipping regulations, container capacities, transport indices for criticality safety, weight limitations and the physical dimensions of the railcars. These results and the expected accident frequency per metric ton shipped are shown in Table 11.1.

TABLE 11.1. Shipping Characteristics for L-10 and 6M Assumed for Analysis (Based on the Shipment of 1 Metric Ton of Pu)

	PuO_2 Form in 6M Container	$Pu(NO_3)_4$ Form in L-10 Container
Amount Pu/Container, kg	2.55[a]	2.00[b]
Containers/MT Pu	390	500
Containers/Shipment	90[c]	68[d]
Shipments/MT Pu	5	8
Distance/Shipment, mi.	1500[e]	1,500[e]
Total Shipment Miles/MT Pu	7500	12,000
Accident Probability, #/car mile	1.37×10^{-6}[f]	1.37×10^{-6}[f]
Accident Frequency, #/MT Pu	1.03×10^{-2}	1.64×10^{-2}

(a) Limited by 30 watt heat generation rate
(b) 8.0 liters of 250 g Pu/l solution
(c) Limited by dose rate external to vehicle[1]
(d) Limited by criticality safety considerations[2]
(e) Assumed average distance between reprocessing plant and fuel fabrication plant
(f) Reference 3.

The isotopic composition of the plutonium used in this study is given in Table 10.6. The composition represents the average expected from LWR fuel in the early 1980s. Based on 30 watt per container heat generation limit, the mass of PuO_2 permitted in a 6M is 2.9 kg (11.4 watts/kg of PuO_2 for these isotopics). With this limit, 390 containers are required to hold 1 metric ton of plutonium. Based on dose rate calculations, 90 containers can be transported in one shipment if the containers are arranged three across and centered, 45 in each end of the railcar. This means that each shipment would contain no more than 230 kg of plutonium and 5 shipments would be required to transport 1 metric ton of plutonium.

For the liquid nitrate shipment where the number of packages per railcar is assumed to be limited by criticality safety considerations, a centered shipping arrangement of four containers across, 9 rows in one end of the car and 8 in the other was used to minimize the dose rate. With 68 packages per car, a shipment of liquid nitrate with up to 136 kg of plutonium could be made. A total of 8 shipments would be needed to transport 1 metric ton of plutonium.

11.1.2 System Description for Evaluating the Risk of Plutonium Transport in the United States in the Early 1980s

A major portion of the description for the comparison case can be used in the system description for the U.S. annual risk evaluation for the early 1980s. Two additional pieces of information are required. First, the total quantity shipped annually must be specified. Second, a composite shipping route, representative of plutonium transportation throughout the contiguous United States, must be constructed.

As stated in Section 4.1, it is assumed that in the early 1980s the nuclear power industry will have grown to include 100 operating power reactors. It is further assumed that an industry this size will ship 18 metric tons of plutonium annually. For this study, it is also assumed that all shipments will be by rail.

The composite route can be obtained from information developed in Section 4. In the 1980s the reprocessing load is assumed to be met by the Barnwell and West Valley Plants, with Barnwell handling 67% of the load. Using this factor and the distribution of plutonium fuel fabricators listed in Section 4.4, the relative region mileage of a composite shipment route in the United States can be developed. The composite route is shown in Table 11.2.

TABLE 11.2. Characteristics of a Composite U.S. Route for Plutonium Transport in the Early 1980s

Zone Number	Geographical Description	Average Route Length in Zone (weighted by all routes) Miles	Fraction of Total Mileage Transversing the Zone
I	North Atlantic Seaboard	5	0.003
II	Great Lake States	200	0.131
III	North Central and Southeast	690	0.451
IV	West	635	0.415
Total	Entire U.S.	1530	1.000

11.2 RISK EVALUATIONS FOR PLUTONIUM DIOXIDE AND LIQUID PLUTONIUM NITRATE SHIPMENTS

The risk calculated for plutonium shipment by rail is presented in this section. Section 11.2.1 presents a detailed development of the risk equation and a discussion of measures of risk. A comparison of the risk in rail shipment of plutonium dioxide powder in 6M containers and of plutonium nitrate solution in L-10 containers is given in Section 11.2.2. The annual risk in the early 1980s from these two types of shipments is given in Section 11.2.3.

11.2.1 The Risk Equation

As described in Section 3, the total risk is defined as:

$$R = \sum_i R_i \qquad (11\text{-}1)$$

where

$$R_i = \left(AF_{R_i} \times P_{R_i}\right) \times \sum_q \left(C_{E_{i,q}} \times P_{E_q}\right). \qquad (11\text{-}2)$$

The subscript "i" refers to the i^{th} release sequence. In Section 10, a general equation was developed for the terms in the second set of parenthesis in Equation 11-2. Substituting this expression into Equation 11-2 results in the following equation.

$$R_i = \left(AF_{R_i} \times P_{R_i}\right) \sum_{j,k,\ell,m,n} 11.4\ K_{1,i}\ K_2\ A_{n,j,k}\ (\overline{E/Q})_{n,j,k}\ N_{\ell/m}\ P_{j/k}\ P_k\ P_{\ell/m}\ P_m. \tag{11-3}$$

The total risk of shipping one container then becomes

$$R = \sum_{i,j,k,\ell,m,n} \left[11.4\ K_{1,i}\ K_2\ AF_{R_i}\ A_{n,j,k}\ (\overline{E/Q})_{n,j,k}\ N_{\ell/m}\right] \times \left[P_{R_i}\ P_{j/k}\ P_k\ P_{\ell/m}\ P_m\right]. \tag{11-4}$$

Equation 11-4 has been arranged so that the frequency of occurrence terms are separated from the consequence terms. As described in Section 10, each container is analyzed individually. Thus the risk of shipping N_c containers is given by the following equation:

$$R_T = \sum_{i,j,k,\ell,m,n} \left[11.4\ K_{1,i}\ K_2\ AF_{R_i}\ A_{n,j,k}\ (\overline{E/Q})_{n,j,k}\ N_{\ell/m}\right] \times \left[N_c\ P_{R_i}\ P_{j/k}\ P_k\ P_{\ell/m}\ P_m\right]. \tag{11-5}$$

The N_c term is included in the frequency of occurrence term. By putting N_c in this part of Equation 11-4 the consequences of an accident are made proportional to the amount of material in one container and the frequency of release increases with the number of containers shipped in any year. This agrees with the risk model and is valid as long as the likelihood of failure of more than one container in an accident is small. A multiple failure analysis is given in Appendix F.

In Equation 11-5 the frequencies of occurrence and the consequences of all accidents are summed to obtain a single annual risk number. This number can be thought of as the expected frequency of occurrence of a fatality attributable to plutonium transport. As discussed in Section 1, the risk spectrum must also be considered because it differentiates between an event which occurs once a year resulting in one fatality and an event which occurs once in a thousand years but results in 1000 fatalities. In order to distinguish between these two events, which have the same risk but different severities, curves are constructed which plot accident severity versus the expected frequency of accidents with greater severity. The two events described above have discrete contributions to the graph. Thus for the risk of two operations to be truly comparable, they must have both the same risk and the same risk spectrum.

Both the risk and the risk spectrum can be obtained from the terms in Equation 10-5. The number of fatalities from an accident release sequence is expressed by the term inside the first set of brackets in Equation 10-5. The frequency of the consequence (i.e., number of fatalities) is obtained by calculating the terms within the second set of brackets. These two terms can be thought of as pairs of numbers. The risk spectrum curves can be obtained choosing a value for N, the number of fatalities, and then scanning the paired sets of numbers for any first terms which exceed N. The summation of all second terms which have a first term greater than or equal to N is the expected frequency of occurrence of accidents which result in N or more fatalities. This is one point on the risk spectrum curve. This operation is continued until points on the risk spectrum curve are calculated for selected values of N down to one fatality.

11.2.2 Risk Comparison of Plutonium Dioxide and Liquid Plutonium Nitrate Shipments by Rail

Based on the data shown in Table 11.1, accidents are expected to occur at a rate of 1.37×10^{-6}/shipment mile, i.e., once in 730,000 shipment miles.

For a shipping distance of 1500 miles, the expected frequency at which plutonium shipments will be involved in an accident is 1 in 486 shipments. Most accidents will not result in a release of plutonium.

The frequency of a release has been estimated using the data presented in Section 9. For the liquid nitrate shipment, the analysis shows that one out of 5.6×10^5 containers shipped is estimated to release some material as a result of an accident. For the oxide shipment in the 6M container, one release can be expected for every 6.3×10^6 containers shipped.

The risk spectrum curves for shipping 1 metric ton of plutonium across the north central and southeastern United States for the two plutonium forms are shown in Figure 11.1. Also shown in the figure are the risk spectra for meteorites, chlorine shipments, the total of all natural disasters and the total of all man-caused disasters. These later curves were taken from WASH-1400.[4] It can be seen from the figure that the nitrate solution represents a risk of an individual fatality which is more than two orders of magnitude above the dioxide. In addition, the spectrum curves show that the expected number of fatalities is in all cases more than two orders of magnitude above the dioxide at the comparable expected rates of occurrence. One in seven accidents where an L-10 containing nitrate solution fails will result in one or more fatalities attributable to the release. For the dioxide, one release in about 220 will result in one or more fatalities.

From the above occurrence frequencies and the number of containers per shipment, the likelihood of one or more fatalities from plutonium release during a 1500 mile shipment of plutonium nitrate solution in L-10 containers is about 1 in 450,000. The corresponding likelihood for plutonium dioxide powder shipment in 6M containers is 1 in 72 million.

Although not shown in the spectrum curves, the calculations show that the highest number of fatalities occurred under very stable atmospheric conditions (Pasquill F Stability) and at 1 m/sec windspeeds. The curves shown in Figure 11.1 do not consider evacuation of people from the release plume. However, it should be noted that at low windspeeds, there is some

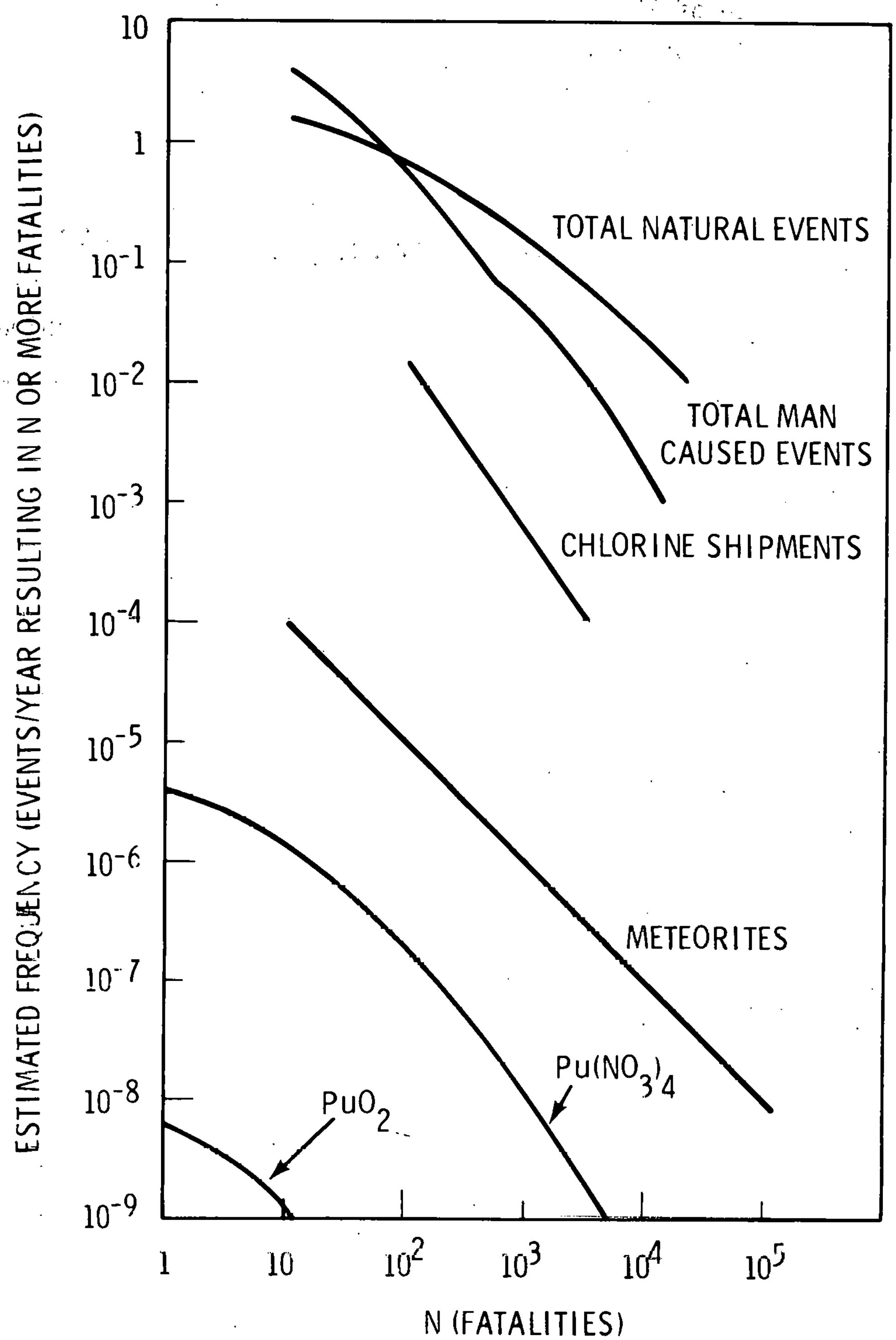


FIGURE 11.1. Risk Spectrum for Shipping One Metric Ton of Plutonium 1500 Miles Across the North Central and Southeastern U.S.

time available to evacuate people before the release plume reaches their location. For example, if the average windspeed is 1 m/sec, approximately 16 minutes is available before the release plume travels 1 km. Only 2.5 hours is available 10 km downwind. Although 16 minutes does not allow time to evacuate individuals, two and a half hours would appear to represent a time interval during which some evacuation might be possible. In this respect, the results presented here represent a conservative upper limit.

Sensitivity analyses presented in Section 11.4 will further analyze the risk spectrum curves and identify the more important contributors to the risk.

11.2.3 The Risk of Shipping Plutonium Dioxide or Liquid Plutonium Nitrate in the Early 1980s

The annual risk to the U.S. from plutonium dioxide powder shipment in 6M containers and plutonium nitrate solution shipment in L-10 containers in the early 1980s is reported in this section. Figure 11.2 shows the risk spectrum for both the dioxide and nitrate shipments. The liquid nitrate fatality spectrum remains more than 2 orders of magnitude more severe than the dioxide case at comparable rates of occurrence. Also shown in Figure 11.2 are the risk spectra for meteorites, chlorine shipments, the total of all natural disasters and the total of all man-caused events. It can be seen that the liquid nitrate shipment risk spectrum is comparable to the risk spectrum for meteorites. Since the risks from chlorine shipments and other man-caused events pose a significantly greater hazard, the conclusion would be that many commonly accepted risks pose a hazard which is greater than that from plutonium shipments.

Discussions of the uncertainties in the results presented in this section and their sensitivity to pertinent parameters in the analysis are presented in Sections 11.3 and 11.4.

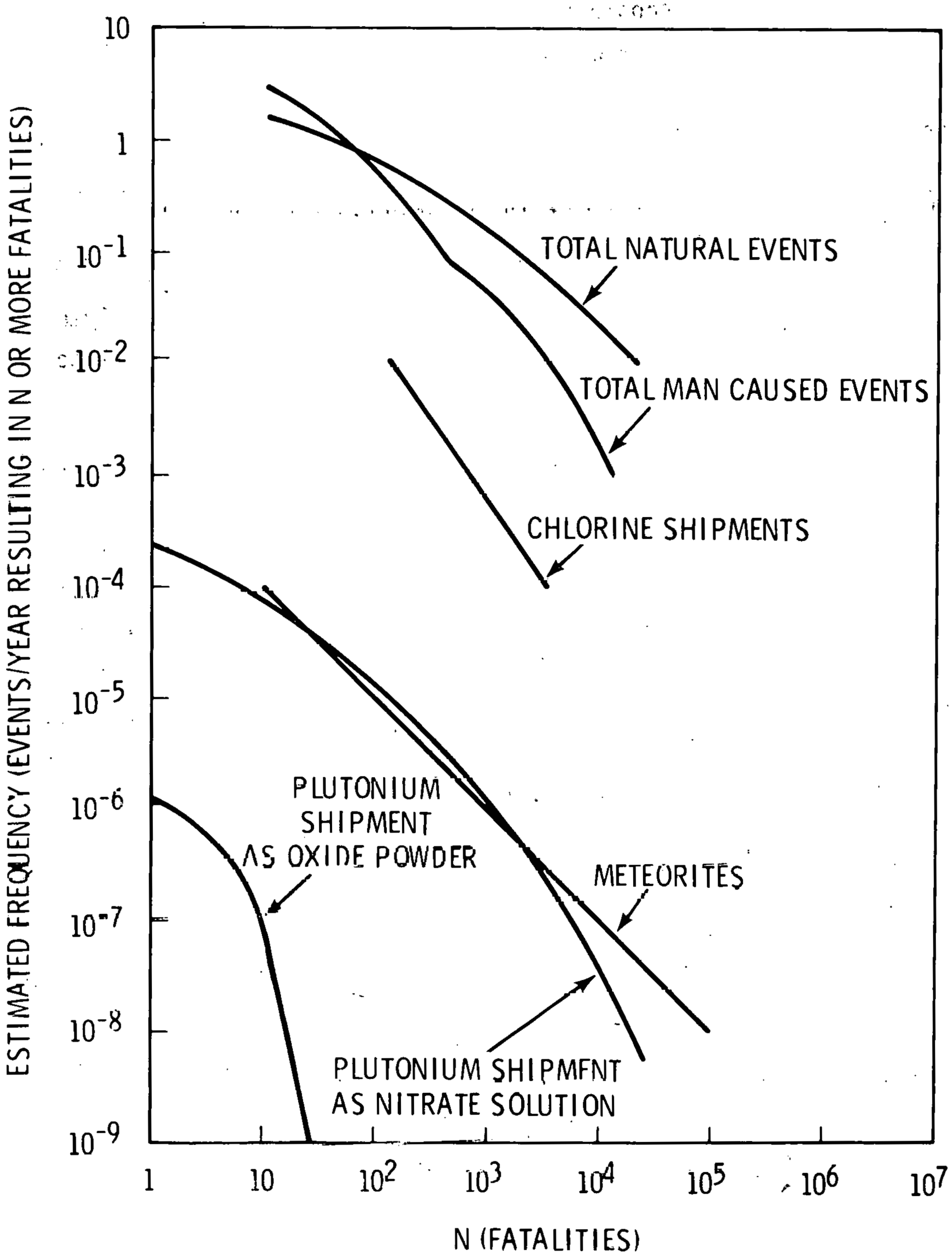


FIGURE 11.2. Risk Spectrum for Plutonium Shipments in the Early 1980s for the Entire U.S.

11.3 RISK CALCULATIONAL UNCERTAINTIES

In this section, two types of calculational uncertainties will be discussed. The first concerns the propagation of uncertainty in the basic risk equation. The second concerns the assumption that multiple container failures are unlikely to occur from the same accident.

11.3.1 Analyses of Variance in Risk Value

The risk value obtained in the evaluation is the linear product of several parameters, each of which has a mean and a distribution of values about the mean. The basic risk equation for the i^{th} release sequence is:

$$R_i = \left(AF_{R_i} \; P_{R_i}\right) \times \left(\sum_q C_{E_{i,q}} \; P_{E_q}\right) \tag{11-6}$$

The terms were defined in Section 3. The first three terms specify the release fraction and the remainder of the environmental consequences. In generating the figures shown in this section, the environmental terms were included in the analysis as distributed variables. However, the mean values were used for the release terms. This section will consider the uncertainties resulting from the use of the mean values.

F_{R_i} and P_{R_i} can be represented by equations of the form:

$$F_{R_i} = f_{1_i} f_{2_i} f_{3_i} f_{4_i} \tag{11-7}$$

$$P_{R_i} = \prod_{n=1}^{N} P_{i_n} . \tag{11-8}$$

In these equations the f's are barrier release fractions and the P's represent the expected frequency of occurrence for the N elements in release sequence i. Since some of the terms are poorly known, it is important to quantify to some extent the effect of the uncertainties on the final result. This section will look primarily at several measures of uncertainties derived from a statistical evaluation of Equations 11-1 and 11-2.

The statistical evaluation requires the definition of several terms. The first is the expected value of a variable "x" which is defined as:

$$E(x) = \int_{-\infty}^{\infty} x f(x) dx \qquad (11\text{-}9)$$

where f(x) is the probability density function. The expected value of x is frequently represented by the symbol "μ" and represents the mean value. The second term is the variance, denoted by the symbol "σ^2" and defined as:

$$\sigma^2 = E(x-\mu)^2 = \int_{-\infty}^{\infty} (x-\mu)^2 f(x)dx = E(x^2) - [E(x)]^2. \qquad (11\text{-}10)$$

The standard deviation, denoted by the symbol "σ" is obtained by taking the square root of the variance. Finally, the coefficient of variation, denoted by the symbol "ν", is defined as:

$$\nu = \frac{\sigma}{\mu}. \qquad (11\text{-}11)$$

The behavior of the coefficient of variation is a measure of how uncertainties propagate through various equations, like Equations 11-7 and 11-8.

Equation 11-7 is the product of four terms. If they are independent then the variance of the product is related to the variance of the terms by the relationship:

$$\sigma^2_{F_R} = E(F_R^2) - \left[E(F_R)\right]^2 = \prod_{r=1}^{4} E\left[f^2_{r_i}\right] - \prod_{r=1}^{4} \left[E(f_{r_i})\right]^2. \qquad (11\text{-}12)$$

The best way to look at the propagation of uncertainties is to look at some examples. Consider the case where the release fractions through each barrier are independent and uniformly distributed between the limits of zero and one. Then:

μ_{f_r} = 1/2 for all values of r $\varepsilon[1,4]$

and

$$\sigma^2_{f_r} = 1/12 \text{ for all values of } r \; \varepsilon[1,4].$$

Then using Equation 11-12.

$$\sigma^2_F = \frac{1}{3}^4 - \left[\left(\frac{1}{2}\right)^2\right]^4 = \frac{1}{81} - \frac{1}{256} = 8.44 \times 10^{-3}$$

and

$$\nu_F = \frac{\sqrt{8.44 \times 10^{-3}}}{0.0625} = 1.47.$$

The coefficient of variation of the individual terms was

$$\nu_{f_r} = \frac{\sqrt{1/12}}{1/2} = 0.5774.$$

Thus the coefficient of variation, which is a measure of the width of the distribution relative to the mean, has increased by a factor of 2.55.

It is interesting to note that the fraction immediately released upon failure determined in Section 10.1 was found to be 0.76×10^{-3} with a standard deviation of 0.46×10^{-3}. This corresponds to a coefficient of variation of 0.60 which is quite close to the value of $\nu_{f_r} = 0.5774$ used in the previous example. If the same relative uncertainty held true for each barrier, then the final result would have a coefficient of variation equal to 1.47. Assuming the final distribution is normal, then there is 95% confidence that the value of the release fraction will not be greater than $1.645\ \sigma_f + \mu$. Thus it can be said with a confidence level of 95% that the release fraction will not be more than 3.4 times the value used.

To evaluate the propagation of uncertainties in the expected release frequency, it is convenient to consider a specific distribution, the log normal distribution. The density function for this distribution is:

$$f(x) = \frac{1}{\sigma x \sqrt{2\pi}} \; e^{-\frac{(\ln x - \mu)^2}{2\sigma^2}} \; . \qquad (11\text{-}13)$$

This is the probability density for x which occurs when the variable lnx is normally distributed.

When the expected frequencies are expressed as their logs then the expression for P_R shown in Equation 11-8 becomes

$$\log P_{R_i} = \sum_n^N \left(\log P_{i_n} \right) . \qquad (11\text{-}14)$$

The variance of a sum of random variables is related to the variance of the individual random variables by the expression:

$$\sigma^2(\log P_{R_i}) = \sum_n \sigma^2 \left(\log P_{i_n} \right) . \qquad (11\text{-}15)$$

Typically, the values of P_i may be only known to an order of magnitude, i.e., 25% of the time the value will be more than a half an order of magnitude lower and 25% of the time it might be more than a half order of magnitude higher. These uncertainty levels correspond to a $\sigma = 0.74$. If there are four terms in Equation 11-8 which have standard deviations approaching this value, then $\sigma(\log P_{R_1}) = 1.48$.

Expressed in terms of uncertainties, the resultant frequency of occurrence can be expected to be two orders of magnitude lower than the value of P_{R_i} 25% of the time and it can be expected to be two orders of magnitude higher 25% of the time.

Since there are some variables which are known no more accurately than a $\sigma = 0.74$ using the log normal distribution, a $\sigma = 1.48$ on the final result, using the same distribution, appears reasonable. Since the one sided 95% confidence interval corresponds to a $(1.645)\sigma = 2.44$, the 95% confidence limit on the occurrence frequency is estimated to be slightly greater than two orders of magnitude above the values presented in the analysis. A more complete analysis may show that a smaller confidence level is warranted.

Since all the risk plots are constructed on a log scale, the 95% confidence level on the release fraction, assuming a normal distribution, is about a half an order of magnitude. This could be considered to be the estimated uncertainty level in the number of fatalities resulting from a given release.

11.3.2 Analysis of Multiple Container Failures

Based on the information presented in Section 11.2, for dioxide shipments there is one container failure out of 12,330 containers which have been involved in accidents. As discussed in Section 11.2.1, this number is based on a single container analysis method and is strictly valid only if it is highly unlikely that two containers in the same shipment will fail from independent causes and if accident environments causing multiple container failure are also unlikely. These points will be addressed in the following paragraphs.

