PNL-SA-6528

CONF-780506--45

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RISKS OF SHIPPING URANIUM HEXAFLUORIDE BY TRUCK AND TRAIN

by
J. F. Johnson
W. B. Andrews

May 1978

Prepared for the
U.S. Department of Energy
under Contract EY-76-C-06-1830

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RISKS OF SHIPPING URANIUM HEXAFLUORIDE BY TRUCK AND TRAIN

J. F. Johnson, W. B. Andrews
Battelle, Pacific Northwest Laboratories

The shipment of uranium hexafluoride is an important transportation link between many of the components of the nuclear fuel cycle. This paper discusses and presents the results of an analysis of the risks of transporting uranium hexafluoride (UF_6) by truck and rail. The study, carried out as a part of Pacific Northwest Laboratory's (PNL) Transportation Safety Studies Project, was conducted for the Transportation Branch of DOE's Division of Environmental Control Technology.

In the context of this paper, risk is defined as the product of the probability of a release of material to the environment and the consequences resulting from the release. Although a few accidents involving UF_6 containers have occurred during transportation, they are insufficient in number and consequences to provide data for a risk assessment of UF_6 transport. For this reason, this study used the predictive risk assessment methodology developed in the Transportation Safety Studies Project. This methodology was discussed in a number of papers presented at the Fourth International Symposium on Packaging and Transportation of Radioactive Materials and earlier studies.[1,2,3] The methodology is composed of four basic steps:

- A detailed description of the transportation system
- The identification of possible material release sequences
- The evaluation of the probabilities and the consequences of the releases
- Calculation and assessment of the risk.

The system description includes projected industry characteristics, amounts to be shipped and the number of shipments required, material characteristics, transport mode and carrier, container types, routes (and any restrictions), and weather and population zones. Release sequences are identified using fault tree analyses. Releases are evaluated using container failure data and mathematical models for dispersion and health effects. The risk is then calculated and compared to other known risks. Only releases resulting from transportation accidents or nonstandard container closures (or combinations of both) were considered.

SYSTEM DESCRIPTION

The transportation system considered in the study was based on a reference year in which 100 one-thousand megawatt capacity light water reactors are operating in the U.S. This capacity was chosen to allow comparisons to be made with the relative risks involved in shipping plutonium, which were evaluated in earlier studies.[1,2,3] The materials considered in this study were natural and slightly enriched (approximately 4% ^{235}U) UF_6. Although UF_6 at higher enrichment levels is transported, shipping regulations differ greatly, and quantities involved are insignificant when compared to the amounts of natural and slightly enriched material shipped. Shipments of UF_6 from reprocessing plants were also considered, although this may or may not be a future option. Their inclusion causes the results to be conservative.

This study represents a departure from the format used in earlier risk assessments. Previous studies[1,2,3] analyzed the risk involved in shipping all material used in the reference year by one transportation mode. This study analyzes a system using both truck and train transportation. To accurately represent and yet reasonably evaluate the UF_6 shipment system, some simplifying assumptions were made. Piggy-back shipments were combined with rail shipments to reduce transportation modes to two. Assumptions on container types reduced the number of cylinder configurations to four: 1) 14-ton-cylinders; 2) 10-ton-cylinders without overpack; 3) 10-ton-cylinders with overpacks; and 4) 2 1/2-ton-cylinders with overpacks. A diagram of the modified shipping system is shown in Figure 1.

RELEASE SEQUENCE IDENTIFICATION

In order to determine the probability of a container failing during a transport accident, possible release sequences must be postulated. These sequences may be identified in a variety of ways. It was felt that the most complete listings of release sequences are obtained by deductive reasoning processes that work backwards from a release through the possible chain of events that could produce the release. As in the previous studies, fault tree analysis was used to perform these reasoning processes. Only those release sequences within the selected scope of analysis were evaluated. In addition to releases caused by forces produced in transportation accidents, releases resulting from package closure errors or deterioration in the condition of the packaging resulting from the normal transportation environment were considered. Failure associated with deliberate sabotage or diversion attempts was not considered.