What is the probability that two containers will fail in the same accident? In this first case we will consider the causes of the failure to be independent, i.e., that there are no accident stresses capable of causing many simultaneous failures, then the probability of "x" failures in a shipment of "n" containers given the probability of one defective container is:

$$P(x) = \binom{n}{x} P^{x} (1-P)^{n-x} \qquad (11\text{-}16)$$

where

$$\binom{n}{x} = \frac{n!}{x!\ (n-x)!} .$$

Then the probability of one container out of 90 in the shipment failing in an accident is:

$$P(1) = \binom{90}{1}\left(\frac{1}{12330}\right)\left(1 - \frac{1}{12330}\right)^{89} = \binom{90}{1}\left(\frac{0.9928}{12330}\right) = 7.3 \times 10^{-3} .$$

The probability of two failing in the same accident is:

$$P(2) = \binom{90}{2}\left(\frac{1}{12330}\right)^{2}\left(1 - \frac{1}{12330}\right)^{88} = \frac{(90)(89)}{(1)(2)}\ \frac{(0.9929)}{(12330)^{2}} = 2.6 \times 10^{-5}.$$

Thus two container failures in the same accident are expected less than once in 38,000 accidents. This is greater than two orders of magnitude less frequent than the single container failure statistics and can be neglected in the risk assessment. Although the difference is not as great, the same conclusions also hold for the liquid nitrate shipment.

The above analysis postulated that there are no accident stresses capable of causing many simultaneous failures. However, two accident stresses which do not meet this criterion are criticality and inertial crush.

If criticality occurs, the internal pressures generated within each container could rupture the containers. Based on the results presented in Sections 7.0 and 9.0, and Appendix C, criticality would not be an initiating event. However, events and conditions following a severe accident in which plutonium is released could result in criticality. Nevertheless, the necessary events and conditions for criticality to occur were found to be so limited that this stress does not significantly contribute to the risk levels.

The crush environment requires more detailed analysis because in accidents involving extreme decelerations multiple containers could fail by drum lid removal due to inertial crush. Since Sandia estimates that about 1/3 of the cargo could be lost in 6.8% of all accidents, more than one failed container would likely be removed from the railcar in this case. Failed containers which lose vermiculite when removed from the railcar are then susceptible to releasing plutonium if a fire occurs after the accident.

The detailed evaluation of the crush environment is presented in Appendix F. The results of this supplemental evaluation for the L-10 shipment are shown in Figure 11.3. The basic risk analysis model assumes that only one container fails in an accident but at an accident frequency multiplied by the number of containers in the shipment. Examination of Figure 11.3 shows that this assumption is nonconservative at the high consequence end of the risk spectrum, but conservative at the low consequence end. Since crush is an important factor in the nitrate shipment risk (see Section 11.4) the multiple container evaluation of crush risk was used together with the independent container evaluation for all other release

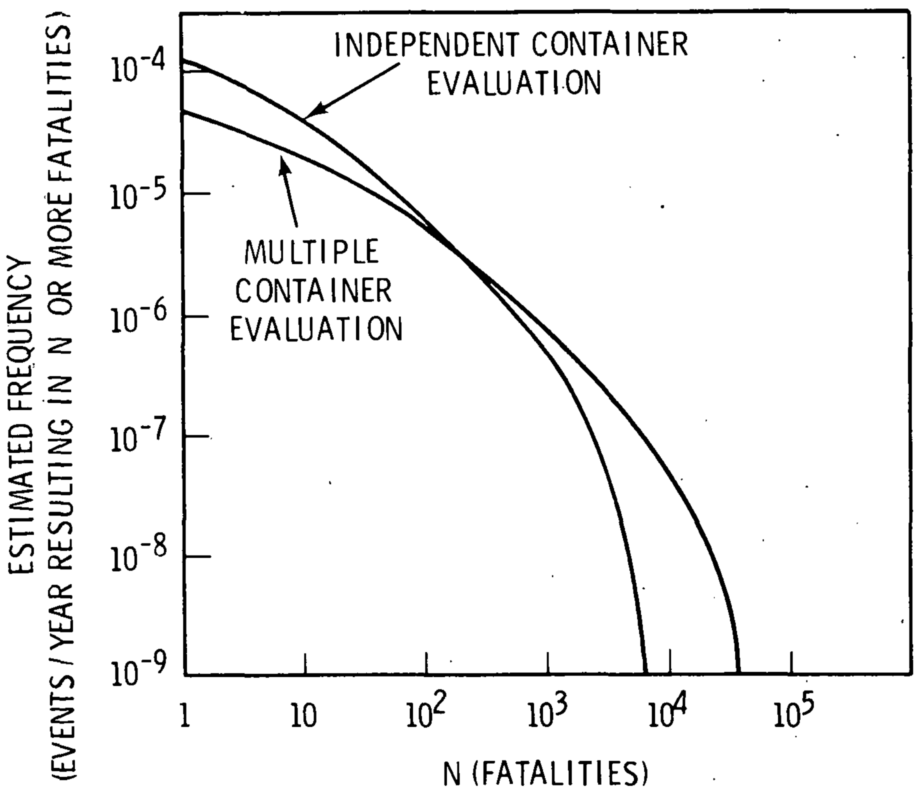


FIGURE 11.3. Risk Spectrum Evaluation of Single and Multiple Container Failure from Crush Forces Imposed on the L-10 Container in the Accident Environment

sequences. Since crush is not an important factor in the dioxide shipment risk, and since the difference in the multiple and independent container evaluations is less, the independent container evaluation was used to express the dioxide shipment risk.

11.4 RISK SENSITIVITY EVALUATIONS

Prior to discussion of the sensitivity of the risk evaluation to the values of certain system parameters, it is important to point out a fundamental sensitivity of the risk evaluation; i.e., the calculated risk is a function of the shipping assumptions. The present risk assessment is made for the system described in Section 11.1. Shorter shipment distances, the use of different shipping containers, etc., would result in a different risk. In general, re-evaluation would be required to determine the risk under these changed conditions. However, for some simple changes in shipment conditions, determination that the risk would be less than, or greater than, that calculated for the systems considered in this analysis could be made without recalculation.

Risk sensitivity evaluations permit analysis of the importance of the various factors which contribute to the risk. They can be used: 1) to identify and quantify the effects of the major contributors to the risk, and 2) to identify ways to improve the certainty in the risk evaluation.

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 of complex. In some cases, however, a parameter enters simply and directly into the risk equation and the sensitivity can be determined directly.

The results of the risk sensitivity studies for the L-10 liquid plutonium nitrate shipment analysis are given in Table 11.3. The effects on

TABLE 11.3. Risk Sensitivity Cases for Liquid Nitrate Shipments for U.S. in the Early 1980s

Description of Sensitivity Case	Risk Level (Estimated Annual Frequency of Occurrence of One or More Fatalities)	Risk Level Relative to Base Case
Base Case[a]	3.16×10^{-4}	1.00
Stabilized Vermiculite	7.31×10^{-6}	0.02
Zero Low Vermiculite	3.14×10^{-4}	0.99
Zero Packaging Condition Deficiencies	3.14×10^{-4}	0.99
Zero Crush of Outer Drum	1.84×10^{-4}	0.58
Zero Puncture of Pressure Vessel	3.16×10^{-4}	1.00
2-Hr Release Duration	3.16×10^{-4}	1.00
Release Fractions = 1.0	5.98×10^{-3}	19
Improper Shipment (Overpressurization)	3.16×10^{-4}	1.00

a. Shipment in early 1980s as described in Section 11.1.2.

the risk spectrum of the more important of these are also shown in Figure 11.4. For the liquid nitrate shipment, the controlling releases involve a fire acting on a container which has less than the required coverage of vermiculite over the pressure vessel. To evaluate the effect of the loose vermiculite, a case was run in which the containers had the required vermiculite level and the vermiculite was stabilized so that loss of integrity of the outer drum in an accident would not result in loss of vermiculite and subsequent failure of the pressure vessel in a short duration fire. The results, shown in Table 11.3 and Figure 11.4 with the designation "Stabilized Vermiculite," indicate a reduction of about 50 in the risk level.

A sensitivity run was made to further analyze the cause of the risk reduction seen in the previous case. In this run the vermiculite was required to be in place (i.e., the package was not shipped with a low vermiculite level) but was not stabilized. The results of this case, designated "Zero Low Vermiculite" in Table 11.3, showed only a 1% reduction in risk level. This indicates that low vermiculite level during shipment, which is a packaging deficiency, contributes to the risk but is not a controlling factor.

To study the effect of other packaging deficiencies on the risk, a case entitled "Zero Packaging Deficiencies" was run. For this case the occurrence frequencies of all packaging deficiency elements (see Section 9) were set at zero. It is seen from Table 11.3 that this essentially does not reduce the risk level beyond that in the previous case, indicating that low vermiculite level is the most important packaging deficiency and that packaging deficiencies are not a controlling factor in the risk.

To evaluate the effect of crush of the outer drum on the risk, a case was run in which the likelihood of crush was set to zero. The results, shown in Table 11.3, indicate that this results in a 42% reduction in the risk. Therefore, crush is a significant contributor to the risk but is less controlling than the loose vermiculite.

A sensitivity case was run in which the probability of puncture of the pressure vessel was set at zero. This resulted in no visible reduction in

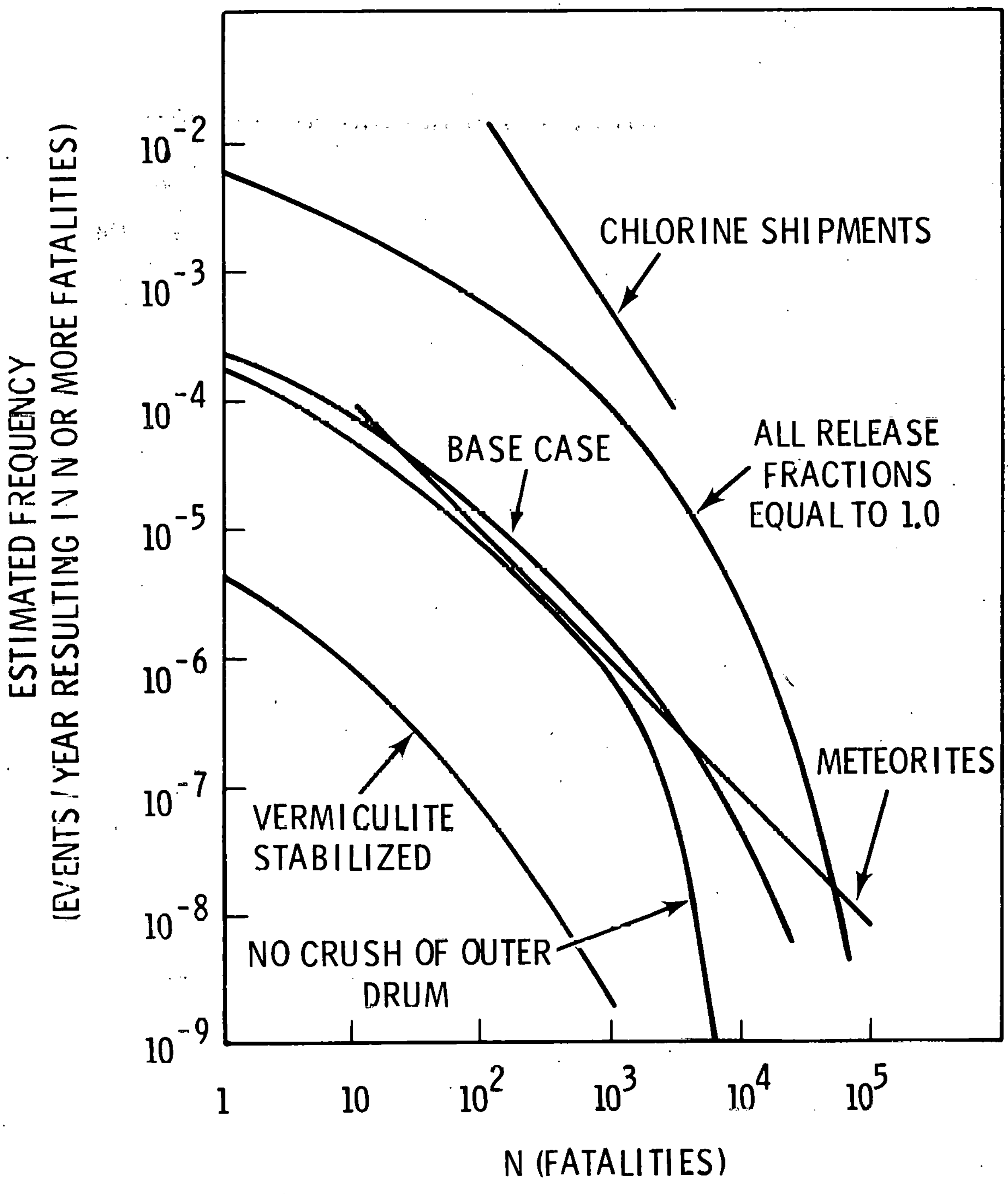


FIGURE 11.4. Sensitivity of the Risk Spectrum Curves to Several Parameters for Liquid Plutonium Nitrate Shipments in the L-10 Container

the risk level indicating that puncture of the pressure vessel is not a significant contributor to the risk of the L-10 shipment.

In the base case it was assumed that actions by escort and emergency personnel could terminate a nonfire-associated release within a half hour after it starts. To study the effect of this assumption a case was run with a 2-hr release duration. It is seen that, due to the characteristics of the nitrate release mechanisms, this has essentially no effect on the plutonium nitrate shipment risk.

As an upper limit example, a case was run which assumed that any release sequence releases the entire content of a container (i.e., the fraction released = 1). It is seen that this increases the risk about a factor of 19.

A possible release mechanism in plutonium nitrate solution shipment is failure of the pressure vessel seal due to extreme pressure resulting from nuclear and chemical actions. Preshipment procedures are designed to preclude the occurrence of this unlikely failure mechanism. It has never occurred in the shipment of plutonium nitrate solution (see discussion for element X64 in Section 9.1.2). However, to study the possible effect of this failure mechanism on the risk an occurrence frequency of 2×10^{-3} per container (10^{-3}/container for both element A58 and element A62) was used in a sensitivity case. This value is considered to be conservative. The results, indicated in Table 11.3 as "Improper Shipment (Overpressurization)," show no significant increase in the risk level.

The results of risk sensitivity studies for the dioxide shipment analysis are given in Table 11.4. The effect on the risk spectrum of the more important cases is also shown in Figure 11.5. It is seen that packaging deficiencies and crush of the outer drum do not contribute significantly to the risk of plutonium dioxide powder shipment in 6M containers.

For the dioxide shipment, puncture of the 2R vessel contributes to greater than 99% of the risk. There was no accident environment or test data applicable to evaluating the puncture probability of the inner 2R vessel, thus the probability was developed from analysis. Further analyses or test data could better determine the probability of 2R vessel puncture.

TABLE 11.4. Risk Sensitivity Cases for Dioxide Shipments in the U.S. in the Early 1980s

Sensitivity Case	Risk Level (Estimated Annual Frequency of Occurrence of One or More Fatalities)	Risk Level Relative to Base Case
Base Case[a]	1.24×10^{-6}	--
Zero Packaging Condition Deficiencies	1.24×10^{-6}	1.00
Zero Crush of Outer Drum	1.23×10^{-6}	0.99
Zero Puncture of 2R Container	2.84×10^{-9}	0.002
2-Hr Release Duration	4.19×10^{-6}	3.4
Release Fractions = 1.0	4.12×10^{-5}	33

a. Shipment in early 1980s as described in Section 11.1.2.

Unlike the results for the plutonium nitrate shipment, the use of a 2-hr release duration in the plutonium dioxide shipment analysis results in an increase of greater than a factor of three in the risk.

As an upper limit example, a run was made which assumed that any release sequence releases the entire content of a container (i.e., the fraction released = 1). The results indicate that this increases the risk about a factor of 33.

The risks for both the nitrate and dioxide shipments are strongly dependent on the amount of material released and dispersed in an accident. Directly applicable data on these processes are sparse. Conservative extensions of existing data were used in the analyses. Additional data on the fraction released and dispersed under simulated extreme accident conditions could increase the certainty of the evaluation.

These sensitivity studies have identified both the major contributors to the shipment risk and areas in which further studies could result in increased knowledge of events and processes pertinent to the assessment.

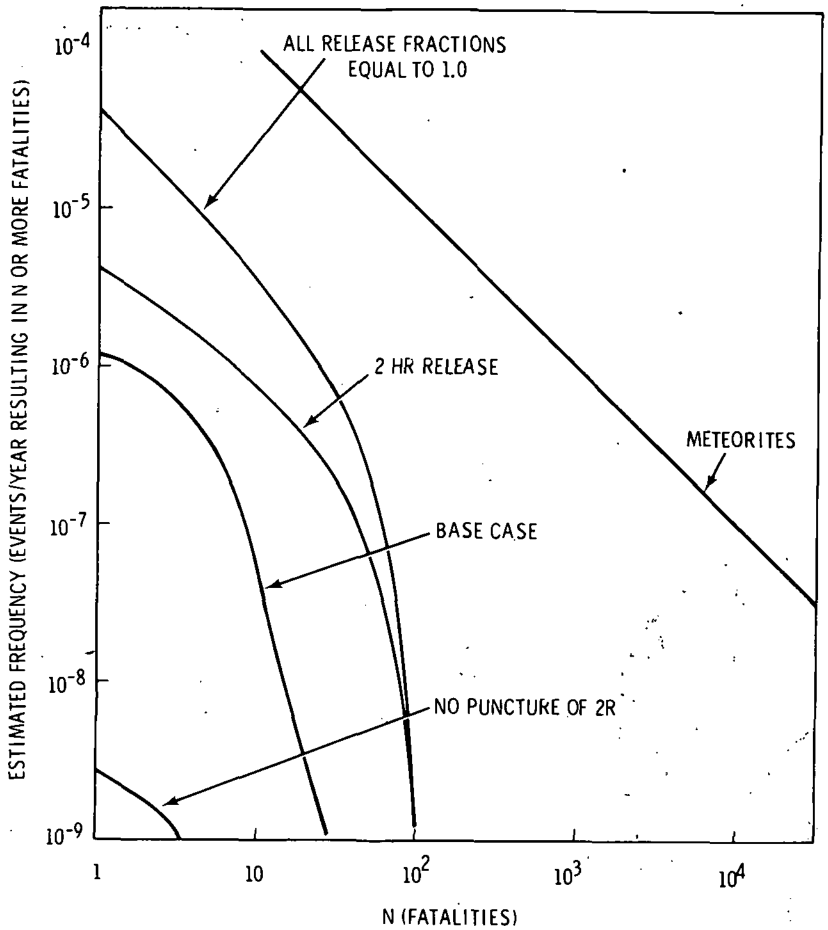


FIGURE 11.5. Sensitivity of the Risk Spectrum Curves to Several Parameters for the Plutonium Dioxide Shipments in the 6M Container

11.5 COMPARISON OF THE ANNUAL RISK USING RAIL SHIPMENT WITH THAT OF USING TRUCK SHIPMENT

The risks in truck shipment of liquid plutonium nitrate and plutonium dioxide powder were assessed in the initial report in this series.[5] The truck shipment risk spectra and the rail shipment risk spectra are shown in Figure 11.6. Each is based on the annual shipment of 18 MT of plutonium. It is seen that the risks for the same form of plutonium are fairly similar for the two transportation modes. The liquid nitrate risk spectrum is slightly higher, and the dioxide powder risk spectrum is slightly lower, for train shipment than the corresponding spectra for truck shipment.

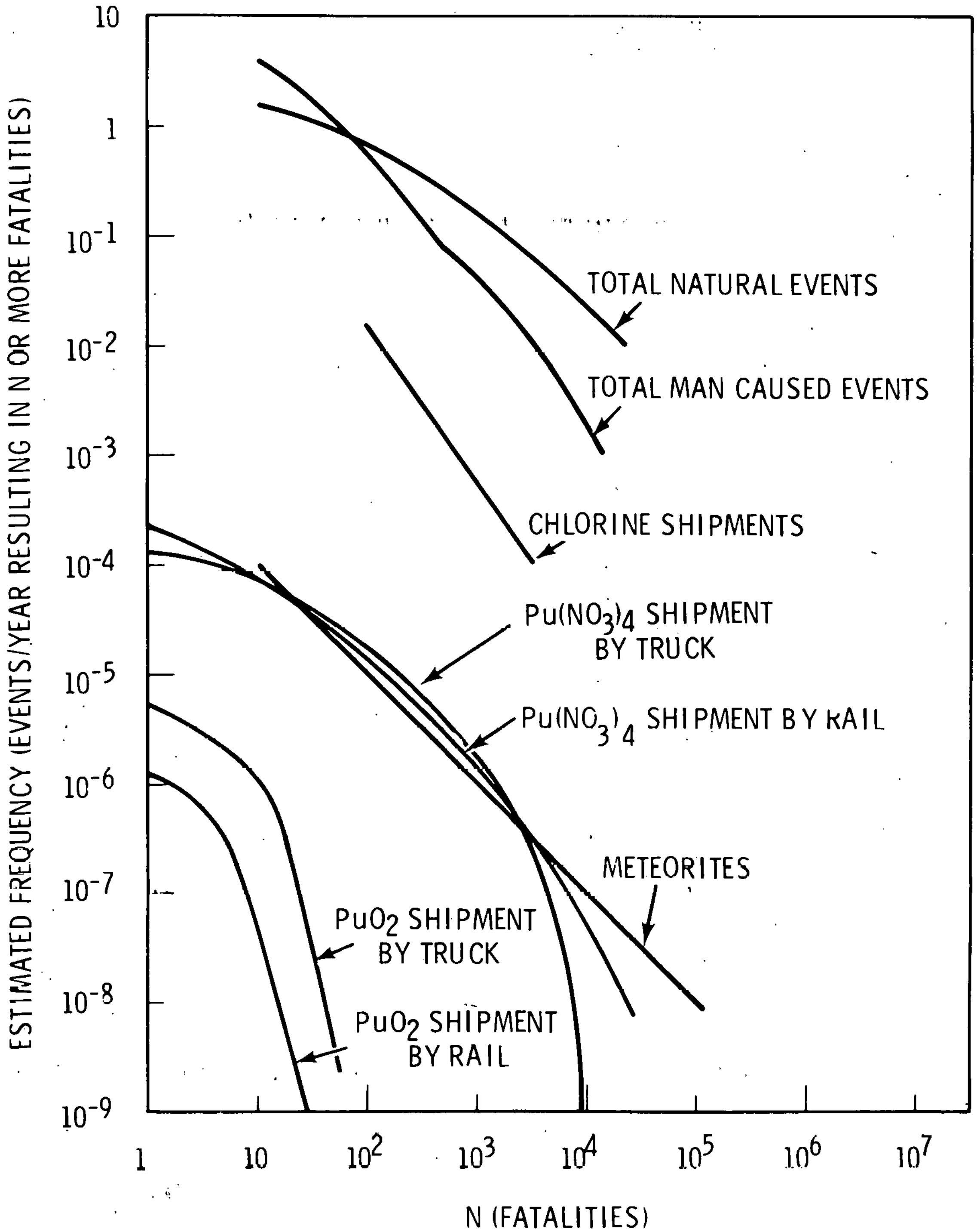


FIGURE 11.6. Comparison of Risk Spectra for Truck and Rail Shipment of Plutonium in the Early 1980s for the Entire U.S.

Another point of interest in comparing the risks in shipments by the different modes is the difference in the factors controlling the risk. This is determined by the sensitivity studies. A comparison of the risk sensitivity results for dioxide shipment by rail and truck is shown in Table 11.5. It can be seen that the mode change essentially has no effect on the parameters controlling the risk for the dioxide shipment. Table 11.6 compares the risk sensitivity results for liquid nitrate shipment by rail and truck. It is seen that in this case the mode change does affect the parameters controlling the risk. Loss of vermiculite in an accident is controlling in both cases but is about half as significant in the rail shipment risk as in the truck shipment risk. Likewise, crush of the outer drum in an accident is about seven times more significant in the rail risk than in the truck risk. Packaging deficiencies play a lesser role in the rail shipment risk than for truck shipment. Differences also exist in the effects of assuming total release and shipment of overpressurized containers.

TABLE 11.5. Comparison of Risk Sensitivities for Rail and Truck Shipment of Plutonium Dioxide Powder in the U.S. in the Early 1980s

Sensitivity Case	Risk Level Relative to Base Case	
	Rail Shipment	Truck Shipment
Base Case	1.00	1.00
Zero Packaging Conditions Deficiencies	1.00	0.98
Zero Crush of Outer Drum	0.99	1.00
Zero Puncture of 2R Container	0.002	0.003
2-Hr Release Duration	3.4	3.7
Release Fractions = 1.0	33	32

TABLE 11.6. Comparison of Risk Sensitivities for Rail and Truck Shipment of Liquid Plutonium Nitrate in the U.S. in the Early 1980s

Description of Sensitivity Case	Risk Level Relative to Base Case	
	Rail Shipment	Truck Shipment
Base Case	1.00	1.00
Stabilized Vermiculite	0.02	0.01
Zero Low Vermiculite	0.99	0.89
Zero Packaging Condition Deficiencies	0.99	0.87
Zero Crush of Outer Drum	0.58	0.94
Zero Puncture of Pressure Vessel	1.00	0.97
2-Hr Release Duration	1.00	1.00
Release Fractions = 1.0	19	3.3
Improper Shipment (Overpressurization)	1.00	1.2

The conclusions from the comparisons are that there is little difference in the risk in shipping plutonium dioxide by rail and shipping it by truck. Likewise, there is little difference in the risk spectra for liquid plutonium nitrate shipment via the two modes. However, vermiculite loss, which controls the risk in both cases, is somewhat less important in rail shipment. In addition, due to the increased number of containers per shipment and the higher deceleration environment in rail accidents, the L-10 response to crush is more important in rail transport.

REFERENCES

1. Code of Federal Regulations, 49CFR, §173.393.

2. R. D. Carter, G. R. Kiel, K. R. Ridgway, Criticality Handbook, ARH-600, Vol. I, June 1968; Vol. II, May 1969.

3. R. K. Clarke, T. J. Foley, W. F. Hartman and D. W. Larson, Severities of Transport Accidents, Volume IV - Trains, SLA-74-001, Sandia Laboratories, Albuquerque, NM, (To be published).

4. Reactor Safety Study - An Assessment of the Accident Risks in U.S. Commercial Nuclear Power Plants, WASH-1400 (DRAFT) U.S. Atomic Energy Commission, Washington, D.C., August 1974.

5. 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.

APPENDIX A

DESCRIPTION OF L-10 AND 6M PACKAGES USED TO SHIP $Pu(NO_3)_4$ AND PuO_2

L-10 PLUTONIUM NITRATE PACKAGE

In fuel reprocessing plants, the initial form of the plutonium produced is plutonium nitrate [$Pu(NO_3)_4$] in 3 - 6 molar nitric acid. Plutonium nitrate solution is normally shipped at a concentration of about 250 g Pu/liter. In the past, the L-10 container, which holds approximately 10 liters of solution, was commonly used for $Pu(NO_3)_4$ shipment. The outer container of the L-10 is two 55-gal drums welded end-to-end.

A single shipment is limited by criticality safety considerations to 68 bottles, or a total of 170 kg of plutonium. A diagram of the L-10 container is shown in Figure A.1. Further details taken from the "Directory of Packagings for Transportation of Radioactive Materials"(1) are summarized below:

Authorized Contents:

Up to 10.5 liters per package of: UNH solutions having concentration of ^{235}U not exceeding 350 g/liter, or having a combined concentration of ^{233}U and ^{235}U not exceeding 250 g/liter; or plutonium nitrate solutions of concentration not exceeding 250 g ^{239}Pu/liter; or 4.5 kg dry Pu-U compounds and mixtures.

Interior and Exterior Dimensions:

Pressure vessel - 4.8 in. ID x 52.2 in. deep inside; Drum - 24 in. diam. x 66-2/3 in. high outside x 18 ga. wall.

Description of Container:

Outer container consists of two 55-gal DOT Spec. 17H drums end-to-end. Inner container is a stainless steel pressure vessel (3000 psi at 600°F) supported inside the drum by a tubular steel frame. Annular space is

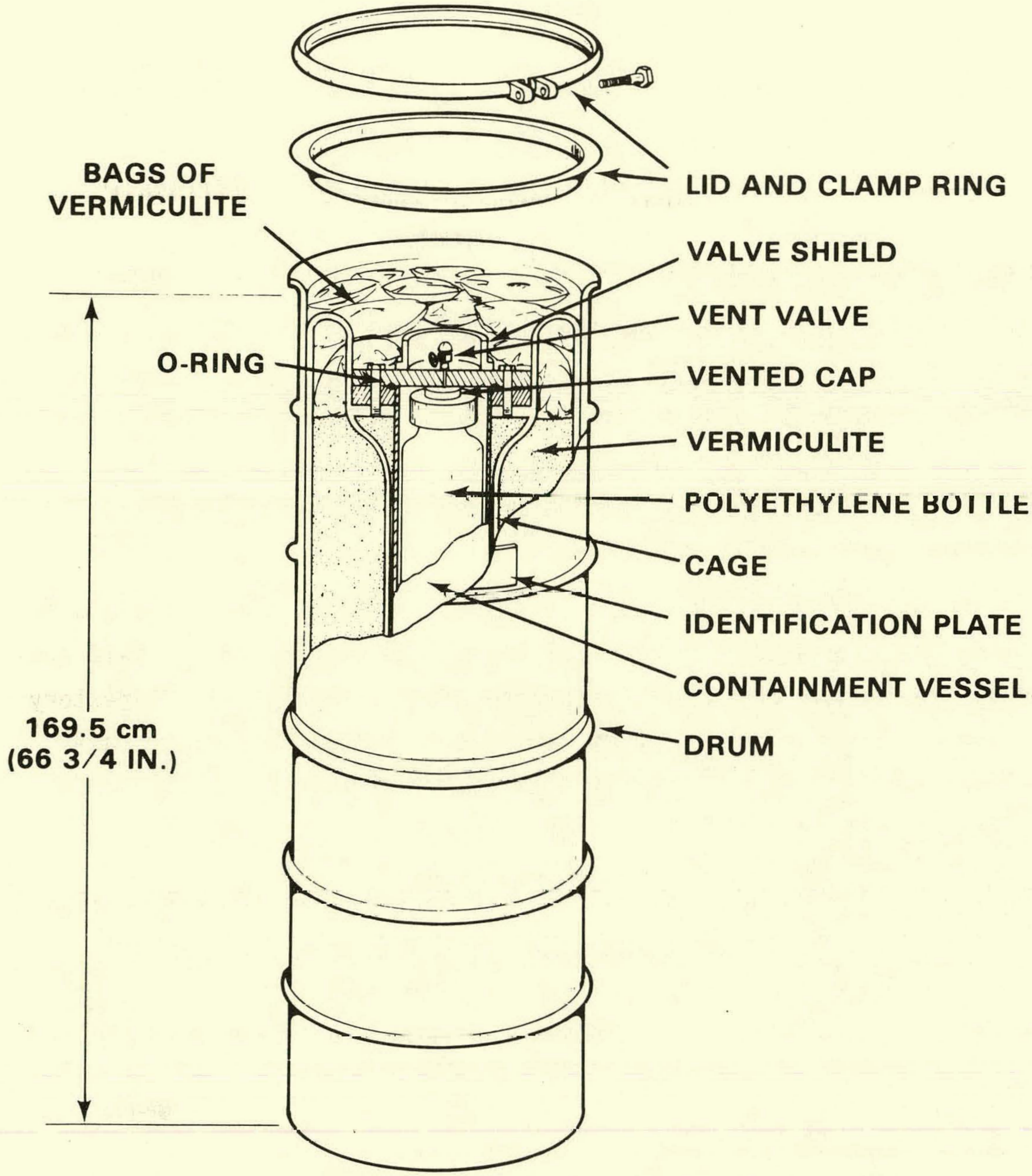


FIGURE A.1. L-10 Container

filled with vermiculite for thermal insulation. The product solution is contained in a 10-liter polyethylene bottle sealed in a polyvinylchloride bag and then inserted into the pressure vessel, with a thin neoprene pad to cushion the bottom of the bottle. Weight: 510 lb, total; 455 lb without bottle.

Type and Thickness of Shielding:

Nine inch vermiculite insulation.

Heat Removal Capacity:

Not applicable.

Authorized Modes of Transport:

Cargo-only aircraft, motor vehicle, rail and vessel. May be used for fissile Class II or Class III.

6M PLUTONIUM DIOXIDE PACKAGE

The 6M designation represents a class of containers which have been approved for radioactive material transport. The general set of design criteria are found in 49CFR 178.104. The outer drum must conform to Spec. 6C and 17C as defined under paragraph 178.99 and 178.115, respectively. The inner container design must meet or exceed the 2R specification presented in paragraph 178.34.

The outer container of the 6M can vary from a 10 to 110 gal capacity. The following description is based on the 15-gal size. This size 6M was used throughout the report and is shown in Figure A.2. Much of the information shown below was taken from Reference 1. Other information has been obtained from actual container measurements.

Authorized Contents:

Up to 4.5 kg of plutonium metal, alloy or compound or up to 13.5 kg of uranium 235 metal or alloy. Additional details and restrictions are provided in 49CFR 173.396.

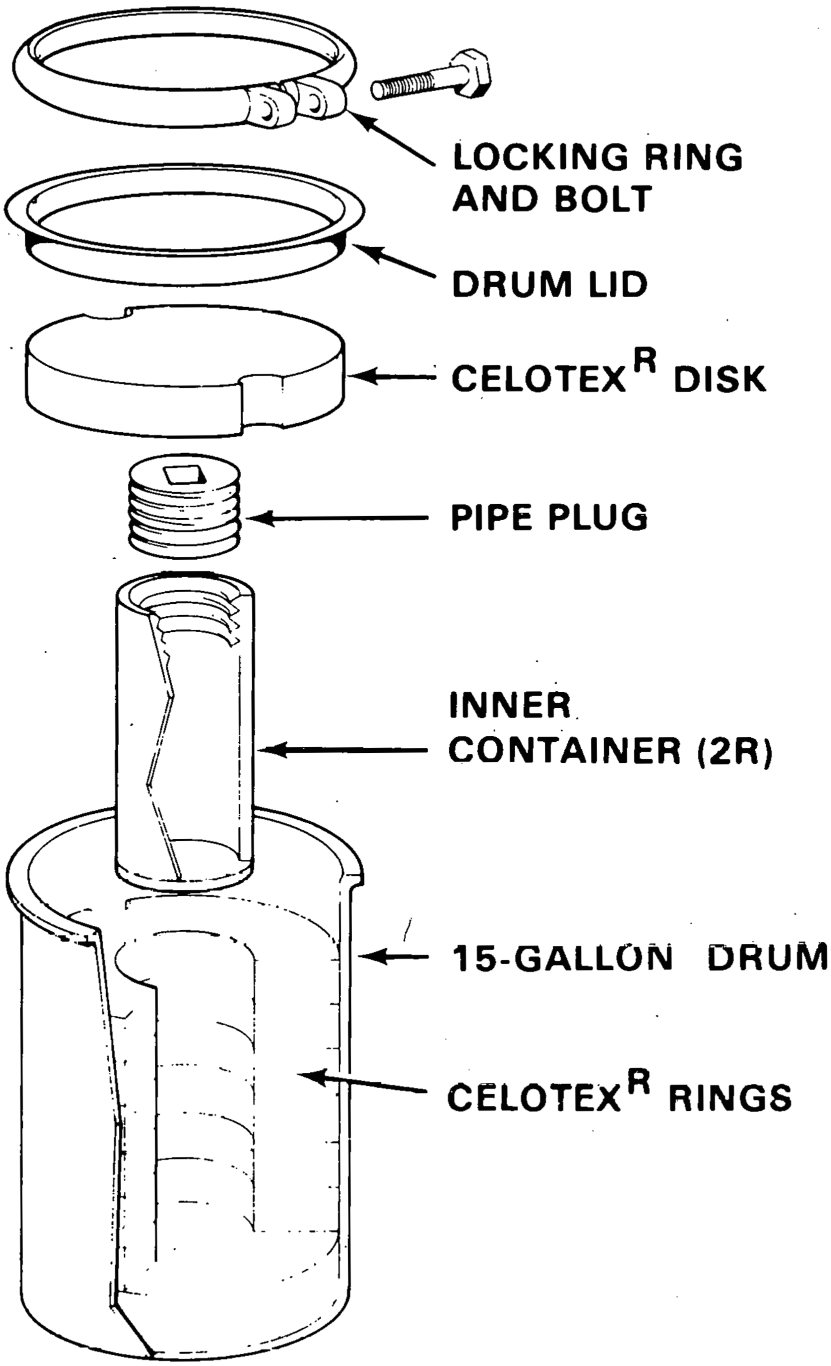


FIGURE A.2. 6M Container

Interior and Exterior Dimensions:

Interior 5.25 in. ID x 10.5 in. deep inside; Drum - 15.57 in. diam. x 21.25 in. high outside with 18 ga. wall.

Description of Container:

The outer container is a 15-gal DOT Spec. 17C drum. The inner container is a 5-in. Sch. 80 steel pipe with a threaded plug. The bottom end is closed by welded 1/2-in. thick steel cap. The oxide powder is contained in two sealed No. 8 steel cans which are placed inside the inner container. The inner container is lined with padding to minimize damage to the steel cans during a shipment.

Type and Thickness of Insulation:

The inner container is insulated by Celotex^R Industrial Board with a minimum thickness of 3 in.

Shielding:

None provided, may be added within the containment vessel when required.

Heat Removal Capacity:

Normal licensed limit of 10 watts. Special permits have been issued for designs which allow for up to 50 watts. The 10 watt limit results in a containment vessel temperature limit of 155°F for a 70°F ambient temperature. Special handling requirements are required when materials that generate more than 10 watts are shipped.

Authorized Modes of Transport:

Vessel, cargo or passenger-carrying aircraft, motor vehicle, rail freight, and rail express.

REFERENCE

1. Division of Waste Management and Transportation Directory of Packagings for Transportation of Radioactive Materials, WASH-1279, United States Atomic Energy Commission, Washington, D.C., 1973.

APPENDIX B

PHYSICAL AND CHEMICAL PROPERTIES OF PLUTONIUM DIOXIDE AND PLUTONIUM NITRATE SOLUTION

Plutonium has commonly been shipped in two different forms, solid plutonium dioxide and plutonium nitrate solution. The truck shipment risk report[1] contains a discussion of the physical and chemical properties of these materials. A brief summary of those properties applicable to the present study is given in this appendix.

PROPERTIES OF PLUTONIUM DIOXIDE

Plutonium dioxide may be prepared in many ways. It is normally a buff powder, but its color and particle size are a function of the method of preparation. Its desirable properties include high melting point, irradiation stability, compatibility with metals, and ease of preparation.[2] A listing of some of the physical characteristics of plutonium dioxide is given in Table B.1.

TABLE B.1. Selected Summary of PuO_2 Properties[3]

Theoretical Density (g/cm^3)	11.45
Melting Point	2400 ± 30°C
Coefficient of Linear Thermal Expansion ($°C^{-1}$, Range 25° to 1000°C)	10.9×10^{-6}
Thermal Conductivity (W/cm - °C, at 95% TD)	0.023 at 1000°C
Resistance to Thermal Shock	Fairly Good

Plutonium dioxide is practically insoluble in water and dilute acids, but is difficultly soluble in some concentrated acids. The best solvents are 12 to 16 normal (N) HNO_3 with 0.01 to 0.1 N HF, 5 to 6 N HI, and 9 N HBr. Increasing acidity generally increases the rate of dissolution.[4] The dioxide calcined at temperatures below 275°C is soluble in hydrochloric acid. Concentrated sulfuric acid will dissolve dioxide calcined at temperatures up to 600°C.[5] Refluxing is necessary in all cases, and dissolution is very slow, generally requiring at least several hours to dissolve small samples.[4]

If exposed to humid air, calcined plutonium dioxide powder will adsorb moisture. The powder eventually saturates at about 1 to 2 wt% water.

Study of the size of plutonium dioxide particles reveals that it is an extremely fine powder. Some distributions of particle size are shown in Figure B.1.[6] Many of the particles are small enough to become airborne and be inhaled.[7]

PROPERTIES OF PLUTONIUM NITRATE

Plutonium nitrate is shipped as a dark brown aqueous solution. It is somewhat more viscous than water but is easily pourable. The nitrate may be shipped with a concentration of up to 250 g of plutonium per liter of solution. It is commonly shipped in concentrations of about 200 g/liter.[8]

Plutonium nitrate solution is generally quite dilute in nitric acid. The lower limit is 2 N nitric acid to prevent plutonium (IV) polymer formation. The expected composition range for shipping solutions is from 3 to 6 N nitric acid. Above 50 g plutonium per liter, polymer forms quickly if the acidity is less than 0.3 N nitric acid. It is practically impossible to dilute plutonium nitrate solutions with water without the formation of a colloidal solution because of regions of momentary low acid concentration. The polymerization is rapid, but it takes a long time for depolymerization.[9]

The gas pressure in a sealed container of plutonium nitrate solution is controlled by three phenomena. These are the vapor pressure versus temperature curve for the solution, the radiolytic decomposition of the solution and the radiolytic reduction of the solution if any plutonium (VI) is present. During transport the pressure in an L-10 pressure vessel should be controlled by the vapor pressure versus temperature curve. The latter two phenomena are of lesser importance provided that the solution is

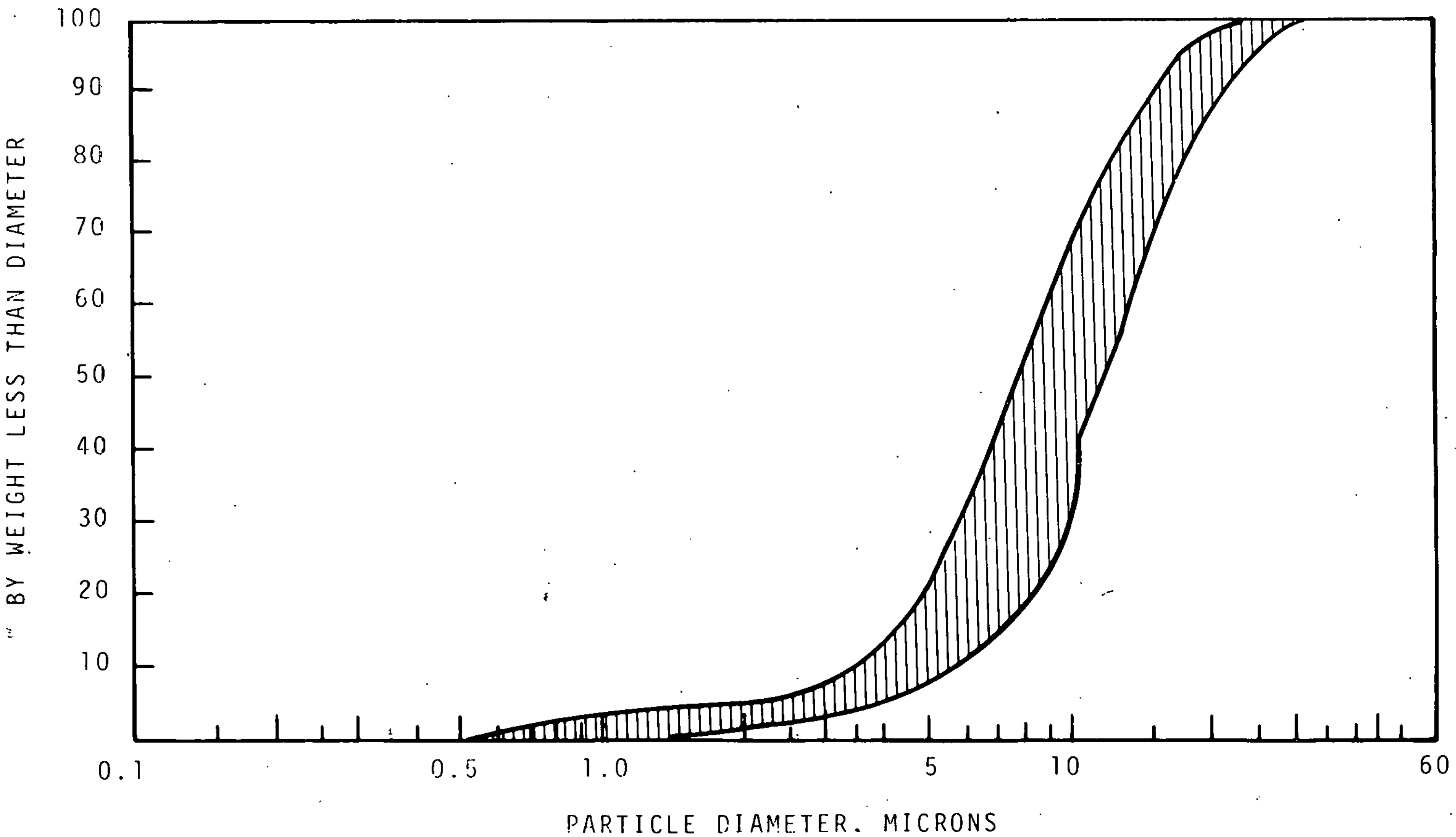


FIGURE B.1. Plutonium Dioxide Particle Size Distribution Formed by Calcination of Plutonium Oxalate[6] adequately aged to permit reduction of plutonium (VI) to plutonium (IV) and the containment vessel is vented prior to shipment. Although the vapor pressure versus temperature curve for 1 M $Pu(NO_3)_4$ in 3 to 6 M HNO_3 has never been measured, the vapor pressure can be expected to be due almost entirely to the vapor pressure of HNO_3.[10]

Using the equation:

$$\ln P = A - B/T \tag{B-1}$$

where P is in psi, T is in °K, Staples, Procopio and Su[11] present values of A and B for various HNO_3 concentrations. For the 6M HNO_3 solution, A = 16.6749 and B = 5399.03. Using these constants, a pressure of 3000 psi is reached at 350°C. For pure water a 3000 psi vapor pressure is reached at 370°C. This shows that the vapor pressure is due primarily to the water with a very small vapor pressure contribution from the HNO_3. Equation B-1 will be used in the thermal analysis section (Appendix E) to predict times to failure for the 2R containment vessel.

Radiolytic decomposition of the nitrate solution by alpha decay of plutonium results in gas release from nitrate solutions. The principal component of the gas evolved is oxygen with lesser but very significant amounts of nitrogen and hydrogen. The gas mixture has a potential for ignition and subsequent explosion. The mechanism for the gas formation is not fully understood.[9]

Radiolytic reduction of the higher oxidation state plutonium (VI), which appears in the form PuO_2^{+2}, has been observed to be associated with oxygen gas formation.[9,12] Presumably the plutonium (VI) is reduced to plutonium (IV) by the hydrogen radical or hydrogen peroxide formed by the alpha radiolysis of water. The formation of plutonium (VI) by disproportion action reactions is highly sensitive to the acidity. At nitric acid concentrations of less than 1 N the amount of plutonium (VI) may be very significant, but higher acidity favors the stabilization of plutonium (IV).

Oxygen and hydrogen are also formed directly from the radiolysis of water. Other radiolytic reactions in nitric acid generate gaseous oxides of nitrogen. Since the gaseous products are the result of a chain of chemical reactions initiated by alpha radiolysis, the amount of gaseous products formed should be directly proportional to the alpha radiation energy absorbed by the system.[12]

An analysis presented in reference 1 shows that sealed containers must be periodically vented to relieve the pressure buildup from gas formation. However, the rate of buildup is only a few psi/day for the isotope mixture being analyzed in this report (Table 10.6). Thus, the pressure buildup is only of significant concern during long term storage; not for short time intervals such as time in transit.

If the solution is spilled and allowed to evaporate slowly, plutonium nitrate pentahydrate, $Pu(NO_3)_4 \cdot 5H_2O$, crystallizes out. This solid salt is readily soluble in water. When heated to 40°C, the hydrated plutonium nitrate begins to decompose, and it melts at 95 to 100°C. An intermediate material thought to be plutonyl nitrate, $PuO_2(NO_3)_2$, is formed at 150 to 200°C. Decomposition of the nitrate to the dioxide proceeds rapidly at 220°C and is essentially complete at 250°C. Thus, if air-drying occurs at temperatures high enough to produce the dioxide, the danger of human inhalation is increased. If the proper conditions of temperature, atmosphere, and gas velocity are present, the plutonium dioxide powder may become airborne.[13]

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. B. R. Fish, G. W. Keilholtz, W. S. Snyder and S. D. Swisher, Calculation of Doses Due to Accidentally Released Plutonium from an LMFBR, ORNL-NSIC-74, November 1972.

3. B. F. Rubin, Comp., Summary of (U,Pu)O_2 Properties and Fabrication Methods, GEAP-13582, November 1970.

4. J. D. Moseley and R. O. Wing, Properties of Plutonium Dioxide, RFP-503, August 1965.

5. O. J. Wick, Ed., Plutonium Handbook, A Guide to the Technology, Gordon and Breach, 1967.

6. C. S. Caldwell, "Relationship Between Process Variables and Final Properties of UO_2, UO_2-PuO_2, and PuO_2," Meeting on Characterization of Uranium Dioxide Held at Oak Ridge National Laboratory, December 12-13, 1961, TID-7637, pp. 249-271.

7. J. Mishima, L. C. Schwendiman and C. A. Radash, Plutonium Release Studies III. Release from Heated Plutonium Bearing Powders, BNWL-786, Battelle, Pacific Northwest Laboratories, Richland, WA, July 1968.

8. L. M. Knights, "Evaluation of Product Form in Safety of Plutonium Transportation (ARH-SA-108)," Proceedings of the Third International Symposium on Packaging and Transportation of Radioactive Materials, Richland, WA, August 16-20, 1971, BNWL-SA-3906, Battelle, Pacific Northwest Laboratories, Richland, WA, pp. 227-240.

9. J. T. Byrne, R. L. Delnay, W. E. Domning, L. F. Grill and F. J. Miner, Measurements of Plutonium Nitrate Shipping Solutions, RFP-436, October 1964.

10. R. D. Scheele, personal communication to T. I. McSweeney, November 21, 1973.

11. B. G. Staples, J. M. Procopio, Jr. and G. J. Su, "Vapor Pressure Data for Common Acids at High Temperatures," Chem. Eng., vol. 77, no. 25, pp. 113-115, 1970.

12. J. C. Sheppard, Alpha Radiolysis of Plutonium (IV) - Nitric Acid Solutions, BNWL-751, Battelle, Pacific Northwest Laboratories, Richland, WA, May 1968.

13. J. Mishima, L. C. Schwendiman and C. A. Radasch, Plutonium Release Studies IV. Fractional Release from Heating Plutonium Nitrate Solutions in a Flowing Air Stream, BNWL-931, Battelle, Pacific Northwest Laboratories, Richland, WA, November 1968.

APPENDIX C

CRITICALITY CONSIDERATIONS IN TRANSPORTATION ACCIDENT STUDIES

The possibility of criticality must be considered in the transportation of fissile material. This appendix provides data required for the evaluation of the importance of criticality as a mechanism for rupturing the containment vessel (the 2R container for the 6M; the pressure vessel for the L-10) in an accident.

Data are presented on the L-10 plutonium nitrate solution shipping package and the 6M plutonium dioxide powder shipping package. During transportation of plutonium in these packages, criticality cannot occur if the array of packages is not deformed and if no significant amount of plutonium leaks out of the containment vessel. This is true even if the shipment is somehow flooded with water.

Basic criticality theory says that a system becomes more reactive (closer to critical) if compressed. Therefore this appendix presents the criticality aspects of shipping package arrays which have been deformed by crushing.

The subcriticality of the deformed 6M array can be demonstrated by comparison to the results found in the truck shipment study.[1] Accordingly, no new computer calculations were performed for the 6M shipment criticality analysis. The conditions and results of the previous analysis[1] are repeated here for completeness. Because of different deformation conditions, new criticality calculations were required for the deformed L-10 array. In both the 6M and L-10 criticality calculations the plutonium isotopic mixture used was more reactive than that analyzed in the risk assessment. Thus the calculational results are conservative.

For the 6M packages, which are loaded in a square pitch, the deformed array analyzed was one completely compacted (i.e., with inner containment vessels touching) along the long axis of the vehicle. For the L-10 packages, also loaded in a square pitch, the deformed array had the first eleven rows with inner containment vessels touching, two rows of less deformed containers and four undeformed rows. The likelihood of having these extreme deformations in an accident is discussed in Section 9 and Appendix F and is not addressed in this appendix.

RESULTS OF STUDY

Several plutonium dioxide shipping package deformed arrays were studied; all were found to be subcritical. This included 6M (15 gal) container arrays at the fissile Class III container/vehicle limit under flooded, partially wetted, and dry conditions. The deformation model was to reduce the dimension of each container in the array along the long axis of the railcar to that of the 2R containment vessel while maintaining the outer vessel dimensions in the transverse and vertical directions.

For the L-10 plutonium nitrate shipping package a deformed array consisting of 17 rows of four across was studied and found to be subcritical. The first eleven rows were compacted until the inner containers touched. The next row was placed 7 in. center-to-center from the eleventh row. The thirteenth row was located 9 in. center-to-center from the twelfth. The remaining four rows were not deformed and retained their 24-in. center-to-center spacing. As in the dioxide packages the pre-accident transverse spacing was maintained. For the optimally moderated plutonium nitrate solution used in the calculations, the dry array is known to be more reactive than a partially wetted or flooded array. Therefore only dry array results are reported.

In all cases containment vessel integrity was assumed.

ASSUMPTIONS AND MODELING

A complete consideration of the possibility of criticality during shipment requires analysis of both original loading patterns and the post accident arrangement of the containers. The containers themselves must be modeled to allow criticality calculations to be made.

Original Loading Pattern

The pre-accident loading pattern is described by Table C.1. The 6M/III Calculated array is an array whose reactivity was studied in the truck shipment report.[1] The 6M/III Rail array is the largest array allowed in a railcar by dose restrictions. It will be shown that the 6M/III Rail array is less reactive than the 6M/III Calculated array. The dimensions of the individual packages are given in Table C.2.

TABLE C.1. Loading Pattern for Plutonium Shipping Packages

Package/Class	Max. No. Allowed	No. Across	No. Deep	No. High	No. Used In Model
L-10/III	68[a]	4	17[b]	1	68
6M/III Calculated[1]	125	5	8	3	120
6M/III Rail	90[c]	3	30	1	90

(a) Limited by criticality safety criteria.[2]
(b) Split array, 9 rows in front of railcar and 8 rows in back.
(c) Limited by radiation dose rate criteria.

Post-Accident Pattern

The post-accident pattern for the 6M dioxide packages was developed by reducing the depth of the array of packages until the inner containment vessels of the respective packages were touching. The vertical and transverse spacing was maintained in the pre-accident dimensions.

The post-accident pattern for the L-10 packages was developed by first assuming that the split array moves together in an accident forming an

TABLE C.2. Plutonium Shipping Package Dimensions

Package	Containment Vessel ID, in.	Containment Vessel OD, in.	Containment Vessel Height, in.	Outer Container OD, in.	Outer Container Height, in.
L-10	4.813	5.563	52.25	24	66.75
6M (15 gallon)	5.047	5.563	14	16.5	21.5

array 4 packages across by 17 deep by 1 high (68 packages). The first eleven rows were compacted until the inner containment vessels were touching. This gives a center-to-center spacing of 5.56 in. The twelfth row was separated from the eleventh by 7 in. center-to-center and the thirteenth from the twelfth by 9 in. The next four rows were not compacted. Their spacing is that of the undeformed packages, 24 in. center-to-center. The transverse spacing was maintained at the pre-accident condition. This compaction is consistent with the crush analysis in Appendix F.

The compacting of each vessel type assumed in the analysis is shown in Figure C.1. It is assumed that all of the inner containment vessels remain intact.

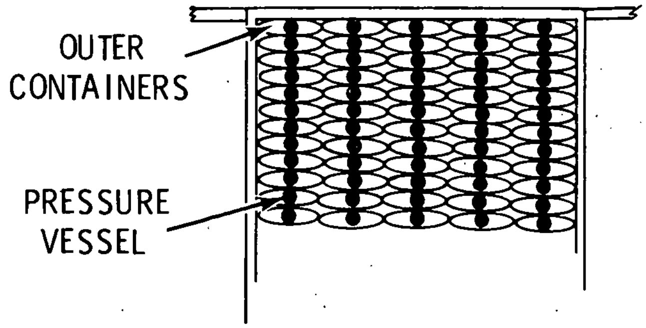
Deformed Container Modeling

In the calculational modeling, the outer vessel and packing material were neglected. The model consists of the containment vessel and the fissile material within. Each vessel is further described below.

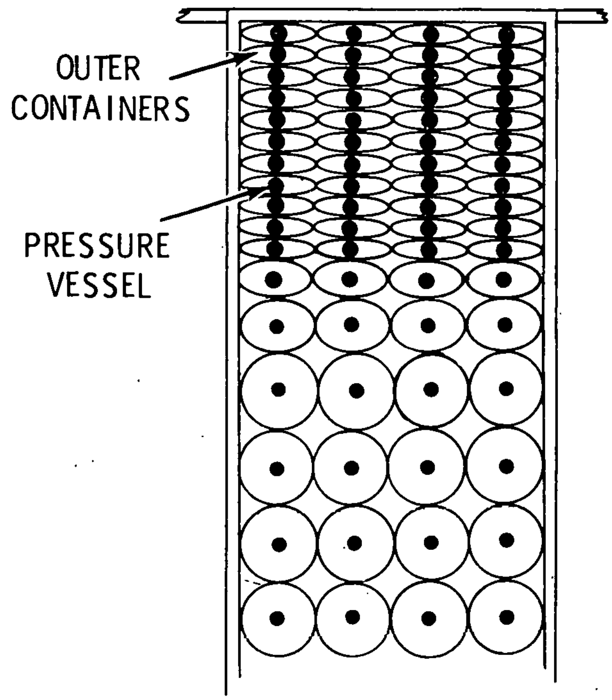
L-10

The L-10 is modeled as two concentric cylinders corresponding to the pressure vessel and space within. The height of the plutonium nitrate solution is that required to give the maximum permissible volume of 10.5 ℓ in an 11.0 cm ID polyethylene bottle (the size bottle normally used in shipment). This height is 108.5 cm. The radius of the solution used in the model was 6.113 cm, that of the interior of the pressure vessel. This results in a conservative volume of 12.7 ℓ of plutonium nitrate solution, 2.2 ℓ more than the maximum allowed. The pressure vessel is made from 5 in. schedule 80 stainless steel pipe. Its radius and thickness are modeled accordingly. The thickness of the top and bottom end caps were taken as equal to the 0.95 cm wall thickness.

The fissile material used in the L-10 model was $Pu(NO_3)_4$ at 100 g Pu/ℓ the optimum (most reactive) plutonium concentration for the plutonium nitrate solution. The plutonium was assumed to be 80 wt% ^{239}Pu and 20 wt% ^{240}Pu.



6M
COMPLETE ARRAY - 120 CONTAINERS - 5x8x3



L-10
COMPLETE ARRAY - 68 CONTAINERS - 4x17x1

FIGURE C.1. Compacted Package Arrays Used in Criticality Calculations

6M

The 6M plutonium dioxide package has an inner 2R containment vessel. The 2R container and plutonium are modeled as a pancake of plutonium dioxide in the center of the steel containment vessel. The height of the pancake is that required to give 4.5 kg of PuO_2 at a density of 5.6 g/cm^3 and a diameter of 12.82 cm. This gives a height of 6.23 cm. The 2R pressure vessel has a thickness of 0.66 cm and an exterior height of 38.10 cm. The actual and modeled 2R containers are sketched in Figure C.2.

The 6M outer drum diameter is 41.91 cm and its height is 54.61 cm. These dimensions were used to give the respective spacings across the vehicle width and in the vertical direction.

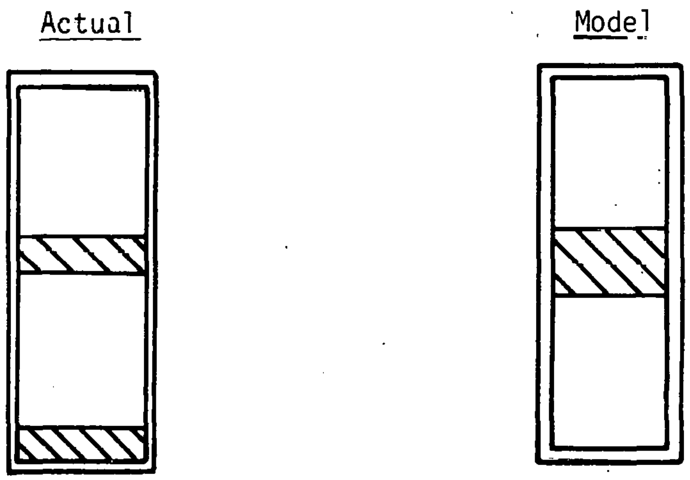


FIGURE C.2. Actual and Model 2R Container (Containment Vessel for LLD-1 and 6M Packages)

The fissile material was plutonium dioxide at 5.6 g PuO_2/cm^3 with 1 wt% water, and the ^{240}Pu content was assumed to be 5 wt%.

Other Post-Accident Conditions

For the L-10 array all space within the array but external to the pressure vessels was considered to be void. This dry condition is more reactive than a case with external moderator between the pressure vessels. Since the nitrate solution is already at optimum moderation, external water tends to isolate the individual L-10's, which reduces interaction and thus the overall reactivity of the array. Test calculations have shown this effect.

In addition to flooded and dry arrays, partially wetted arrays were calculated for the plutonium dioxide container (6M). This was done because it was felt that while water moderation increased reactivity, full flooding may cause partial vessel isolation. The partially wetted cases were modeled by placing water at reduced density outside the containment vessels. The arrays were calculated with water at 5%, 6% and 7% of normal density. For the 6M the 6% density case proved to give the highest value of k_{eff}.

In all instances the array was surrounded by a 30-cm water reflector. This was done to account for any neutron reflectors that might be encountered in the extreme instance.

CALCULATIONAL METHODS AND RESULTS

The calculations were performed using the KENO II Monte Carlo computer program. The 16-group Hansen-Roach neutron cross-section set was used. A differential albedo deck was used to simulate the 30-cm water reflector. The k_{eff}* values calculated for the 6M plutonium dioxide package arrays are given in Table C.3. It is shown below that this is a more reactive array than the actual railcar array.

The results in Table C.3 show that the PuO_2 arrays studied were all far subcritical. As expected, the partially wetted arrays gave a slightly higher value of k_{eff}. The 6% of normal water density was found to be more

* k_{eff} is a measure of the criticality of a system. k_{eff} = 1.0 for a critical system. Criticality cannot occur in a system with k_{eff} less than one.

TABLE C.3. k_{eff} for Deformed Plutonium Dioxide Shipping Package Arrays[a] Under the Assumed Conditions

Package	k_{eff} Flooded	Partially Wetted (6% Normal H_2O Density)	Dry
6M (15 gallon)	0.560 ± 0.010	0.636 ± 0.006	0.609 ± 0.005

a) 125 packages (5 x 8 x 3 array).

reactive than the 5% and 7% water density cases. The 6% water density values for k_{eff} are given in Table C.3. The k_{eff} values for the 5% and 7% cases were lower with the differences near the statistical accuracy of the KENO II code.

The actual railcar array has a 30 x 3 x 1 pattern. This results in dimensions of 13.9 ft x 4.1 ft x 1.8 ft for the deformed array, which has the shape of a long flat slab. The calculated 6M array is a 5 x 8 x 3 pattern or 6.9 ft x 3.7 ft x 5.4 ft. This is more nearly a cube in shape. Generally speaking the more compact a given amount of fissle material is the more reactive it is. As the surface to volume ratio decreases the number of neutrons leaking from the system is reduced. If neutron leakage is reduced more neutrons are available to cause fissions within the material, and the reactivity increases.

A quantitative measure of neutron leakage fraction from a given shape is the geometric buckling. For a rectangular parallelepiped the geometric buckling is given as:

$$B_g^2 = \left(\frac{\pi}{A + \lambda}\right)^2 + \left(\frac{\pi}{B + \lambda}\right)^2 + \left(\frac{\pi}{C + \lambda}\right)^2 .$$

Where A, B, C are the dimensions of the parallelepiped, λ is the extrapolation distance or distance from the fissile material surface at which the extrapolated neutron flux would drop to zero. In this case it is taken to be 7 cm. Using this formulation the geometric buckling for the Rail array is 3.21×10^{-3} cm^{-2} while the Calculated array is 1.23×10^{-3} cm^{-2}.

This indicates that the neutron leakage is greater from the Rail array and the array is less reactive. Since the Calculated array was subcritical under all conditions, clearly the Rail array is also subcritical and has a k_{eff} less than 0.636 ± 0.006.

The deformed L-10 array is also subcritical. KENO II calculations gave k_{eff} = 0.895 ± 0.006 for the conservatively modeled array. Preliminary calculations showed that if the array were to be flooded k_{eff} would be reduced to about 0.80.

It is important to recall that the integrity of the containment vessel was assumed in these calculations. Were multiple vessels to leak and a sufficient amount of the fissile material to collect in a particular geometry, it is possible that criticality could be achieved with any of the plutonium shipping packages.

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. D. Carter, G. R. Kiel, K. R. Ridgway, Criticality Handbook, ARH-600, Vol. I, June 1968; Vol. II, May 1969.

APPENDIX D

MECHANICAL ANALYSIS OF L-10 AND 6M CONTAINERS

The L-10 and 6M containers are designed to withstand, without failure, the hypothetical accident conditions specified in 10CFR71. These hypothetical conditions involve: (1) a free drop onto a flat essentially unyielding surface from a height of 30 ft, (2) a free drop through 40 in. onto the top end of a 6 in. diameter cylindrical mild steel bar, (3) exposure to a thermal radiation environment of 1475°F for 30 min, and (4) immersion in 3 ft of water for 8 hrs. The qualification tests demonstrate that the container can withstand the simulated accident conditions, but yield no information regarding failure points. Tests that exceed the qualification tests for a limited range of container orientations and other test parameters have been performed by Sandia Laboratories and others.[1,2,3,4,5] The analytical results presented herein have been compared with the test data available and found to be in general agreement.

Several analytical approaches are available to determine failure thresholds of the L-10 and 6M containers, including: (1) force-displacement methods outlined in the Cask Designer's Guide,[6] (2) finite element analysis using computer codes, and (3) mass-spring models. The use of the more precise, but expensive, computer analysis methods was considered inappropriate for the purposes of the present study. The general analytical approach used in this appendix is the force-displacement method based on linear-elastic structural behavior. This approach is considered sufficiently accurate as to not control the risk assessment uncertainties.

This appendix presents the mechanical analyses used in the determination of the failure drop heights shown in Table 6.1, Section 6 of this report. Failure of the outer container by impact or crush forces is assumed to occur when the perimeter of the lid in the deformed state becomes smaller than the undeformed inside circumference of the clamp ring. The analysis is based on elastic deformation of the outer container and should be conservative because significant energy would be dissipated in localized buckling or plastic deformation. However, local buckling or oblique angles of impact could lead to other undefined mechanisms of failure. Load-bearing structures such as the L-10 birdcage space frame have been neglected to keep the analysis on the conservative side.

<u>L-10 CONTAINER ANALYSIS</u>

Case 1: Determine the drop height which results in loss of vermiculite (assuming vermiculite is lost when the container lid comes off). Then determine the time required for a fire to pressurize and rupture the inner pressure vessel.

Specification of L-10 container:

Weight (total) = 510 lbs
OD = 23 9/16 in.
ID = 22 13/16 in.
Shell thickness = 0.0478 in.
End plate = 0.0598 in.
Total length = 66.75 in.

For the analysis it was assumed that the lid will come off when the perimeter of the lid in the deformed state becomes smaller than the undeformed inside circumference of the clamp ring. Using this assumption, the threshold for lid removal was found to be at a point where the diameter had decreased by 5 in.[7] The condition is shown in Figure D.1. The assumption is made that the kinetic energy is expended in two distinct modes described directly below. It is further assumed that the container strikes an unyielding surface, the collision is inelastic, and all the energy is dissipated in the L-10 container. The two assumed independent modes of energy dissipation are as follows: 1) work due to compaction of the vermiculite and 2) work expended in deforming the outer steel container alone.

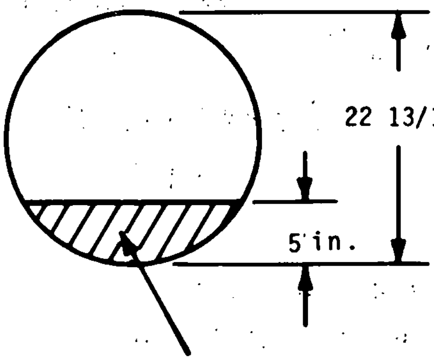


FIGURE D.1. Deformation Threshold for Lid Removal

The work expended during compaction of the vermiculite can be calculated using the expression:

$$W = \int -p\,dv$$

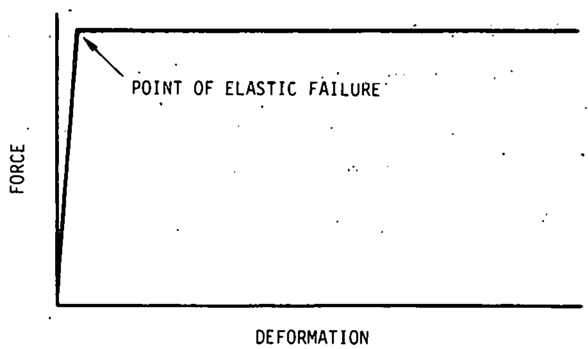
where

W = the energy of compaction

p = pressure in vermiculite

dv = change in volume.

The work performed in deforming the steel container is assumed to involve the action of an initial force that is sufficient to start buckling the rings and shell and then subsequently remains constant over the distance that the container is deformed. The assumed conditions are shown below. Work is the product of the force and the distance.



The following properties of vermiculite compaction have been assumed with respect to increasing compression:(8)

	Compression Pressure
1/12 compression	11 psi
2/12 compression	38 psi

The expression below was developed for the pressure distribution in the vermiculite at the value of deformation that causes lid removal (5 in.):

$$p = 38 \text{ psi } \frac{12}{2} \; \frac{V_i - V_f}{V_i}$$

or

$$p = 228 \frac{V_i - V_f}{V_i}$$

where

V_i = initial volume of the container

V_f = final volume of the container.

The values above can be substituted into the expression $E = \int -pdv$.

$$E = \int_{V_i}^{V_f} -228 \frac{V_i - V_f}{V_i} \, dv.$$

The energy absorbed by the vermiculite is found to be 163,170 in.-lb at the 5-in. deformation shown in Figure D.1.

The work performed in deforming the steel outer container alone, as described above, is the product of a constant force and the distance of deformation through which it acts. A constant force of 25,000 lb has been assumed. The value is based on several Sandia reports which indicate that the onset of failure for the L-10 container is approximately 50,000 lb total load (acting on two sides). The work performed in deforming the shell is:

$$W = Fd$$

where

F is the constant force that will fail the container

d is the decrease in overall diameter due to the deformed area (see Figure D.1).

At the point of lid removal:

$$W = (25{,}000 \text{ lb}) (5 \text{ in.})$$
$$W = 125{,}000 \text{ in.-lb}$$

The total energy absorbed by the L-10 container is the sum of the work performed in compressing the vermiculite and deforming the outer steel container.

$$\text{Total energy absorbed} = 163{,}170 \text{ in.-lb} + 125{,}000 \text{ in.-lb}$$
$$= 288{,}170 \text{ in.-lb.}$$

The drop height which produces the equivalent energy is calculated from the expression for potential energy (the product of container weight and the height):

$$\text{Weight of container} \times \text{height} = \text{total energy absorbed}$$
$$510 \text{ lb} \times \text{height} = \frac{288{,}170 \text{ in.-lb}}{12 \text{ in./ft}}$$
$$\text{height} = 47 \text{ ft.}$$

Using the relationship in Equation 6-1 of Section 6, the corresponding force to cause lid removal is 57,600 lb. An analysis of lid removal under dynamic crush conditions is given in Appendix J.

The rupture of the inner pressure vessel (5-in. diam Schedule 80 SS 304 pipe) under fire conditions was evaluated in reference 7 using two sets of calculations: a) rupture pressure versus temperature and b) vessel internal pressure versus temperature. From these a critical temperature for failure from overpressurization was determined.

a. The rupture pressure versus temperature was calculated using the ASME Section VIII pressure vessel code. The rupture pressures for the following components were calculated:

i) pressure vessel wall (at rupture)
ii) bolts (at yield)
iii) flange (at yield)

The results are shown in Figure D.2.

b. The internal pressure in the vessel at various temperatures (resulting from a fire incident) was calculated in reference 7 using the following equation:[9]

$$\text{Log}_e\ P = A - B/T$$

where

P = pressure in psi
A = constant = 16.6749
B = constant = 5399.03
T = temperature in °K.

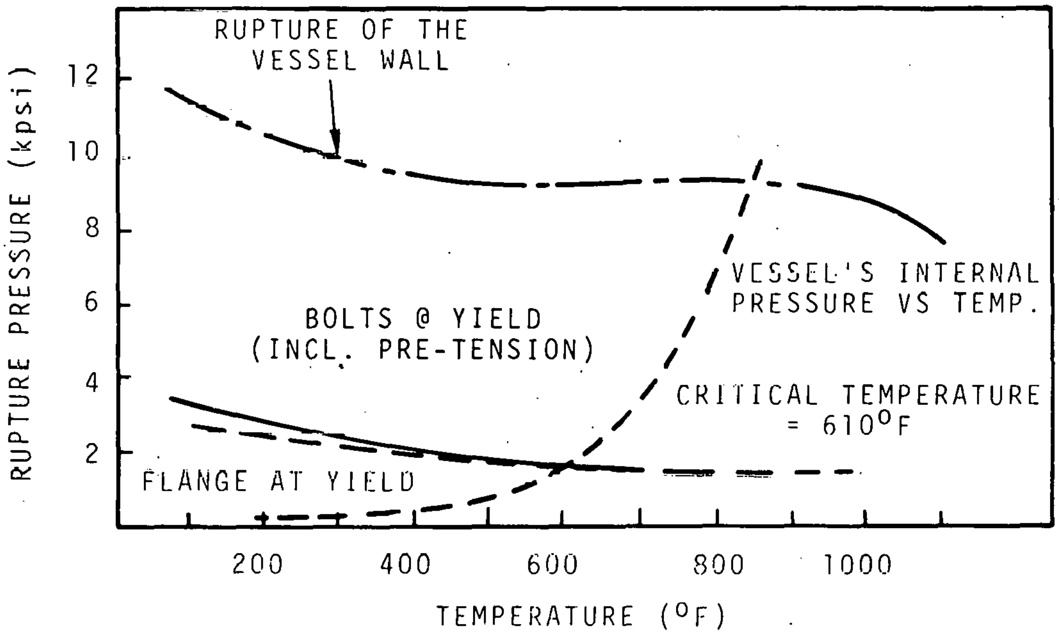


FIGURE D.2. Pressure-Temperature Relationships for the L-10 Container

It is evident that the bolts and flange will yield first. The temperature at which the bolts and flange yield is approximately 610°F. The time required to reach this temperature during a fire incident was determined by a heat transfer analysis reported in Appendix E.

The relative distance between the inner and outer container after drop for use in the heat transfer analysis was derived in reference 7. The result is shown in Figure D.3. The final deformed configuration is shown in Figure D.4.

Following impact a deceleration takes place. The deceleration versus drop height for the outer and inner container is shown in Figure D.5.

A separate analysis was made on the inner container closure bolts. It showed that the deceleration rate for this container would not result in bolt failure.

Case 2: Determine the drop height required to deform the outer container so that a half-hour fire (800°C) results in sufficient pressure to fail inner pressure vessel.

Based on the thermal analysis in Appendix E, the required vermiculite thickness was found to be 1/2 in. Thus, based on the curves presented in

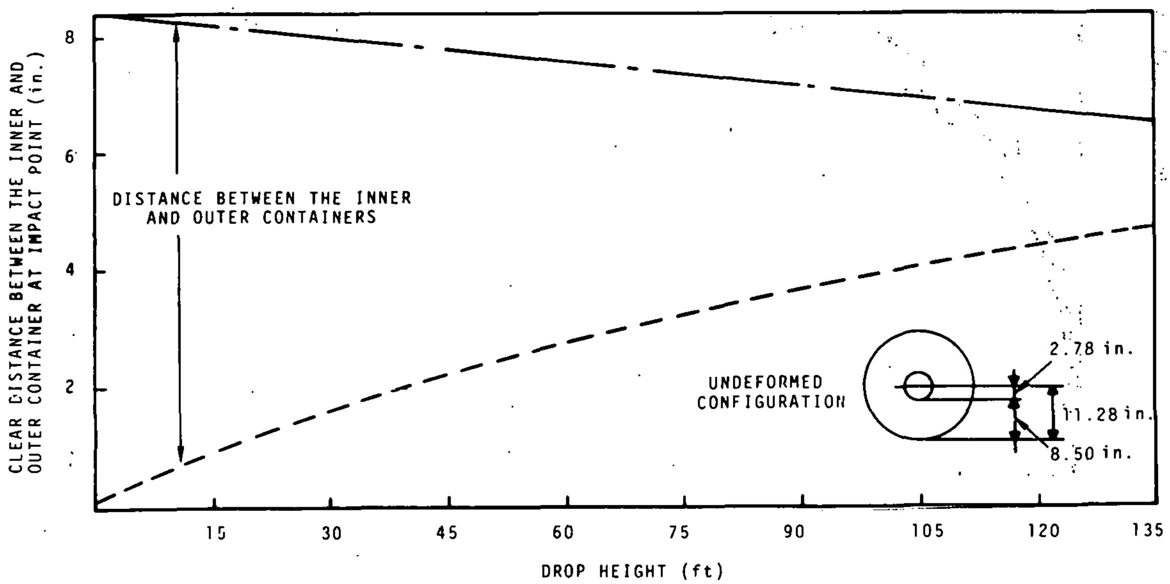


FIGURE D.3. Distance Between L-10 Inner and Outer Containers After Impact as a Function of Drop Height

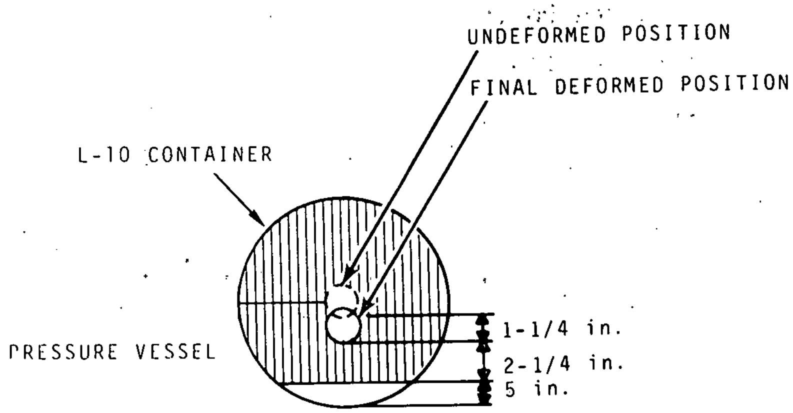


FIGURE D.4. Relative Distance Between Inner and Outer Containers After Drop

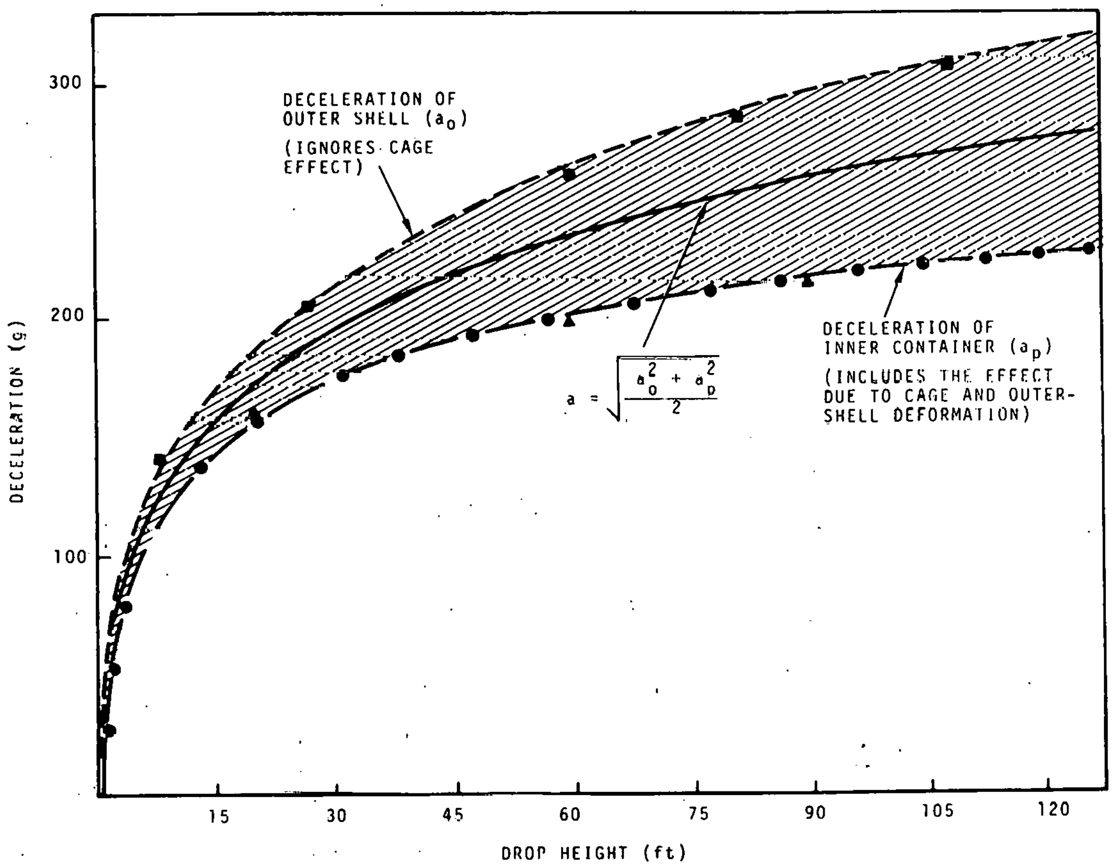


FIGURE D.5. Deceleration of Inner Container and Outer Shell During Impact as a Function of Drop Height

Figure D.3, a drop height greater than 135 ft is required before the container will fail in an 800°C fire with a half-hour duration. However calculations in Case 1 show that the lids would be removed at a lower drop height (47 ft) which coupled with loss of the vermiculite and followed by a subsequent fire could also lead to failure.

Case 3: Determine the drop height onto a 6-in. diam pin required to puncture the L-10 outer container and inner container. (Side drop for upended pin.)

The puncture of the L-10 outer and inner container was calculated in reference 7 using the equation:[9]

$$H = \frac{39\ (S)\ t^{1.4*}}{\overline{W}} \qquad \text{(D-1)}$$

where

H = drop height, in.
S = ultimate tensile stress of container, psi
t = thickness of container wall, in.
$\overline{W}$ = weight of container, lb.

For the outer container

$\overline{W}$ = 510 lb
t = 0.0478 in.
S = 50,000 psi.

The drop height required to puncture the outer container was found to be 42 in.

The drop height to puncture the inner container alone (based on the weight of 160 lb) is 4000 in. The inner container alone, however, will fail due to bending at a much lower height. The drop height to cause such failure is calculated to be 58 in. The total height resulting in the rupture of the inner container is, therefore, 42 + 58 = 100 in. The puncture resistance of vermiculite material was ignored in the analysis.

* For containers less than 30 in. diam (e.g., the L-10 container) $\overline{W}$ in Equation D-1 should be increased by a factor of 1.3.[9]

COMPARISON WITH TEST RESULTS

Reference 1 describes drop tests of a L-10 container onto a 6-in. diam puncture probe. There was no failure on the inner pressure vessel from a drop height of approximately 148 in. However, the outer container was slightly breached which resulted in loss of some vermiculite. The same report indicates that the container will survive impact velocities up to 130 fps (260-ft equivalent height) without breaching the inner container.

6M Container Analysis

Case 1: Determine the drop height which results in rupture of the outer container (side drop).

Specification of 6M Container:

Weight (total) = 160 lb

OD = 15.57 in. x 21.25 in. high (15 gal size)

Shell thickness = 0.0478 in. (18 GA)

Pressure Vessel:

ID = 5-1/4 in. x 10-1/2 in. high

Wall thickness = 1/4 in.

Dynamic Flow Stress:

Shell: σ_s = 50,000 psi[10]

Celotex: σ_c = 100 psi (assumed).

It was assumed that the 6M container was dropped on an unyielding surface. All the energy due to impact would be absorbed by the container. The deformation of the shell versus drop height was calculated using an equation from the "Cask Designer's Guide."[6]

$$H = \frac{t_s R L \sigma_s}{W} \left\{ [F_1(\theta)] \left[\frac{R}{t_s} (\sigma_v/\sigma_s) + 2 (R/L)(t_e/t_s) \right] + F_2(\theta) \right\} \qquad \text{(D-2)}$$

where

$$F_1(\theta) = \theta - \frac{1}{2} \sin 2\theta$$

$$F_2(\theta) = \sin \theta \, (2 - \cos \theta) - \theta$$

W = weight of shell, lbs

R = outer shell radius, in.

t_s = outer shell thickness, in.

L = length of shell, in.

σ_s = the dynamic flow stress of the shell, psi

σ_v = the dynamic flow stress of the vermiculite material, psi

θ = the angle associated with the deformed configuration of shell, degrees and radians

t_e = thickness of steel end plate, in.

The equation above was developed for steel-encased solid lead cylinders. An approximation of deformation in a steel-encased cylinder filled with Celotex was obtained by assuming a value for dynamic flow stress for Celotex (100 psi) and substituting for the properties of lead in the equation. The assumed value for dynamic flow stress needs experimental verification.

The deformation of the outer container versus drop height is shown in Figure D.6. The drop height required to pop off the lid of the outer container was found to be 194 ft. Again this was based on the assumption that the lid would come off when the perimeter of the lid in the deformed state is smaller than the undeformed inside circumference of the clamp ring. This drop height corresponds to a force of 95,000 lb using the relationship in Equation 6-1 of Section 6.

Case 2: Determine the drop height which would cause rupture of the inner container.

It was assumed that the inner 2R vessel would not deform until the outer shell contacted the inner vessel. The drop height to cause this contact was found to be approximately 260 ft.[7]

The deformation versus drop height for an inner vessel is shown in Figure D.7. The point at which rupture would occur due to deformation cannot be defined. The solution may only be found by a physical test. The data used in determining deformation using Equation D-2 are:

t_e = Thickness of steel end plate = 1/2 in.

t_{es} = Thickness of screwed end plug = 1.31 in.

σ_s = The dynamic flow stress in steel = 50,000 psi

t_s = The outer shell thickness = 0.25 in.

R = The outer shell radius = 2.875 in.

L = The length of shell = 10.5 in.

It was also assumed that the contents of the inner pressure vessel were compressible.

Additional calculations regarding the puncture of the 6M container in a side drop onto a 6-in. diam pin were made in reference 7 using Equation D-1. The drop height required to puncture the outer container was found to be 133 in. The inner container will fail due to bending at a drop height of 37 in. The total drop height required to rupture both the outer and inner containers is 170 in. It is interesting to note that in a controlled drop test carried out by Sandia,[1] a 6M container was side dropped onto a 6-in. diam pin from a height of 119 in. without puncturing the outer container. The results of this test tend to verify these calculations.

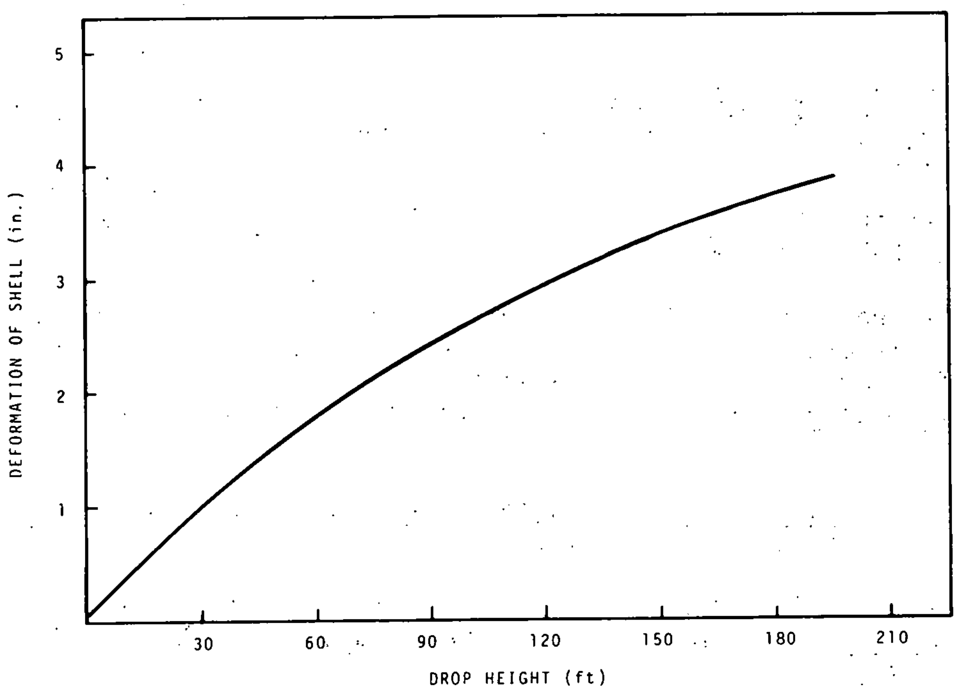


FIGURE D.6. Shell Deformation from Impact Versus Drop Height for the 6M Container

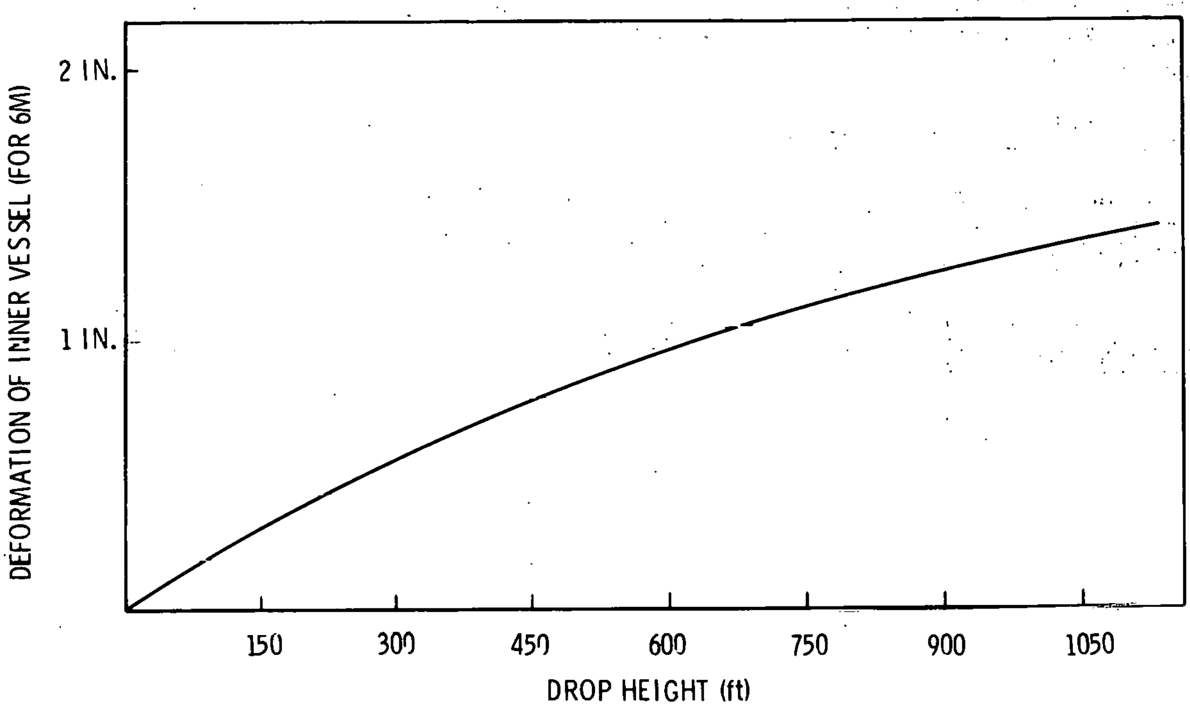


FIGURE D.7. Deformation of Inner Vessel from Impact as a Function of Drop Height - 6M Container

REFERENCES

1. L. F. Stravasnik, Special Tests for Plutonium Shipping Containers 6M, SP5795, and L-10, AEC R&D Report TID-4500, Sandia Report SC-DR-72 0587, September 1972.

2. M. C. Jurgensen, The Vermiculite Shipping Package: Drop Tests on the Closure, ORNL-TM-1312, Vol. 15, January 1975.

3. O. A. Kelly and C. W. C. Stoddart, "Highway Vehicle Impact Studies: Tests and Mathematical Analyses of Vehicle, Package and Tiedown Systems Capable of Carrying Radioactive Materials," ORNL-NSIC-61, Nuclear Safety Information System, Oak Ridge National Laboratory, Oak Ridge, TN, 1970.

4. J. V. Otts, Special Closure for Radioactive Shipping Container, SAND75-0517, Draft of November 1975.

5. M. McWhirter, et al., Final Report on Special Tests of Plutonium Oxide Shipping Containers to FAA Flight Recorder Standards, SAND75-0446, September 1975.

6. L. B. Shappert, A Guide for the Design, Fabrication, and Operation of Shipping Casks for Nuclear Applications, ORNL-NSIC-68, February 1970.

7. 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.

8. Journal of the American Concrete Institute, p. 628, May 1949.

9. H. A. Nelms, Structural Analysis of Shipping Casks, Vol. 3, Effects of Jacket Physical Properties and Curvature on Puncture Resistance, ORNL-TM-1312, Vol. 3, June 1968.

10. L. B. Shappert, A Guide to the Design, Fabrication, and Operation of Shipping Cask for Nuclear Applications, ORNL-NSIC-68, February 1970.

APPENDIX E

THERMAL ANALYSIS OF THE L-10 CONTAINER

The transient response of an L-10 container to a 1475°F thermal environment was analyzed in the truck shipment risk report.[1] The analytical approach for assessing response of the container to the fire environment resulting from a truck accident relates directly to railroad accident environments. This appendix is a summary of the results reported in Reference 1 and limited test results found in the literature.

Three cases of container degradation were analyzed for transient thermal response:

Case I. Inner pressure vessel exposed directly to 1475°F thermal environment (unprotected)

Case II. Exposure of crushed but intact L-10 package to the same thermal environment

Case III. Exposure to the same thermal environment of an L-10 package having only a fraction of the vermiculite insulation present.

Case I represents a worst-case situation in which the inner pressure vessel is expelled from the outer drum during an accident and subsequently exposed directly to a fire environment. Case II considers an intact outer container with a reduced thickness of insulation in the crush zone. Case III was established to determine the minimum thickness of vermiculite insulation required to prevent failure of the inner pressure vessel when exposed to a 1475°F fire for 30 minutes. In all cases, only failure by overpressurization is considered.

The results below were obtained by correlation of temperature/time history derived by the transient thermal analysis presented in this appendix to the temperature/stress analysis shown in Appendix D. Failure was assumed when the temperature of the inner stainless steel pressure vessel reached 610°F. The results for the three cases analyzed are as follows:

Case I. Failure is predicted to occur within 6 to 7 minutes following direct exposure of the inner pressure vessel to the fire.

Case II. Failure is predicted to occur approximately 240 minutes after exposure of the degraded container.

Case III. Approximately 0.38 in. of vermiculite thermal insulation is required to protect the inner pressure vessel for thirty minutes.

The 1475°F thermal environment used in the analysis was derived from 10 CFR 71. In the risk assessment in this report the most likely hydrocarbon fire temperature (1850°F) from the Sandia accident environment analysis was used. The radiant heat flux generated by an 1850°F source is approximately two times greater than the radiant heat flux generated by a 1475°F fire. Computer costs for transient thermal analyses are substantial; therefore, the cases above were not repeated for the higher source temperature. Rather, a factor of two reduction in the time to failure was used in the failure analysis of Section 9. The 50% reduction is felt to be conservative.

PROBLEM STATEMENT

The type L-10 plutonium nitrate shipping container is designed to meet the requirement of 10 CFR 71, Appendix B.[2] These include survival in a 1475°F radiation environment for 30 minutes following a 30-ft free fall onto an essentially unyielding surface and a 40-in. drop onto a 6-in. diameter puncture probe. Survival characteristics of the container in more severe environments were analyzed in Reference 1. The analysis results are repeated here for completeness. Specific cases studied were the entry of fire into a partially insulated container, direct exposure of the inner pressure vessel to a fire, and the insulation required to prevent failure of the inner pressure vessel for 30 minutes.

ANALYTICAL APPROACH

Heat transfer analyses were performed using the HEATING4 computer program. HEATING4 is derived from the HEATING3 program.(3) The program is a generalized steady-state and/or transient heat conduction code written in Fortran II and IV and modified to operate on the CDC-6600 computer. The failure condition used was a temperature of 610°F in the stainless steel of the inner pressure vessel. The failure temperature was derived in the temperature/stress analysis shown in Appendix D.

The following is a list of symbols used in the analysis detailed in the following subsections:

C_p	Heat capacity (Btu lb^{-1} $°F^{-1}$)
h_c	Convection heat transfer coefficient (Btu min^{-1} $in.^{-2}$ $°F^{-1}$)
h_r	Radiation heat transfer coefficient (Btu min^{-1} $in.^{-2}$ $°R^{-4}$)
k	Thermal conductivity (Btu min^{-1} $in.^{-1}$ $°F^{-1}$)
T	Temperature (°F or °R)
r,θ	Coordinate axes
ΔT	Temperature difference (°F)
X	Product of Grashof and Prandtl numbers defined in Reference 4.
ε_A	Ambient emissivity
ε_S	Single surface emissivity
ε_F	Emissivity of fire
ρ	Density (lb $in.^{-3}$)
σ	Stephan-Boltzmann Constant (1.983×10^{-13} Btu min^{-1} $in.^{-2}$ $°R^{-4}$)
$\mathcal{F}$	Grey body shape factor

Geometry Models

Geometries for Cases I, II, and III are illustrated in Figures E.1, E.2, and E.3, respectively. The principal assumption in all cases is a two-dimensional (r,θ) heat transfer situation, representing either a symmetrical or conservative case by a quadrant section perpendicular to the axis of the pressure housing.

In Cases I and II the thermal analyses modeled a lower quadrant section with the principal axis of the container horizontal prior to onset of the fire. An upper quadrant (Figure E.3) was modeled in Case III.

Figure E.2 shows a geometry with a 5-in. vertical crush depth on the carbon steel container and a vertical displacement of 1.25 in. of the stainless steel housing axis below the original major axis of the container. These values correspond to a free fall case given in Appendix D.

The outer carbon steel container was neglected in all computations, based on anticipation that this would have negligible influence on the heating rate of the pressure vessel. This assumption is obviously valid in Case I, where fire is considered to have entered the container. In Case II inclusion of the container would have complicated the noding of asymmetric regions and increased computation time excessively. Neglect of the container should change the outer boundary temperature distribution in the vermiculite less than 10°F. The absence of the outer container in Case III is conservative by allowing fire to exist directly at the outer vermiculite boundary.

The material/region boundary dimensions are summarized in Table E.1.

TABLE E.1. Radial Material Distribution for all Cases

Material	Boundary Radius (in.) Inner Boundary	Boundary Radius (in.) Outer Boundary
Plutonium Nitrate Solution	0.0	2.24
	2.25	2.41
Polyethylene	2.24	2.25
304 Stainless Steel	2.41	2.78
Vermiculite	2.78	>2.78

Boundary radii correspond to dimensions of the L-10 shipping container described in Reference 5 and shown in Appendix A. Plutonium

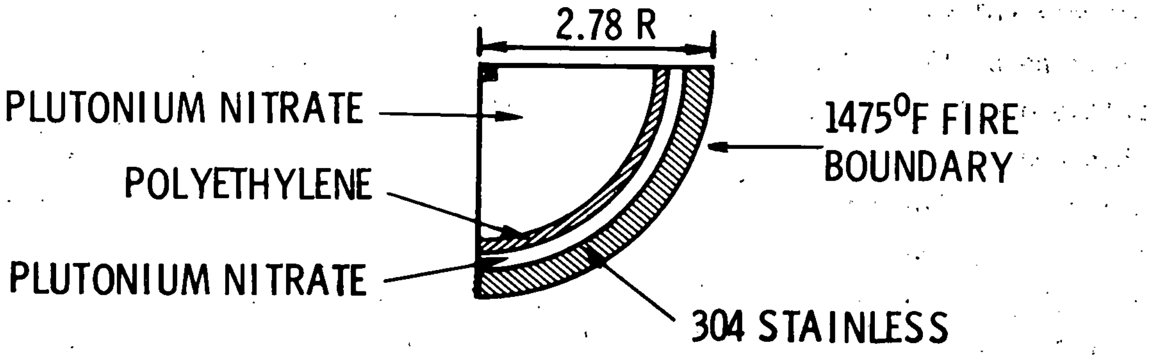


FIGURE E.1. L-10 Case I Geometry

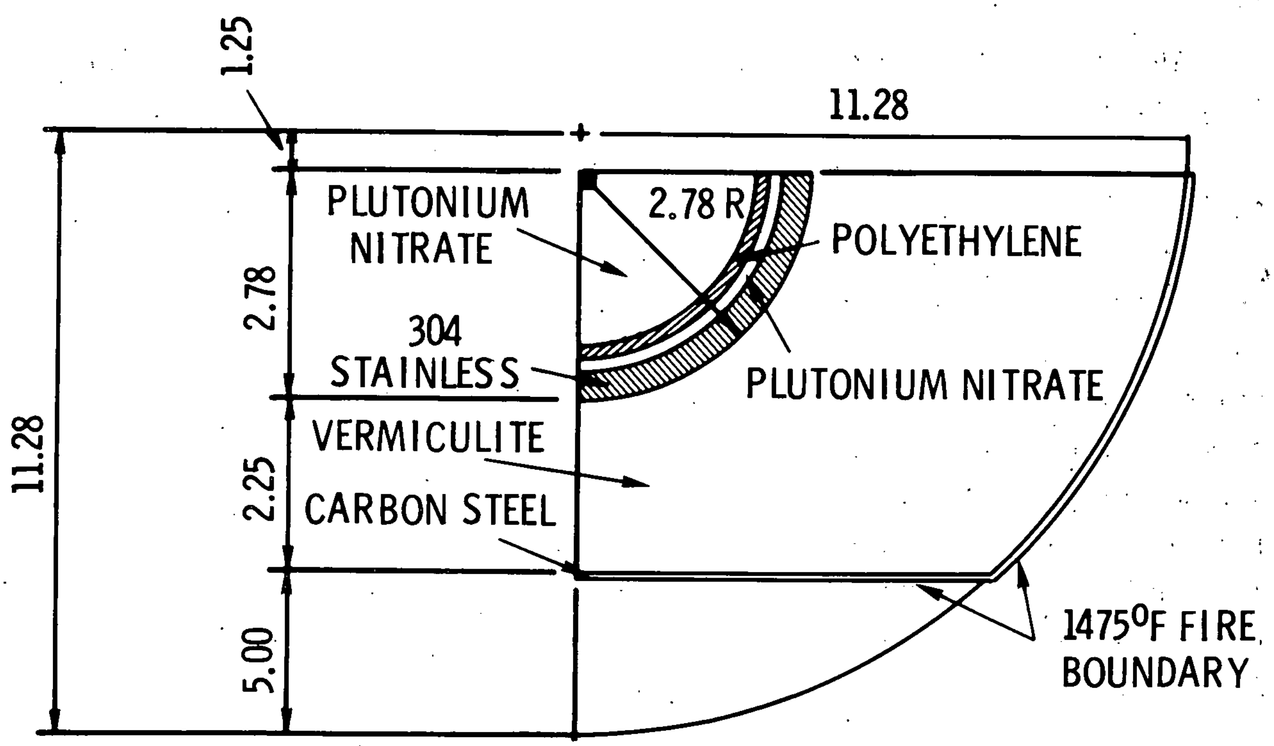


FIGURE E.2. L-10 Case II Geometry

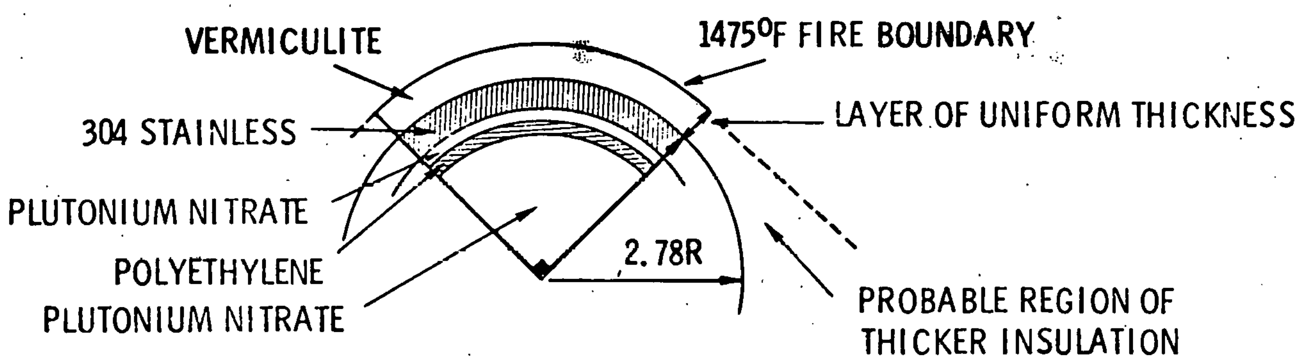
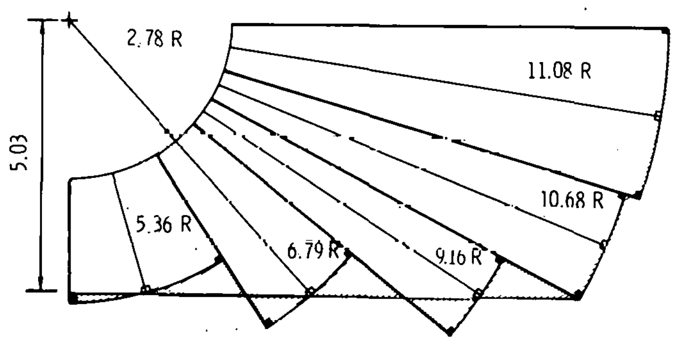


FIGURE E.3. L-10 Case III Geometry

nitrate solution is considered to fill the quadrant inside the polyethylene bottle and the region between the average outer diameter of the bottle and the internal surface of the stainless steel pressure vessel. This configuration allows consideration of plutonium nitrate heat generation in the annular clearance between the polyethylene and the stainless steel. This represents the conservative assumption that the annulus fills by leakage from the bottle after the axis of the container becomes horizontal. The regions containing plutonium nitrate are considered to be full of the solution for conservatism.

The principal difference between cases is contributed by the vermiculite distribution models. In Case I, no vermiculite is considered. For the crushed container (Case II) the vermiculite distribution is modeled by five circular segments shown in Figure E.4 assuming the heating to be axisymmetrical. Shading indicates regions which are either external to the flat bottom crush geometry of Figure E.2 or for which no account was taken. The model is considered representative, however, because the exact shape of the crushed surface is unknown. For Case III vermiculite is modeled as a layer of uniform thickness, (Figure E.3) which represents the worst-case region of a vermiculite distribution resulting from partial loss of this material after crushing occurs. It is assumed that thicker layers of vermiculite and, hence, slower heating rates would exist in other regions surrounding the pressure housing (dashed line, Figure E.3).



APPROXIMATELY 1/2 SCALE
DIMENSIONS IN INCHES

FIGURE E.4. L-10 Case II Vermiculite Model

In all thermal models the influence of the PVC bag in the annulus between the polyethylene bottle and the pressure vessel was considered negligible. Similarly, no account was taken of the thermal characteristics of the case structure.

Material Properties

References 6 through 12 provided thermophysical material properties. Table E.2 contains the C_p, ρ and k values with the appropriate temperature dependences used in these analyses.

The emissivity of stainless steel in Case I was taken as 0.5 to estimate the gray body shape factor. In Case II the gray body factor was computed for the equivalent fire/container interface specified in Reference 2. A value ε = 0.8 was assumed for Case III to allow for direct exposure of the vermiculite to the fire. Any error in assumptions relating to radiant heat transfer at the fire boundary was considered to be conservative. In Cast I, the emissivity of the stainless steel may increase during the fire. This tendency would increase the rate of heating and decrease the time for failure. In Cases II and III, the gray body shape factor ($\mathcal{F}$) will have a tendency to be lower than assumed values. Computed failure times will therefore tend to be shorter than may occur in reality, and survival to 30 min may be achieved with a slightly thinner vermiculite layer than the results indicate. It is expected generally that the uncertainty in $\mathcal{F}$ will cause significantly less perturbation than similar variability in C_p and k values found in the literature.

Phase change was anticipated for the polyethylene bottle. Heat of fusion and melting point temperature was obtained from Reference 9. Contact resistance between regions was neglected.

Heat Generation Rate

A constant uniform heat generation rate of 3.26 x 10^{-3} Btu min^{-1} $in.^{-3}$ was calculated [7] for all plutonium nitrate solution regions.

Boundary Conditions

Boundary parameters were estimated to provide appropriate initial

TABLE E.2. Material Description Data[a]

Conductivity as a Function of Temperature

Material	Temperature (°F)	$k(x10^{-5})$	Derivation[b]
Polyethylene	40	32.5	Reference 9
	140	29.4	
	240	23.8	
	290	22.2	
304 Stainless Steel	212	13.1	Reference 10
	392	14.3	
	572	15.3	
	752	16.4	
	932	17.4	
Plutonium Nitrate	40	46.1	Reference 7 Recommendation to use conductivity of water.
	100	50.6	
	200	54.4	
	300	54.9	
	400	53.3	
	500	49.4	
Vermiculite	85	5.55	Reference 11 and 12
	410	8.33	
	670	11.1	
	895	13.9	
	1110	16.7	
	1335	19.4	

Density as a Function of Temperature

Material	Temperature (°F)	$\rho(lb/in.^3)$	Derivation[b]
Polyethylene	68	0.0346	Reference 9 Temperature dependence calculated from specific volume.
	140	0.0335	
	212	0.0315	
	302	0.0295	
304 Stainless Steel	0	0.29	Reference 10
Plutonium Nitrate	40	0.05	Reference 6 Temperature dependence proportional to that of water with (ρ25°C) = 1.385 g/cm^3.
	100	0.0497	
	200	0.0482	
	300	0.0459	
	400	0.0430	
	500	0.0393	
	600	0.0340	
Vermiculite	0	0.00463	Reference 11 and 12

TABLE E.2. (Contd)

Heat Capacity as a Function of Temperature

Material	Temperature (°F)	C_p	Derivation[b]
Polyethylene	50		Reference 8
	100		
	150		
	200		
	225		
	250		
	268		
	288	0.868	
	300	0.854	
	400	0.782	
	500	0.707	
304 Stainless Steel	0	0.012	Reference 10
Plutonium Nitrate	0	1.0	Reference 7 as for water
Vermiculite	32	0.2	Reference 12
	1400	0.24	

Material	Melting Point	Latent Heat	Derivation[b]
Polyethylene	266°F	93.97 Btu/16	Reference 9

(a) Material properties, unless otherwise noted were input to the computer code with the following temperature dependence. Appropriate references are noted.
(b) The reference for each property is cited once at the beginning of the values for which it is appropriate.

steady-state and fire-initiated transient conditions.

Steady-state initial conditions were assumed to be controlled by radiation and free convection from the undamaged container in a 130°F ambient air environment. A radiation heat transfer coefficient h_r was calculated from

$$h_r = \sigma \mathcal{F} . \tag{E-1}$$

The gray body shape factor ($\mathcal{F}$) was determined by

$$\mathcal{F} = \left[\frac{1}{\varepsilon_S} + \frac{1}{\varepsilon_A} - 1\right]^{-1} . \tag{E-2}$$

Assuming the ambient to be a black body in effect

$$\mathcal{F} = \left[\frac{1}{0.8}\right]^{-1} = 0.8 .$$

By substitution in (1)

$$h_r = 1.59 \times 10^{-13} \text{ Btu. min}^{-1} \text{ in.}^{-2} \, {}^\circ\text{R}^{-4} .$$

An expression for an appropriate free convection heat transfer coefficient (h_c) for vertical cylinders in air was obtained from Reference 4:

$$h_c = 2.2 \times 10^{-5} \, \Delta T^{1/3} . \tag{E-3}$$

The validity of this expression is determined by

$$10^9 < X < 10^{12} .$$

A value $X \sim 2.3 \times 10^9$ was calculated for steady-state conditions.

Solar energy input was neglected with the assumption that the container is shaded from the sun prior to imposition of the fire.

Consideration was given to the effect of free convection in the plutonium nitrate solution. Using expressions in Reference 4, it was found that the effective conductivity of the solution could be enhanced 29% by free convection. To provide a conservative estimation of heating rate in the pressure housing, this effect was neglected.

A steady-state temperature distribution was established by running the HEATING4 code with the above values for heat generation, free convection and radiation.

In all transient calculations the fire boundary was coupled to the container by radiant energy transfer. A radiation heat transfer coefficient defined in (1) was used with $\mathcal{F}$ variable according to the case. $\mathcal{F}$ was calculated from (2) by substituting ε_F for ε_A. Table E.3 indicates h_r for each case.

TABLE E.3. Radiation Heat Transfer Coefficient for Transient Fire Conditions

Case	ε_S	ε_F	$\mathcal{F}$	h_r (Btu min.$^{-1}$ in.$^{-2}$ °R^{-4})
1	0.5	0.9[a]	0.474	9.40×10^{-14}
2	0.8[a]	0.9[a]	0.734	1.46×10^{-13}
3	0.88[b]	0.9[a]	0.80	1.59×10^{-13}

a. Hypothetical accident for Class II containers.[2]
b. Assumed value to achieve $\mathcal{F} = \varepsilon_S$ for conservative case.

RESULTS

The results of the L-10 shipping container thermal analyses for three hypothetical fire accidents may be summarized as follows:

Case I-Fire on Surface of Stainless Steel Pressure Housing

Figure E.5 shows temperature versus time for the mean diameter of the stainless steel pressure housing with a 1475°F fire at the outer diameter. Extrapolation shows incipient failure of the pressure housing after 6.4 min exposure to the fire. Failure temperature was taken as 610°F from the analysis in Appendix D. At approximately 600°F, a 23°F ΔT exists across the wall of the pressure housing. For the assumed boundary conditions, the corresponding range of uncertainty at the time for failure is ± 0.19 min.

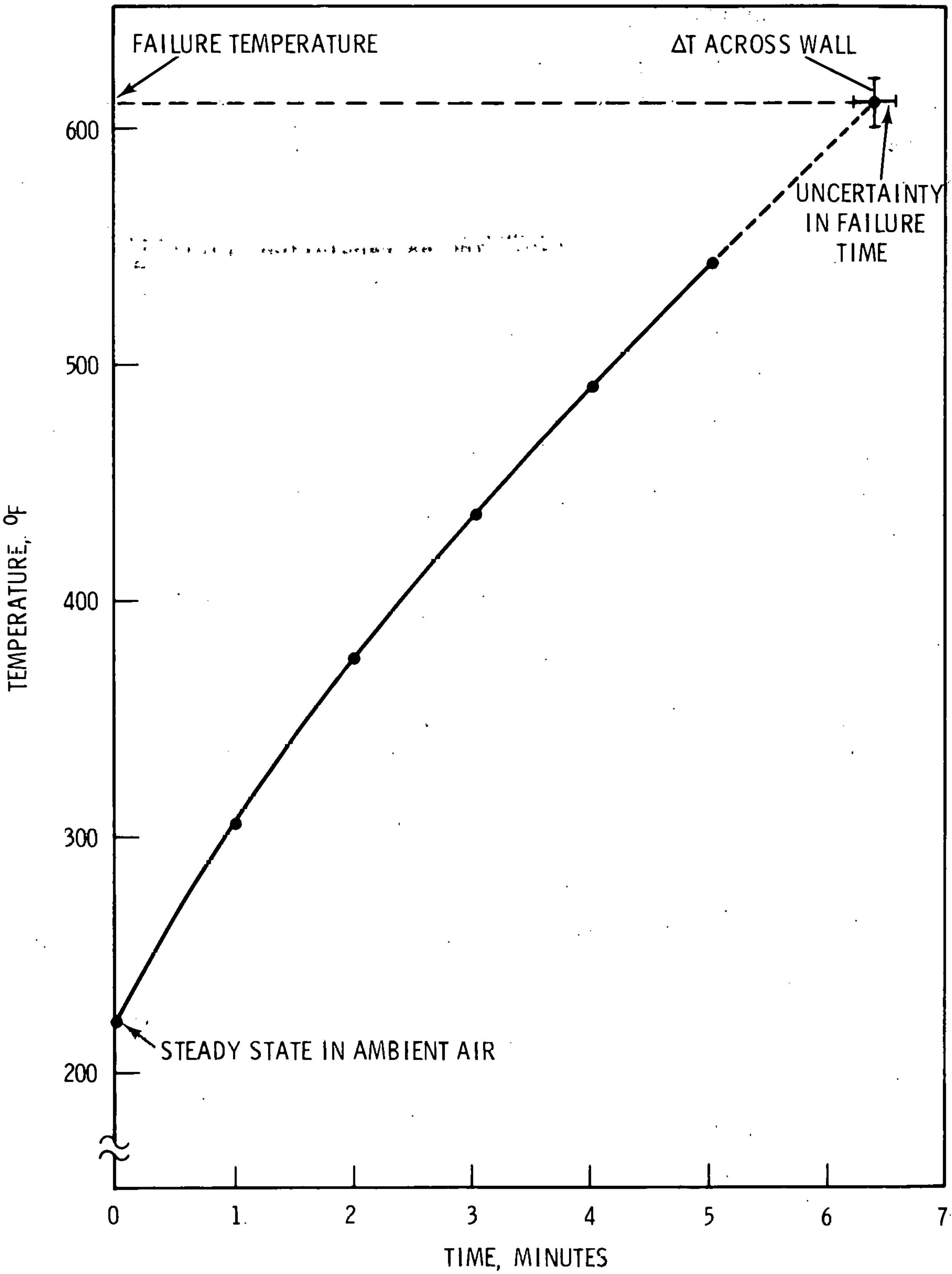


FIGURE E.5. L-10 Case I Temperature Versus Time of Pressure Housing Exposed Directly to 1475°F Fire

Case II-Fire on Crushed Container

Using the geometry of Figure E.4, transient heat transfer analysis showed that the pressure housing temperature ranges from 298°F to 317°F after 56 min of fire exposure. The nodal temperature distribution after a 56-min fire is shown in Figure E.6. The extrapolations plotted in Figure E.7 roughly indicate that incipient failure may not be anticipated before approximately 240 min. The computer run was arbitrarily limited to a 60-min fire transient case to avoid excessive computer costs. The computer reached its time limit before the 60-min transient history was completed.

Case III-Fire with Variable Insulation Thickness

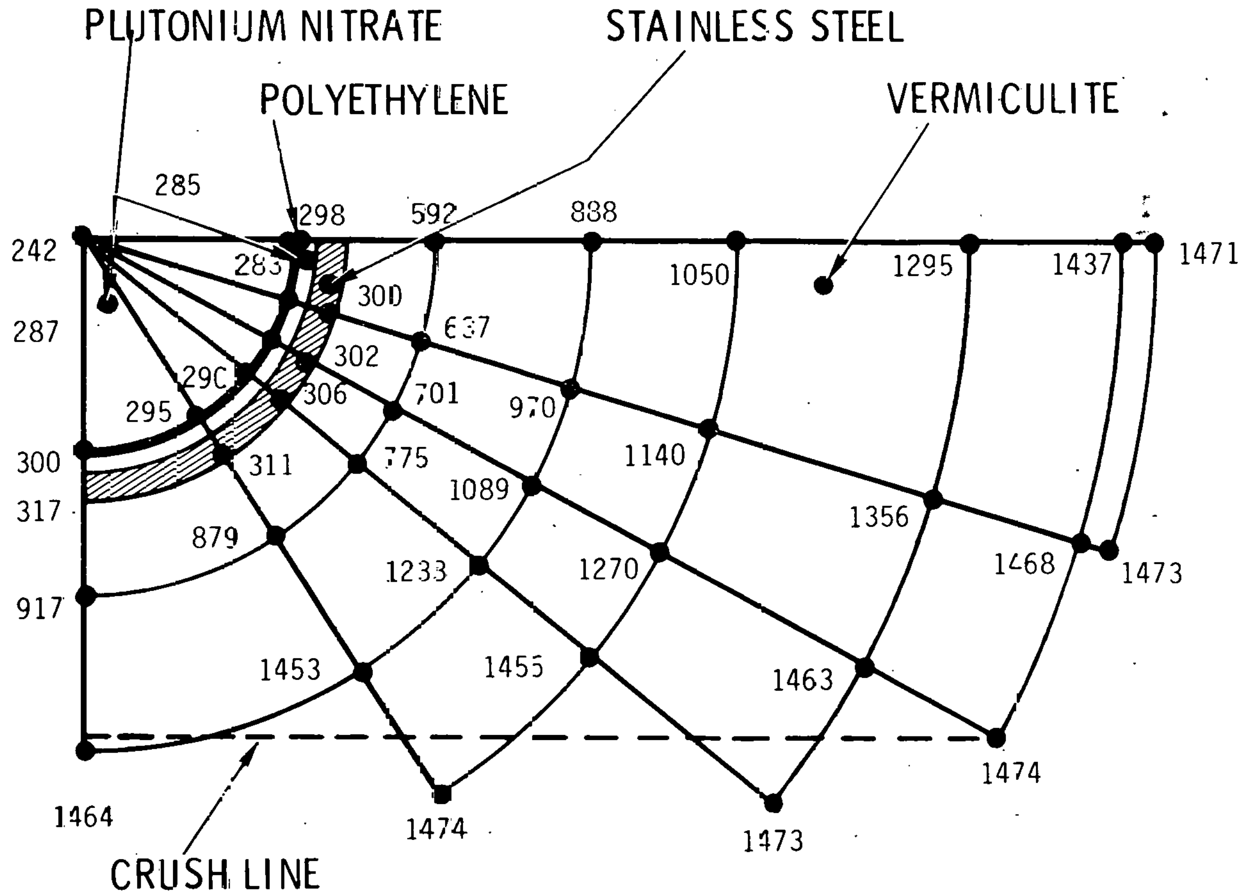
This situation is shown in Figure E.3. A fire-initiated transient heat transfer analysis was run for several vermiculite insulation thicknesses. Figure E.8 shows temperature versus time for four cases. Using these data, the time for 610°F to be reached at the mean diameter of the stainless steel is plotted as a function of vermiculite thickness in Figure E.9. A vermiculite thickness of approximately 0.38 in. is shown to be sufficient to prevent pressure housing failure for 30-min exposure to the hypothetical fire.

DISCUSSIONS AND CONCLUSIONS

With the assumed boundary conditions the principal conclusions of the thermal analysis are:

1) A 5-in. crush depth and associated displacement of the pressure housing does not degrade the L-10 container below test fire survival requirements if no loss of vermiculite occurs. The trend indicated by a 56-min transient analysis indicated failure would occur at approximately 240 min.

2) If vermiculite is partially lost, a relatively thin layer (∿0.38 in. thickness) would protect the pressure housing for 30 min in the hypothetical fire test.



1/2 SCALE

TEMPERATURES IN °F

FIGURE E.6. L-10 Case II Nodal Temperature after 56 min Fire Exposure

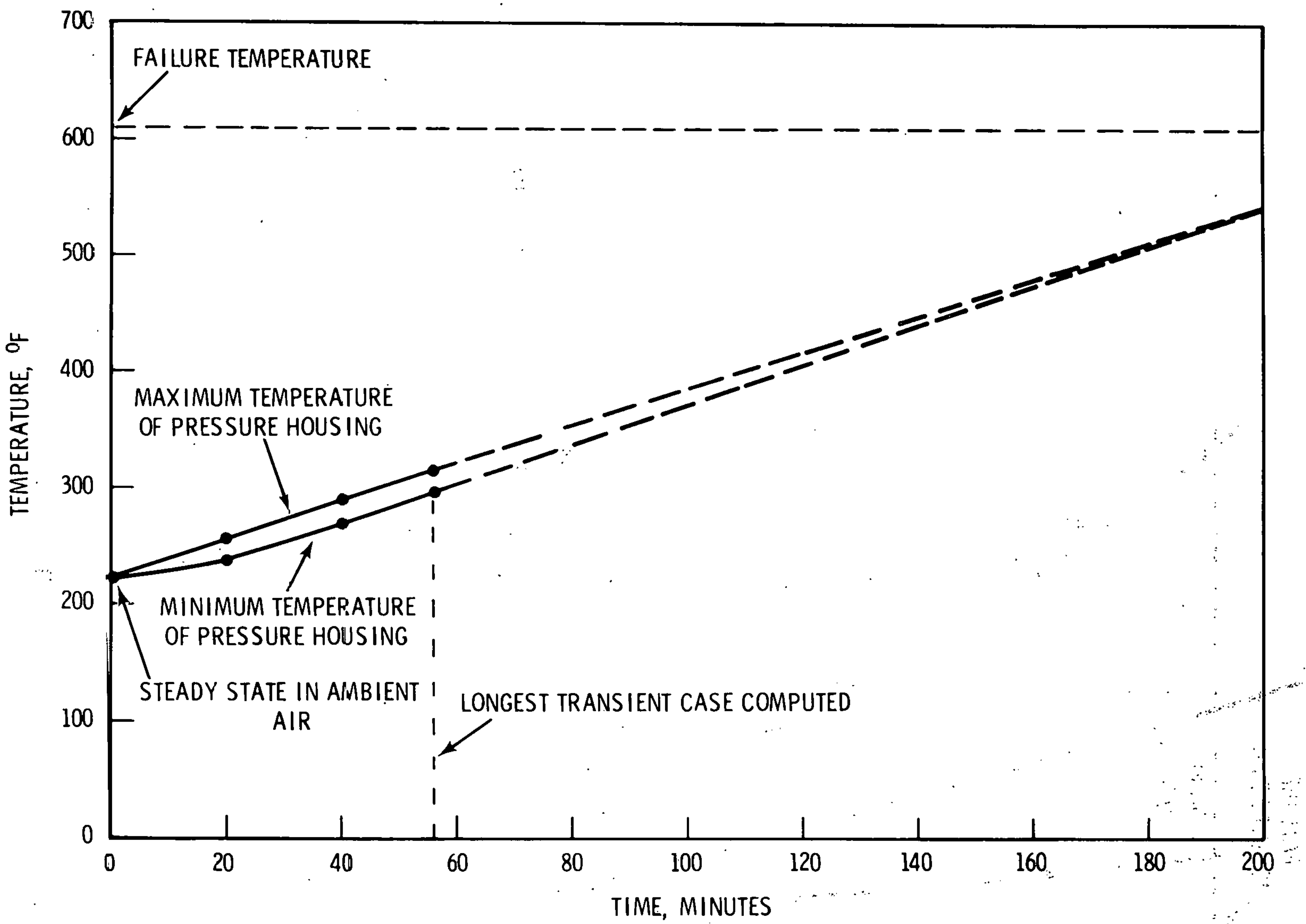


FIGURE E.7. L-10 Case II Temperature Versus Time of Pressure Housing in Crushed Container Exposed to 1475°F Fire

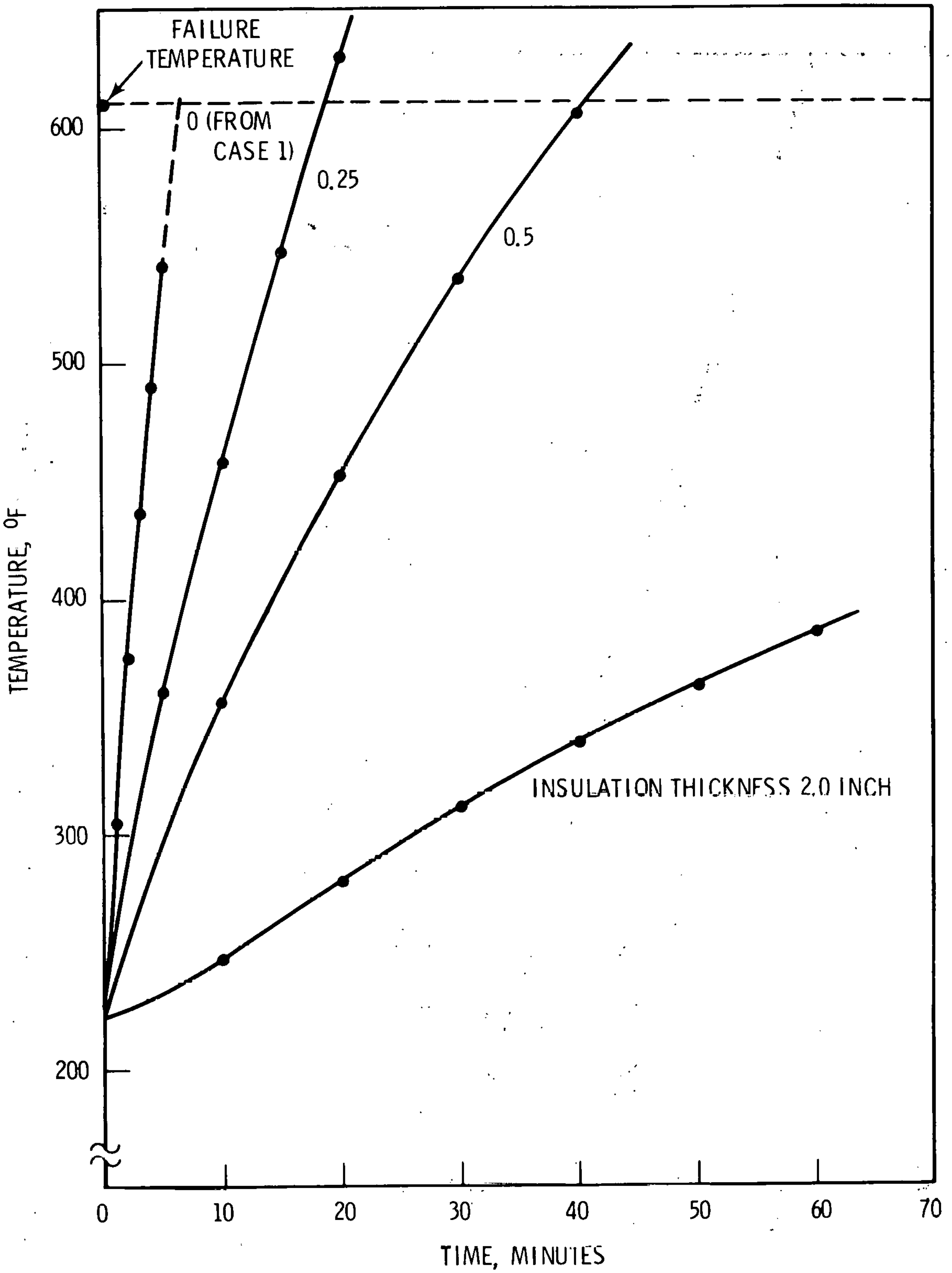


FIGURE E.8. L-10 Case III Temperature Versus Time of Pressure Housing with 1475°F Fire Inside Container

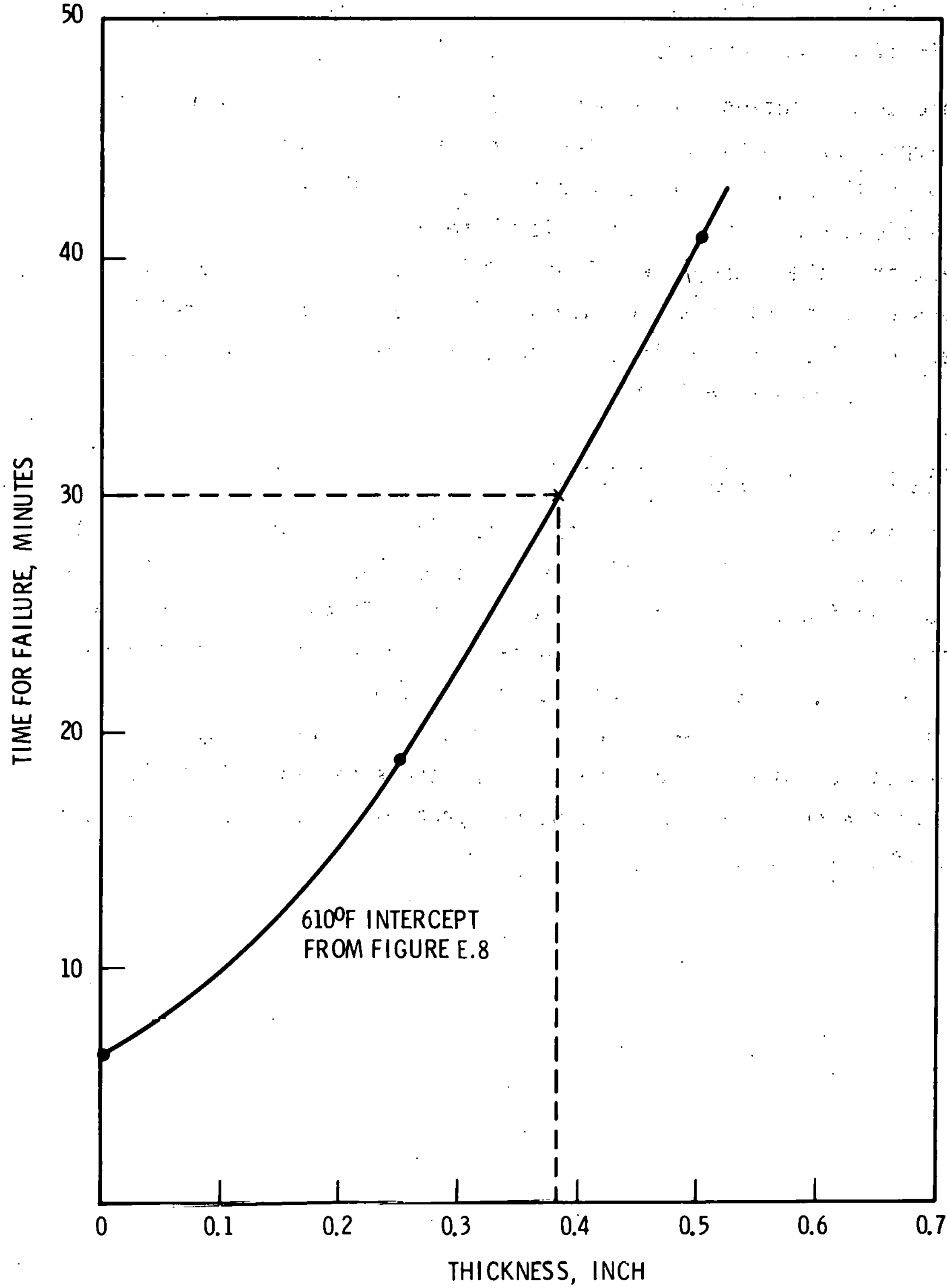


FIGURE E.9. L-10 Case III Time for Pressure Housing Failure Versus Vermiculite Insulation Thickness

3) The pressure housing alone is predicted to survive between 6 and 7 min if exposed directly to the test fire.

Some uncertainties were generated in Cases I and III by the computational approach. To avoid computer costs, a single fire steady-state boundary condition was computed and applied to all runs. This started some transient computations with initial temperatures as much as 40°F different from their probable values. This effect was observed as the thickness of vermiculite was changed in Case III. Linear corrections for these displacements of initial temperature were applied to results plotted in Figure E.5 and E.8.

CORRELATION TO PUBLISHED TEST RESULTS

A series of fire tests were conducted at Sandia Laboratories that included an L-10 container.[13] The container was placed directly above a pool of burning aircraft fuel for a period of 55 minutes. The fire temperature was 1800°F. The L-10 container remained intact during the test. The vermiculite was charred to some extent. The polyethylene bottle inside the pressure vessel reached a temperature of approximately 250°F and showed signs of melting. The pressure vessel did not leak. Failure of the outer drum did not occur, probably because of vents near the top edge of the drum.

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. Code of Federal Regulations, Title 10, Part 71, Appendix B-Hypothetical Accident Conditions

3. W. D. Turner and M. Siman-Tov, HEATING3 - An IBM 360 Heat Conduction Program, Oak Ridge National Laboratory Report No. ORNL-TM-3208, February 1971.

4. W. H. McAdams, Heat Transmission, McGraw-Hill Book Company, 3rd Edition, 1954.

5. E. F. Curren, Evaluation of the Type L-10 Class II Shipping Container for Conformance with AEC Manual Chapter 0529 Appendix, Isochem, Inc., Report No. ISO-970, July 1967.

6. T. I. McSweeney et al, Transportation Safety Studies - The Risk of Plutonium Shipments, Battelle, Pacific Northwest Laboratories Summary Report No. BNWL-B-295, August 1973.

7. T. I. McSweeney, private communication to J. G. DeSteese, both of Battelle-Northwest.

8. E. C. Bernhardt, Processing of Thermoplastic Materials, Reinhold Publishing Co., New York, NY, 1959.

9. J. Brandrup and E. M. Immergut, Polymer Handbook, Interscience Publishers, 1966 Edition.

10. Amer. Soc. of Metals, Metals Handbook, Vol. 1 - Properties and Selection of Metals, 8th Edition, 1961.

11. J. B. Loser et al, Thermophysical Properties of Thermal Insulating Materials, Technical Documentary Report No. ML-TDR-65-5, Midwest Research Institute, Kansas City, MO, April 1964.

12. Zonolite Branch Vermiculites, Zonolite Division W. R. Grace and Co. Brochure G-231, 1964.

13. L. F. Stravasnik, Special Tests for Plutonium Shipping Containers GM, SP5795, and L-10, Sandia Laboratory Report No. SC-DR-72-0597, September 1972.

APPENDIX F

EVALUATION OF MULTIPLE CONTAINER FAILURES FROM INERTIAL CRUSH

Inertial crush is the squeezing action on the containers which occurs as the load shifts following an accident involving deceleration. Eventually all the containers will come to rest, however the containers closest to direct involvement in the accident will decelerate first followed by the deceleration of successive rows of containers. The highest crush forces will be experienced by the row which is first to experience deceleration since essentially the entire weight of the cargo presses against the first row. Successive rows experience smaller crush forces.

Since crush forces result from the action of many containers, the question of multiple container failures in an accident must be considered. The main analysis model considers container failures to be independent events which are so rare that the likelihood of two containers failing in the same accident is extremely small. This appendix will evaluate the possibility of more than one container failing in the crush environment. The development of the L-10 deformed array configuration evaluated for criticality in Appendix C is also presented.

THE ACCIDENT ENVIRONMENT AND FAILURE MECHANISMS

Figures F.1 and F.2 show the loading configuration of the L-10 and 6M containers used for the risk assessment. In the worst case, a fully-loaded railcar impacts directly against a flat, relatively unyielding surface such that all containers in each row (a total of 17 in the case of L-10's and 30 in the case of 6Ms) press against the forward containers while coming to rest. The analysis below is an evaluation of failure thresholds in that situation. The extreme case of deceleration (80 g's) is also presented for criticality evaluation because inertial crush produces, by far, the most close-packed final configuration of containers.

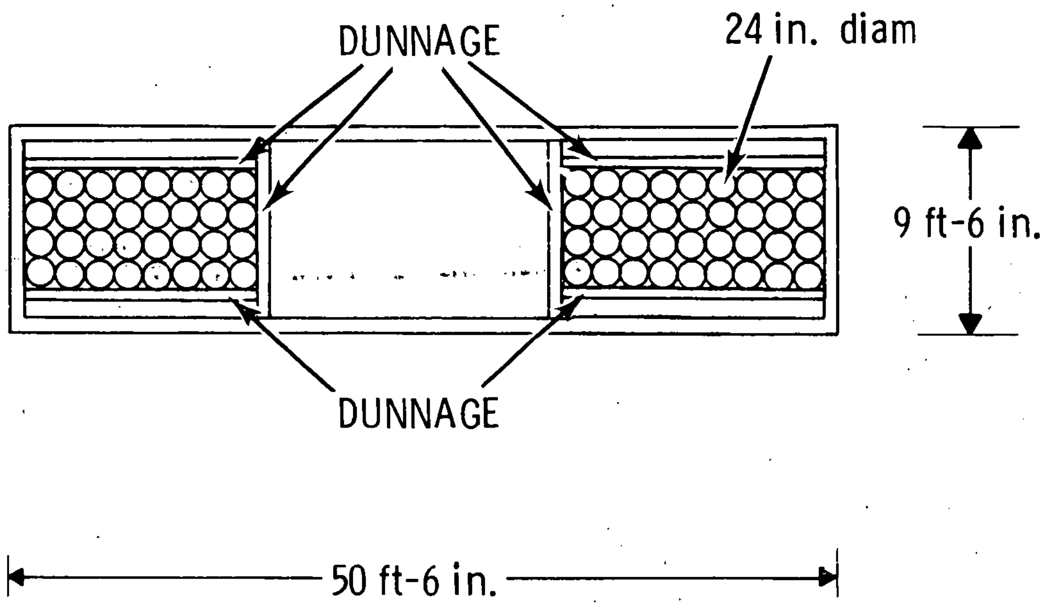


FIGURE F.1. Loading Configuration of L-10 Containers for Rail Transportation

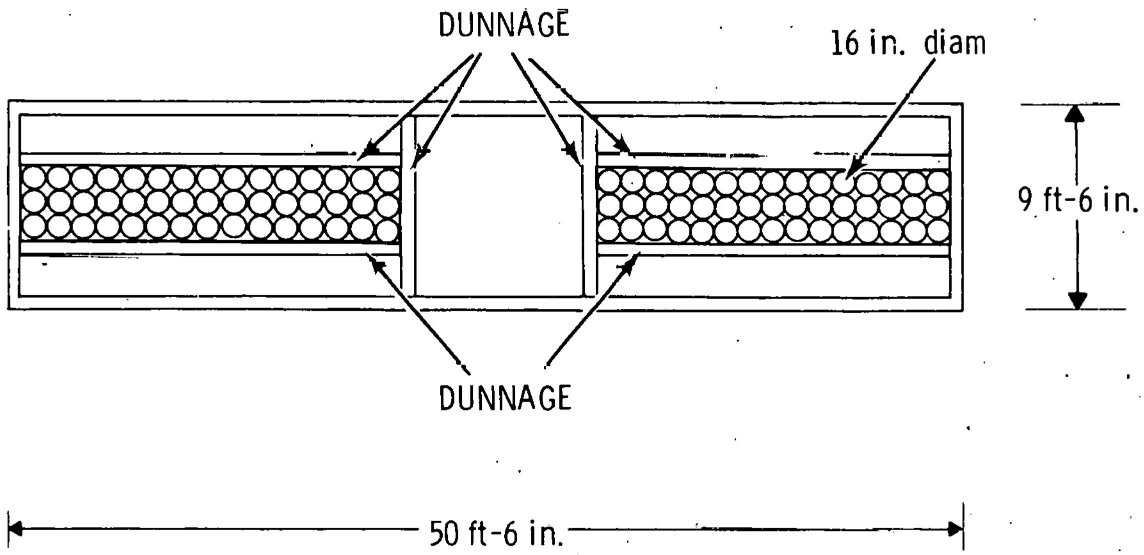


Figure F.2. Loading Configuration of 6M Containers for Rail Transportation

The accident conditions which are most likely to produce severe inertial crush involve the front (or rear) end of a railcar colliding with a relatively fixed barrier directly along the longitudinal axis. This implies that the relative position on the containers with respect to the sides of the cars will not change (i.e., each container in a row will move directly forward). Two successive failure mechanisms may occur: 1) the sides of the container deform sufficiently that the lid pops off, and 2) the containers deform sufficiently to subsequently fail the inner container.

Forces on a container moving in pure translation along the longitudinal axis of the railcar act only on two opposing sides of the container. The situation is similar to static loading between plates positioned at 180° along the longitudinal axis of the container. Interaction with containers in other rows and with the sides of the railcar is insignificant and can be ignored. Typical dunnage bars restraining the rear section of containers in a front end collision or the front section of containers in the event of a rear end collision have been analyzed by Sandia and found to provide restraint up to 4 g's deceleration.(1)

Sandia studies(1) indicate that the maximum credible level of deceleration between the containers and the wall of the railcar in extreme accidents is about 80 g's. This value was derived from a mass-spring model of two trains colliding head-on, each with a speed of 90 mph. To experience this deceleration the containers would essentially have to be located on the engine of one train or in the car directly behind. A more typical level of deceleration in severe accidents is 30 g's. As shown in Figure 5.1, 99.95% of all collision and derailment accidents are expected to produce levels of deceleration below 30 g's. Analysis of failure at both the 30 g and 80 g levels are included in the analysis below.

The inner vessel of the L-10 and 6M containers (5-in. diameter, Schedule 80 pipe) will fail in buckling while undergoing inertial crush if the forces are sufficient. The force transmitted through the inner container under maximum inertial loading (80 g's between the first container and the railcar wall) was calculated and found to be substantially below the force required to buckle the Schedule 80 pipe in both the L-10 and 6M containers. The calculation was based on the assumption that the outer drum had buckled flat against the inner container and that the entire inertial force acted through the inner container. This assumption is conservative because a substantial fraction of the force can be expected to act through the compressed shell and insulation material between the inner vessel and outer drum.

Case 1 - Crush of L-10
Containers at 80 g Deceleration Level

Calculation of the total energy absorbed by an L-10 container during crush perpendicular to the longitudinal axis of the container is based on the approach used in Appendix D. The assumed loading configuration shown in Figure F.1 limits the applied forces to two directions (i.e., two diametrically opposed forces). The following assumptions were used to calculate the number of lid failures and final configuration of the containers following an accident:

- The equivalent force on each side of the container can be derived from the sum of the work of a constant force acting through the distance of deformation on each side plus the work expended in compaction of the vermiculite.
- The outer container will crush to the point that the shell is touching the inner container as shown in Figure F.3. Beyond that point the inertial forces are transmitted directly through the inner container.
- Energy absorption by the vermiculite can be calculated from the expression $E = \int - pdv$ up to the point of lid failure. Beyond that point energy absorption is limited to 50% of that absorbed up to the point of lid failure.
- The velocity of the railcar is 90 mph (132 ft/sec) and the railcar impacts directly against a flat essentially unyielding barrier. The condition is shown in Figure F.4.

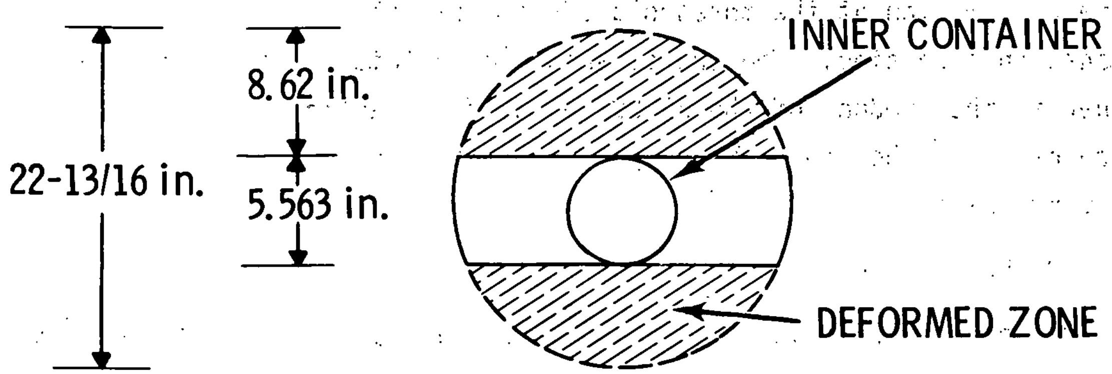


FIGURE F.3. Configuration of Completely Crushed L-10 Container

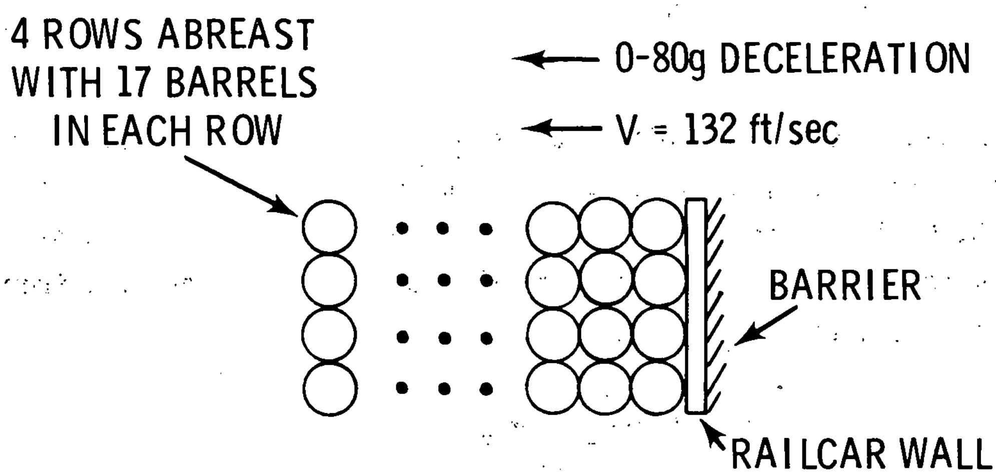


FIGURE F.4. Assumed Conditions at Onset of Accident

The deformation at the threshold of lid removal was calculated to be 3.2 inches on each side. The energy absorbed to this point by the L-10 container is the product of the 25,000 pound force acting through a distance of 3.2 inches on each end plus the energy expended in compression of the vermiculite.

$$E = 2 (Fxd) + \int - pdv$$

The derivation of the above expression appears in Appendix D. The energy absorbed due to the constant force at each end acting through 3.2 inches is 160,000 inch-pounds. The total energy absorbed by the vermiculite compaction was calculated to be 180,000 inch-pounds, using the relationship

$$E = \int_{V_i}^{V_f} - 228 \frac{V_i - V_f}{V_i} \, dv$$

derived in Appendix D. Each side of the container will absorb 90,000 inch-pounds. The total energy absorbed by one side of the L-10 container is therefore 80,000 inch-pounds plus 90,000 inch-pounds, or 170,000 inch-pounds. The force equivalent to produce this deflection is derived from Equation 6-1 in Chapter 6:

$$E = F \times d$$

$$\text{or } F = \frac{170{,}000 \text{ inch-pounds}}{3.2 \text{ inches}}$$

$$F = 53{,}125 \text{ lbs.}$$

The energy absorbed by each end of the container in deforming to the configuration shown in Figure F.3 is the sum of the force which will result in lid removal (53,125 lbs) plus the equivalent force due to the assumed 50% additional energy absorption by the vermiculite. The 50% additional energy is 45,000 inch-pounds on each side and the container deflects an additional 5.42 inches (8.62 - 3.2). The equivalent force to produce complete deflection is found from Equation 6.1:

$$E = F \times d$$

$$F = \frac{45{,}000 \text{ inch-pounds}}{5.42 \text{ inches}}$$

$$F = 8{,}300 \text{ lbs.}$$

The total force to deform the outer L-10 container against the inner container is 53,125 + 8,300 = ∿ 61,400 lbs (122,800 lbs total load). Any container experiencing a greater force will fail to the configuration shown in Figure F.3.

The force on any container in a row is equivalent to the mass behind the container in the direction of velocity multiplied by the deceleration in g's. The containers in each row will experience the maximum "g" level only if no permanent deformation occurs. When a container deforms, the effective stopping distance is increased which reduces the deceleration level. Table F.1 is a summary of forces acting on the containers in the different rows with an 80 "g" deceleration. The following relationships were used to develop Table F.1:

For the barrier:

$$v = at$$

where

v = initial velocity (132 ft/sec)

a = deceleration in g's

t = time in seconds

$$132 \text{ ft/sec} = 80 \; (32.2 \text{ ft/sec}^2) \; t$$

where

$$t = 0.0512 \text{ seconds}$$

stopping distance of the barrier:

$$s = 1/2 \; at^2$$

where

s = distance (feet)

a = deceleration

t = time (sec)

$$s = 1/2 \; 80 \; (32.2 \text{ ft/sec}^2)(0.0512 \text{ sec})^2$$

$$s = 3.38 \text{ feet.}$$

Containers experiencing complete deformation (outer drum flattening against inner vessel) will move forward a greater distance than an undeformed container (8.62 inches). This additional stopping distance has been added to each container affected in the row.

The inertial crush force is the product of the mass of the containers behind and the level of deceleration at the container under consideration. The restraint (4 g's) provided by the dunnage is subtracted from the g level of the containers affected. The inertial crush force for containers forward of the dunnage was calculated from the following expression:

$$F = [8(g-4) + (9-n)g]m$$

where

- n = container under consideration
- m = mass of each container = 510 lb
- g = deceleration level at the container under consideration.

The force on containers behind the dunnage was calculated by the expression:

$$F = (8-n)(g-4)m$$

where

$$17 < n > 9 .$$

Table F.1 can be used to develop the final configuration of inner containers for criticality calculation purposes. This configuration is shown in Figure F.5. Table F.1 also shows that up to 36 of the 68 containers will lose lids in this extreme accident.

Case 2 - Crush of L-10 Containers at Lower Levels of Deceleration

The same procedure used in Case 1 for calculation of the forces at deceleration levels of 80 g's can be applied to lower levels of deceleration. A deceleration of 30 g's or less would be expected in 99.95% of all railroad accidents as shown in Figure 5.1. The g level below which no damage will occur to any container can be found using the expression F = ma. Considering the first container in a row of 17, and that the

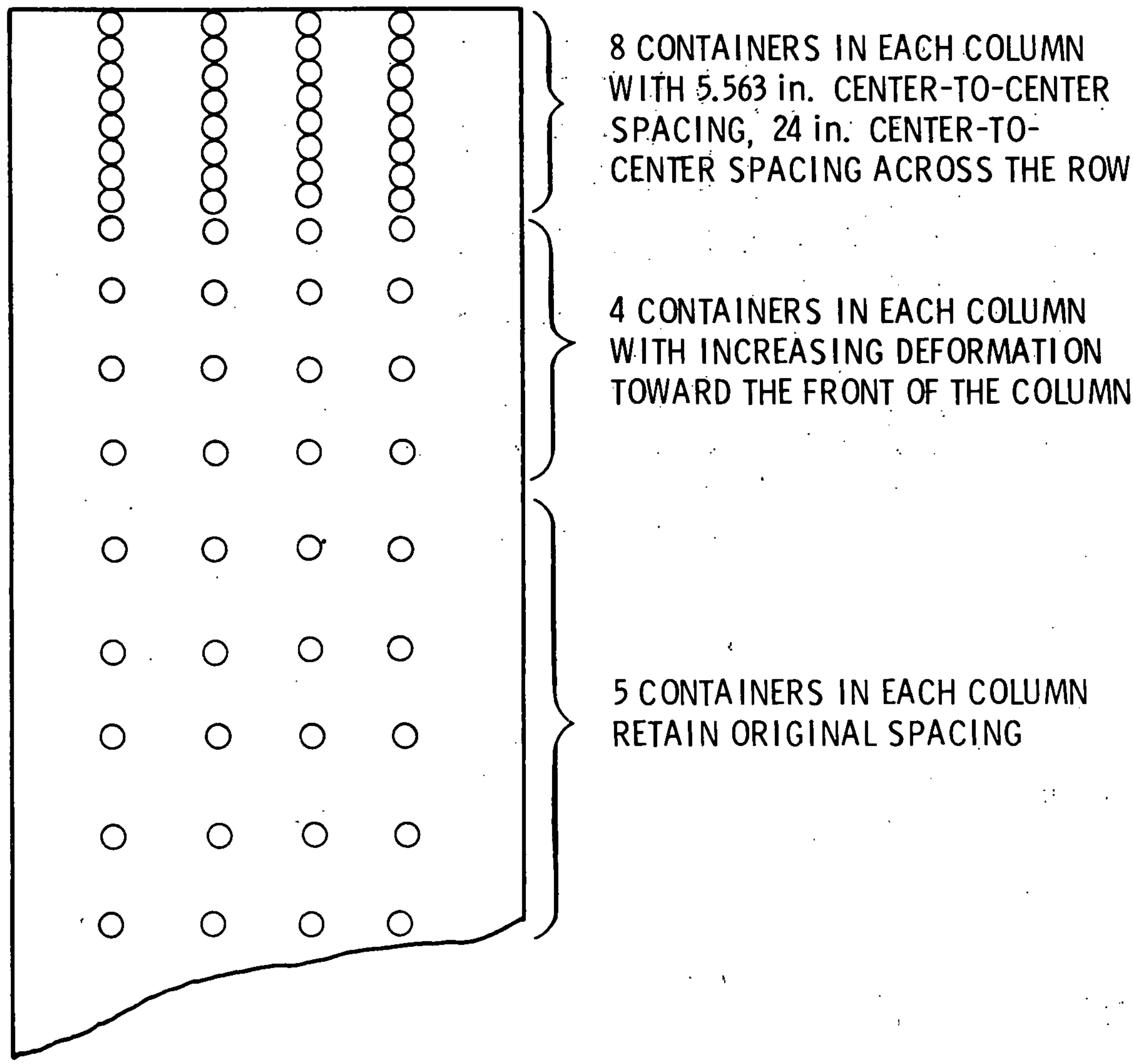


FIGURE F.5. Final Deformed Configuration of Inner Containers Following Accident with 80 g Deceleration Level

TABLE F.1. Crush Forces Experienced by Each Container in a Row of L-10s in an Accident Involving 80 g Deceleration*

Row Number	Stopping Distance (ft)	Equivalent g Level	Number of Containers Behind**	Force on Each Side (from F = ma) (lb)	Lid Lost		Comments
					Yes	No	
0 (Barrier)	3.38	80	17	677,300			
1	4.10	65.95	16	521,800	x		deformed to inner container
2	5.54	48.81	15	357,100	x		deformed to inner container
3	6.97	38.79	14	260,600	x		deformed to inner container
4	8.41	32.15	13	196,800	x		deformed to inner container
5	9.85	27.45	12	151,700	x		deformed to inner container
6	11.28	23.97	11	118,200	x		deformed to inner container
7	12.72	21.26	10	92,100	x		deformed to inner container
8	14.16	19.10	9	71,300	x		deformed to inner container
9	15.59	17.34	8	54,400	x		partially deformed (>3.2 in.)
10	16.57	16.31	7	43,900		x	partially deformed (~3.2 in.)
11	17.10	15.81	6	36,100		x	partially deformed (<3.2 in.)
12	17.60	15.35	5	29,000		x	partially deformed
13	18.10	14.94	4	22,300		x	not deformed
14	18.35	14.74	3	16,400		x	not deformed
15	18.35	14.74	2	11,000		x	not deformed
16	18.35	14.74	1	5,500		x	not deformed
17	18.35	14.74	0	0		x	not deformed

* Velocity of railcar at impact = 90 mph.
** Each container weighs 510 lbs.

force at the onset of deformation is 25,000 lbs:

$$F = m\,[8(g-4) + 8g]$$

where

F = force at onset of deformation = 25,000 lbs

m = weight of each container behind the first container = 510 lbs

g = deceleration in g's

$$25{,}000 = 510\,[8(g-4) + 8g]$$

$$g = 5.1.$$

Thus, any accident involving less than approximately 5 g deceleration between the front container and the wall of the railcar will produce no damage.

The minimum g level to cause lid removal can be similarly calculated by substituting the force for lid removal, 53,125 lbs, for the force at the onset of deformation:

$$53{,}125 \text{ lb} = 510\,[8(g-4) + 8g]$$

$$g = 8.51.$$

Thus, no lids will be lost by inertial crush in accidents involving deceleration below approximately 8.5 g's. Figure F.6 indicates the number of container lids that will be lost as a function of deceleration level between the railcar wall and the first container in the row over the entire range of decelerations assumed credible for the railroad accident environment.

Case 3 - Crush of 6M
Containers at 80 g Deceleration Level

The drop height equivalents at the point of lid removal and complete deformation of outer container of the 6M under impact conditions were presented in Appendix D. The equivalent heights were 194 and 264 feet, respectively. The previous criteria for lid removal (deformed perimeter equal to undeformed inner circumference of clamp ring) derived for impact can also be calculated for crush loads (forces applied in two diametrically opposed directions). The 95,000 lb force existing at the instant of lid removal under impact is reduced to 72,000 lb total force when

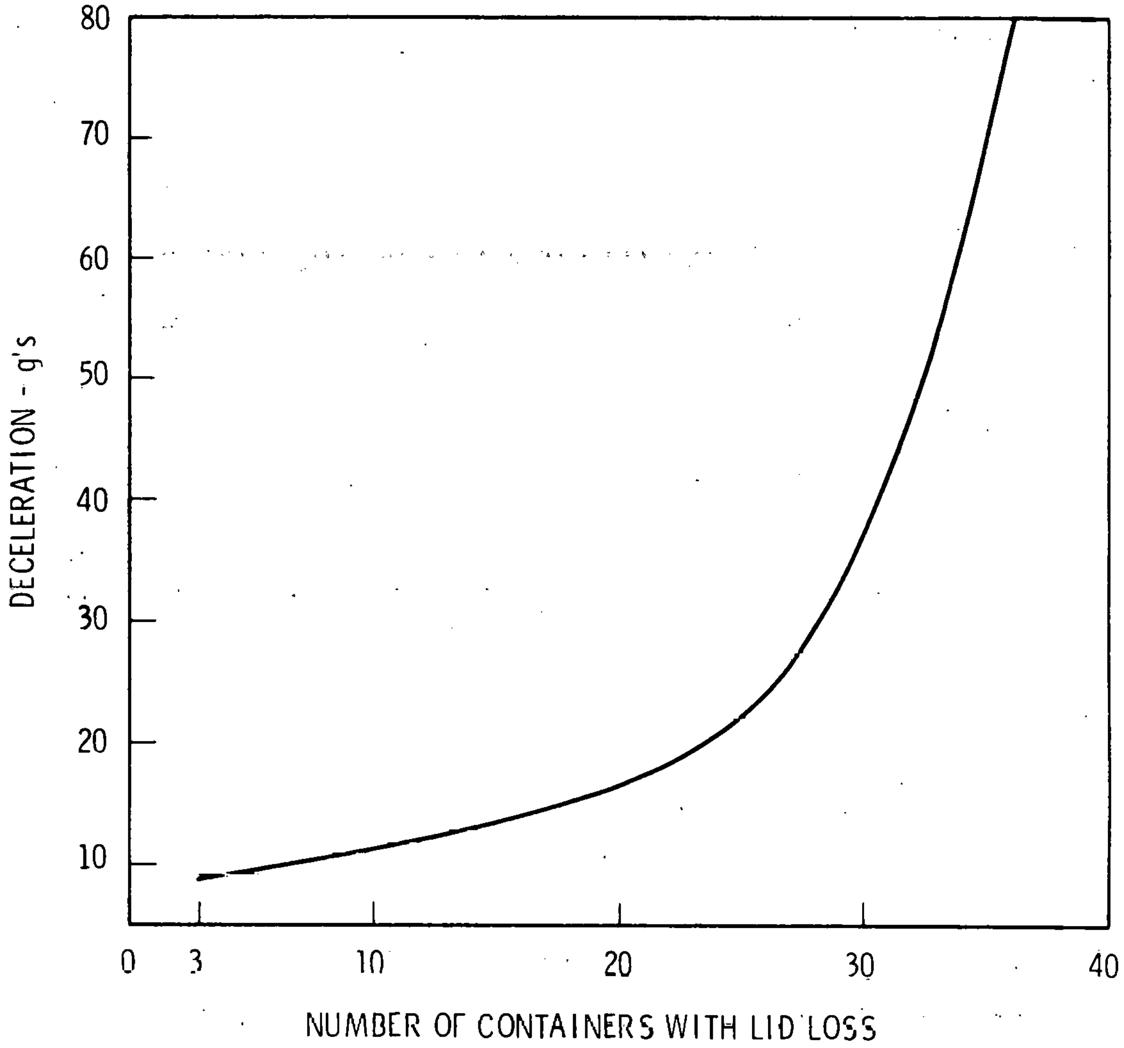


FIGURE F.6. Predicted Number of L-10 Container Lids Lost as a Function of Deceleration Level applied to two sides. The force is derived from Equation 6.1. An applied inertial load equivalent to one-half of the total 72,000-lb force will cause lid removal. Thus, an inertial force on one side of the container of 36,000 lb is the threshold for lid removal on the 6M container. The distance of deflection on each side is 2.58 in. The additional force required to completely deform the outer container can be derived using Equation 6.1 and equating it to the difference in energy between the equivalent drop height at the point of lid removal and the drop height at total deformation. The additional force was found to be 27,000 lb. The total force to completely deform the 6M by crush is therefore, 72,000 + 27,000, or 99,000 lb. The inertial force acting on one side is one-half of total force, or 49,500 lb. The total deformation on each side at total crush was found to be 4.91 inches. Table F.2 indicates the forces and g levels on each container in an 80 g deceleration accident. As indicated up to 42 containers could lose lids in this extreme accident. It was assumed that the same 25,000-lb threshold force was required to cause any deformation.

Case 4 - Crush of 6M
Containers at Lower Levels of Deceleration

The crush forces on each container in a row of 6Ms was calculated for several levels of deceleration. The composite curve shown in Figure F.7 can be used to predict the number of containers losing lids in any accident in which the level of deceleration is known.

The minimum force to remove the lid of a 6M was shown to be 36,000 lb (total load of 72,000 lb). The g level below which no lids are lost was calculated using the same procedures as the L-10 container. The minimum g level for no lid removal was found to be 9.83 g. The threshold force below which no deformation of the outer drum occurs was assumed to be the same as that of the L-10 (25,000 lb). The g level below which no deformation of the outer drum of any container in the row occurs is 7.46 g's.

TABLE F.2. Crush Forces Experienced by Each Container in a Row of 6Ms in an Accident Involving 80 g Deceleration*

Row Number	Stopping Distance (ft)	Equivalent g Level	Number of Containers Behind**	Force on Each Side (lb)	Lid Lost Yes	Lid Lost No	Comments
Barrier	3.38	80	30	374,400			Completely deformed
1	3.79	71.3	29	321,200	x		Completely deformed
2	4.60	58.8	28	253,800	x		Completely deformed
3	5.43	49.8	27	205,500	x		Completely deformed
4	6.24	43.3	26	170,600	x		Completely deformed
5	7.06	38.3	25	143,600	x		Completely deformed
6	7.88	34.3	24	122,100	x		Completely deformed
7	8.70	31.1	23	104,800	x		Completely deformed
8	9.52	28.4	22	90,400	x		Completely deformed
9	10.34	26.2	21	78,400	x		Completely deformed
10	11.15	24.3	20	68,200	x		Completely deformed
11	11.97	22.6	19	59,100	x		Completely deformed
12	12.79	21.1	18	51,200	x		Completely deformed
13	13.61	19.9	17	44,500	x		Almost completely deformed
14	14.43	18.7	16	38,300	x		Partially deformed (> 2.6 in.)
15	15.25	17.7	15	32,900		x	Partially deformed (< 2.6 in.)
16	15.83	17.1	14	29,300		x	Partially deformed (< 2.6 in.)
17	16.33	16.6	13	26,200		x	Partially deformed (<<2.6 in.)
18	16.66	16.2	12	23,400		x	Not deformed
19	16.95	16.0	11	21,100		x	Not deformed
20	17.20	15.7	10	18,700		x	Not deformed
21	17.30	15.6	9	16,700		x	Not deformed
22	17.30	15.6	8	14,900		x	Not deformed
23	17.30	15.6	7	13,000		x	Not deformed
24	17.30	15.6	6	11,100		x	Not deformed
25	17.30	15.6	5	9,300		x	Not deformed
26	17.30	15.6	4	7,400		x	Not deformed
27	17.30	15.6	3	5,600		x	Not deformed
28	17.30	15.6	2	3,700		x	Not deformed
29	17.30	15.6	1	1,800		x	Not deformed
30	17.30	15.6	0	-		x	Not deformed

*Velocity of railcar at impact = 90 mph.
**Each container weighs 160 lbs.

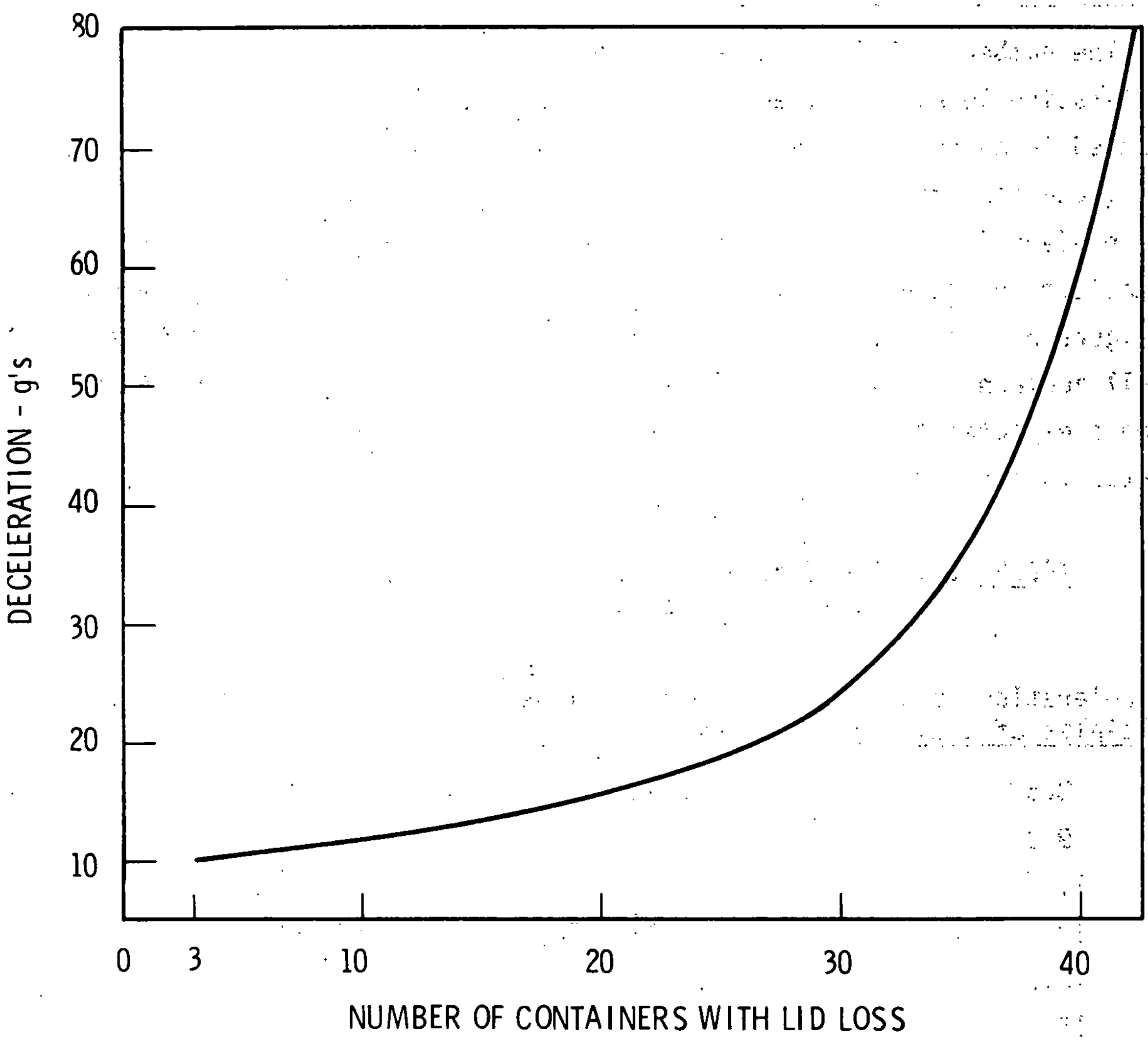


FIGURE F.7. Predicted Number of 6M Container Lids Lost as a Function of Deceleration Level

CRUSH ANALYSIS FOR L-10 SHIPMENT

The number of L-10 containers experiencing lid loss as a function of deceleration level was given in Figure F.6. Combining this with the expected frequency of experiencing a given deceleration level in an accident (obtained from Figure 5.1) results in the accident severity distribution given in Table F.3. The occurrence frequencies in the table are normalized to the 8.5 g failure threshold. Based on the results summarized in Figure 5.1, the 8.5 g deceleration is expected to be exceeded in 3.6% of all accidents. Also shown in Table F.3 is the average number of containers expected to fail in an accident which generated deceleration greater than 8.5 g.

TABLE F.3. Accident Severity Spectrum for L-10 Crush Failure in the Accident Environment

Deceleration Level (Multiples of Gravity)	Occurrence Frequency of Decelerations Greater than 8.5 g*	Number of Containers Losing Lids
8.5	0.248	3
9.8	0.186	6
11	0.152	9
12	0.124	12
13.5	0.097	15
15	0.083	18
17.3	0.055	21
20	0.038	24
26.8	0.014	27
37	0.002	30
53	0.001	33
80	0.0003	36
Total > 8.5	1.000	Avg.** 10.21

* Minimum deceleration for lid removal.
** Occurrence frequency weighted.

Comparison of Independent and Multiple Container Failure Analysis for L-10 Shipments

One release sequence in the independent container evaluation consists of the following set of failure elements, associated occurrence frequencies and titles:

Event Number	Occurrence Frequency	Event Titles
X001	2.05×10^{-3}	Accident Occurs
X082	4.5×10^{-2}	Accident Causes Severe Damage to Railcar
X017	5.4×10^{-3}	Accident Crush Forces Cause Lid Removal
X084	0.33	Container Lost from Railcar
X043	1.0	Bottle Fails in Accident
X004	6.57×10^{-2}	Fire Occurs Somewhere in Train During Accident
X056	0.97	1850°F Fire with Duration Greater than 6 min.

The expected occurrence frequency for this crush-initiated release sequence is the product of all the expected frequencies for each element. The sequence is expected to occur at a rate of 1.05×10^{-8} per container in 1500 miles of travel. To get the annual rate of occurrence for this event during shipment of 18 MT of plutonium 1530 miles in the U.S., this number must be multiplied by the number of containers required to ship 18 MT (9000) and multiplied by the ratio of 1530/1500 to correct the accident frequency for the shorter shipping distance. The resulting multiplier is 9180. These are the values used in the independent container evaluation. The following paragraphs will convert the data for the independent container evaluation to a multiple container evaluation.

In the multiple container analysis, the accident rate is based on 1530 miles, and therefore X001 is set at 2.09×10^{-3}/shipment. The risk multiplier is 133 since that is the number of shipments which will be made in 1980 to ship 18 metric tons of plutonium. The values of X004, X043, X056 and X082 are the same for either a container or a shipment. However, X017 and X084 must be modified to change the crush release sequence from an individual container basis to a whole shipment basis.

The occurrence frequency for X017 in the independent container evaluation was obtained by multiplying the fraction of accidents resulting in decelerations of greater than 8.5 times gravity (3.6×10^{-2}) times the probability that a container will be one of those failed in the crush environment (10.21/68). The resultant value used for X017 was 5.4×10^{-3}. In the multiple container analysis the 3.6×10^{-2} value must be used for X017 and the dependent probability of multiple container failures, shown in Table F.3 must be added to the analysis.

In order to analyze an entire shipment of containers, X084 must also be modified. The value of 0.333 used in the single-container analysis was based on the Sandia[1] estimate that on the average 1/3 of the containers will be ejected from the railcar. The number of failed containers ejected will be developed below. A value of 1.0 is used for X084 in the shipment analysis. Table F.4 compares the occurrence frequencies used for the single container analysis with those used in the shipment evaluation.

TABLE F.4. Comparison of Occurrence Frequencies for Single Container and Shipment Crush Sequence Evaluation

Risk Component	Independent Container Evaluation	Multiple Container Evaluation
X001	2.05×10^{-3}	2.09×10^{-3}
X082	4.5×10^{-2}	4.5×10^{-2}
X017	5.4×10^{-3}	3.6×10^{-2}
X084	0.33	1.0
X043	1.0	1.0
X004	6.57×10^{-2}	6.57×10^{-2}
X056	0.97	0.97
Risk Multiplier	9180	133
Annual Release Frequency*	9.62×10^{-5}	2.87×10^{-5}

* In the analysis year. The assumed number of shipments and shipment distances are given in Section 11.1.

The only terms missing from the multiple container evaluation are the dependent probability of multiple container failures in an accident shown in Table F.3 and the probability that a failed container is removed from the railcar during an accident.

The containers failed are not necessarily released from the railcar. Sandia[1] estimates that on the average only 1/3 of the containers in the railcar will actually escape. Ideally, it would be desirable to know the escape frequency for containers located at various positions in the railcar. However, this information is not available. The alternative is to assume that the containers lost are randomly distributed. The probability that r failed containers will be lost from a railcar containing x failed containers when n are released out of a total shipment of N containers is given by the expression:

$$p(r) = \frac{\binom{x}{r}\binom{N-x}{n-r}}{\binom{N}{n}}$$

where

$$\binom{x}{r} = \frac{x!}{r!(x-r)!} .$$

Using this expression, the probability can be developed that r failed containers will be released in an accident which generates decelerations greater than 8.5 times normal gravity. These are shown in Table F.5 for 1 through 13 failed containers being released. Also shown in Table F.5 is the expected frequency of from one to thirteen containers failing from the crush sequence in the analysis year. The release spectrum curve for the multiple container failure analysis of this release sequence can now be obtained using the data in Table F.5 and the independent container risk spectrum curve. The risk spectrum curve for one failure in the multiple container evaluation can be obtained by multiplying the frequency for each point on the independent container evaluation curve by the ratio of $5.19 \times 10^{-6}/9.62 \times 10^{-5}$. The first term is the expected occurrence frequency for one container in a shipment failing from the

TABLE F.5. Summary of Multiple L-10 Container Failure from Crush, Lost from Railcar and Subsequent Fire

Number of Containers Breached by Crush and Lost from Railcar	Expected Occurrence Frequency in a Crush Accident	Expected Occurrence Frequency in Analysis Year
0	0.0875	2.51×10^{-6}
1	0.1809	5.19×10^{-6}
2	0.1749	5.02×10^{-6}
3	0.1388	3.98×10^{-6}
4	0.1136	3.26×10^{-6}
5	0.0921	2.64×10^{-6}
6	0.0724	2.08×10^{-6}
7	0.0541	1.55×10^{-6}
8	0.0376	1.08×10^{-6}
9	0.0237	6.80×10^{-7}
10	0.0134	3.85×10^{-7}
11	0.0066	1.89×10^{-7}
12	0.0029	8.32×10^{-8}
13	0.0012	3.44×10^{-8}
14 or more	0.0005	1.44×10^{-8}
Total	1.000	2.87×10^{-5}

crush initiated release sequence in the analysis year and the second term is the release frequency used in developing the independent container evaluation shown in Table F.4. To get the curves for more than one container failing in the same accident requires adjusting both the frequency and the consequence levels. Thus for three containers failing in the same accident, the consequence value for each point on the independent container analysis curve is first multiplied by three, since the consequences of the release are three times greater, and then the frequency of a release for the new curve is adjusted by multiplying each release frequency by the ratio of $3.98 \times 10^{-6}/9.62 \times 10^{-5}$. This procedure is followed for successive numbers of containers failing and then all the resultant curves summed to get the multiple container evaluation curve.

Figure F.8 shows the independent and multiple container analysis risk spectra for all L-10 cut sets involving crush. It can be seen that the independent container crush curve closely approximates that of the multiple failure analysis. The main deviation is at the less frequent higher consequence end of the risk spectrum. However, since crush is an important factor in the risk of the L-10 shipment the analysis results reported in Section 11 were developed by combining the multiple container analysis for crush with the independent container analysis for all other release sequences.

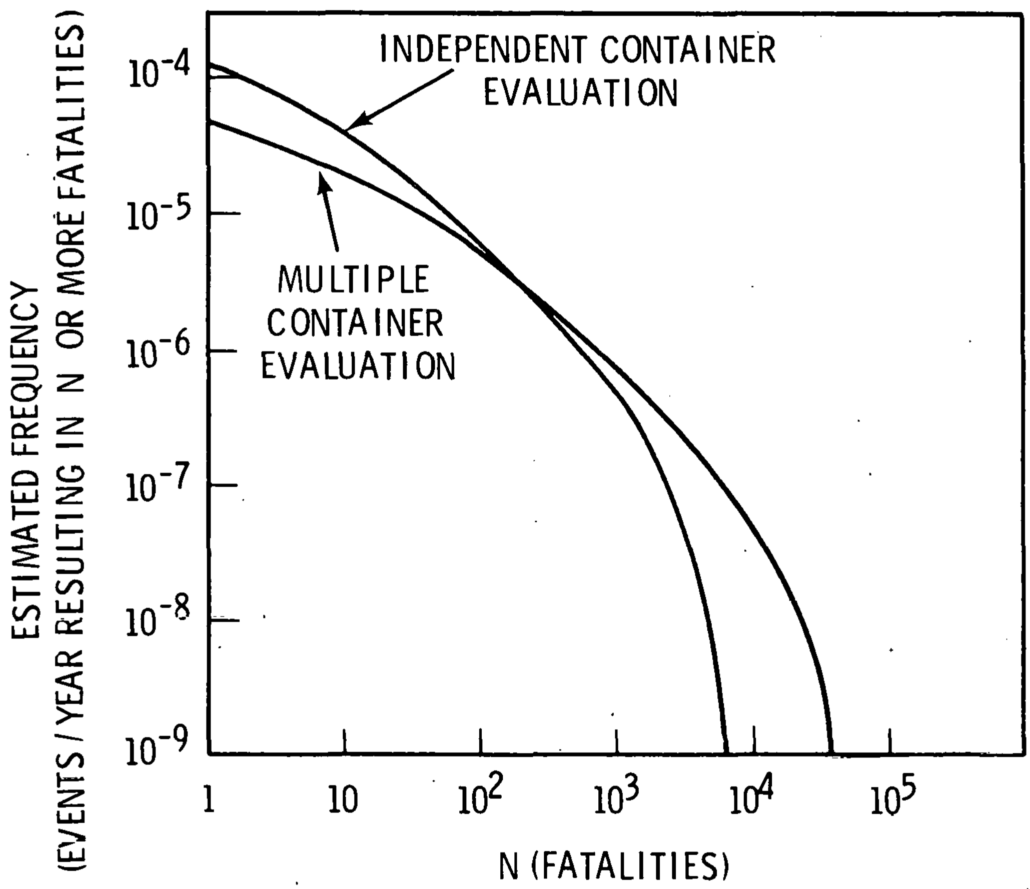


FIGURE F.8. Risk Spectrum Evaluation of the Independent and Multiple Container Failure Evaluation from Crush Forces Imposed on the L-10 Container and the Accident Environment

CRUSH ANALYSIS FOR 6M SHIPMENT

The independent and multiple container analyses for the 6M shipment differ in the same way as those for the L-10 shipment. The differences can be developed as in the previous section. However, since crush is a relatively unimportant factor in the 6M shipment risk, the multiple container analysis would have negligible effect on the risk.

REFERENCE

1. R. K. Clarke, T. J. Foley, W. F. Hartman and D. W. Larson, Severities of Transport Accidents, Volume IV - Trains, SLA-74-001, Sandia Laboratories, Albuquerque, NM, (To be published).

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