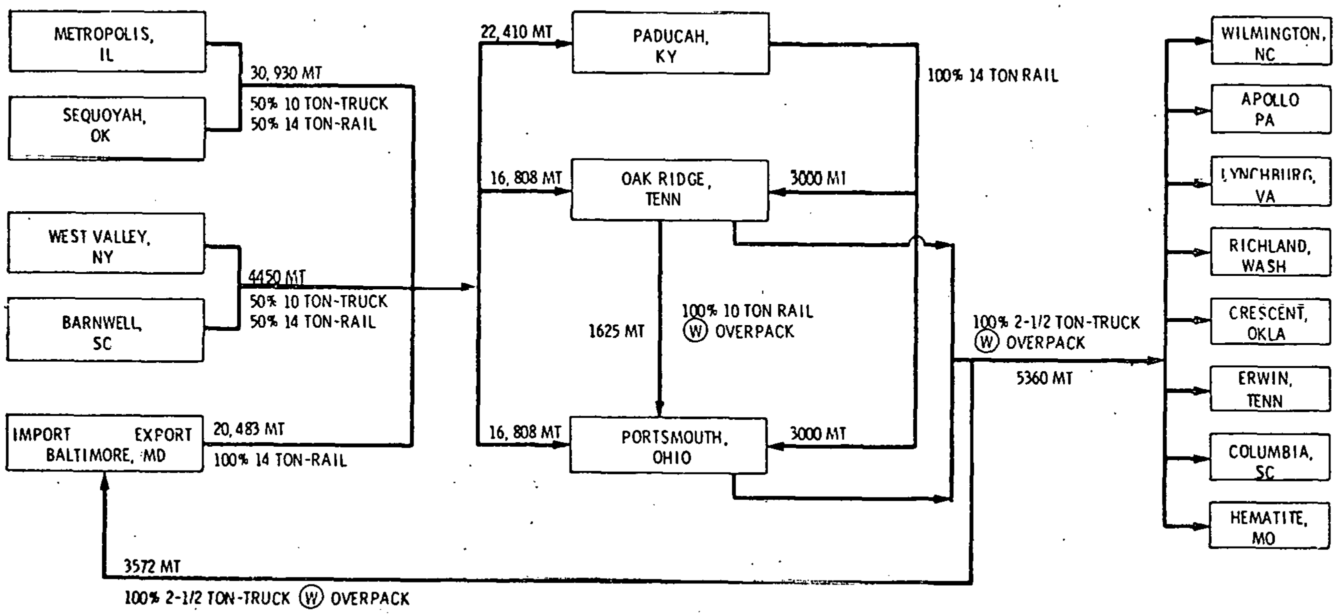

FIGURE 1. Simplified UF_6 Shipping Model

RELEASE SEQUENCE EVALUATION

Identified release sequences were evaluated to determine the probability of occurrence and the resulting environmental consequences. In order to calculate the probability of a container failing during an accident, it was necessary to estimate container failure thresholds, examine the accident environment, and determine package conditions during normal transit.

Both the truck and train accident environments were evaluated using information developed by Sandia Laboratories.[4,5] For this study, the stresses present in truck and train accidents were divided into three categories: fire, impact, and punctures. Other stresses, such as crush and immersion were found to contribute insignificantly to the likelihood of UF_6 cylinder failures and were not included. Puncture data, for both truck and train accidents was very sparse and conservative estimates had to be made. Risk sensitivity studies (discussed later) were carried out to determine the effect of these estimates on the overall risk.

Package failure threshold estimates were obtained using mathematical analysis, the results of destructive tests, and engineering estimates. Only thresholds relating to the accident environment posing a threat to the cylinder (fire, impact, puncture) were evaluated. Conservative assumptions were required in some instances to carry out the analysis. Sensitivity studies were carried out to determine the effect of these assumptions on the overall risk.

To adequately analyze the response of a UF_6 cylinder to an accident situation, it was necessary to determine the general package condition during normal transport. To obtain a data bank of container conditions during normal transport for use in the risk analysis, a survey was conducted of facilities which routinely receive UF_6. Results of this survey are summarized in Table 1. The survey did not indicate that package closure errors were present in significantly large numbers.

The final step in the evaluation of release sequences is the determination of release fractions. When released, UF_6 reacts with water in the atmosphere to form HF (hydrogen fluoride gas) and UO_2F_2 (uranyl fluoride). For the purpose of this risk analysis, the release sequences were placed into one of four categories, and release fractions were assigned to each:

- All release sequences involving a breach of the cylinder with no fire present were assigned a release fraction of 10^{-3}. The duration of the release was assumed to be 15 minutes being limited by the fact that the particulate UO_2F_2 tends to plug up the release pathway.
- Release sequences in which the cylinder was breached (excluding explosive ruptures) with fire present were assigned a release fraction of 0.1. The duration was assumed to be 20 minutes in length. Again, the amount released is limited by clogging of the release path by UO_2F_2.
- The explosive failure of a cylinder without overpack in the fire environment was assigned two release fractions: an initial elevated release (fire plume) of 0.1 with a duration of 1 minute, and a secondary (ground level) release of 0.9 over a span of 4 hours.
- The explosive failure of a cylinder with overpack in the fire environment was also assigned two release fractions: an initial elevated release of 0.8 with a duration of 1 minute, and a secondary (ground level) release of 0.2 over a 4-hour time period.

To express the risk from UF_6 releases in a form suitable for comparison to other societal risks conversion factors were developed to allow modification of the consequence portion of the risk number (in this case, to fatalities). Areas which were evaluated include: health effects, meterology, demography, and quantity made airborne and dispersed.

All products of a UF_6 release represent a health hazard when inhaled. Hydrogen fluoride gas presents a danger which is chemical in nature only. The effects of inhalation of UO_2F_2 are both chemical and radiological in nature. For UF_6 releases involving material with an enrichment of less than 10% ^{235}U, the chemical toxicity is generally considered a far greater threat

TABLE 1. Data Bank-Package Closure Experience Obtained by Survey[a] (For Period 1971-1975)

	2 1/2-Ton Model 30A	2 1/2-Ton Model 30B	10-Ton Model 48X	14-Ton Model 48Y
A. PACKAGES RECEIVED				
1975	431	526	1104	1967
1974	579	691	825	1447
1973	461	688	1032	1029
1972	324	750	1383	1205
1971	695	517	2644	663
TOTAL	2540	3172	698	6311
B. GENERAL CONDITION OF SHIPMENT (1971-1975)				
1. Do you formally examine and record the condition of received cylinders?	Yes = 8	1 = No Ans.	No = 1	
2. Is the H/U ratio verified upon receipt?	Yes = 2	2 = No Ans.	No = 6 (Inspect but do not record)	
3. Number of times H/U ratio exceeded specified limits.	0	0	0	0
4. Number of times enrichment exceeded specified limits.	0	1	0	0
5. Number of cylinders received overfilled.	0	0	0	0
6. Number of cylinders received overpressurized	1	0	20	56
7. Number received with contamination (UF_6, UO_2F_2, etc.) outside cylinder.	0	0	0	0
C. CYLINDER CONDITION (1971-1975)				
1. Number of cylinders removed from service due to deterioration.	1	2	0	0
2. Number of clyinders with badly corroded shells.	0	0	0	0
3. Number of clyinders received without required protective valve cover.	0	0	0	0
4. Number of clyinders received with welds damaged (example, vessel freshly dented in area of weld resulting in possible partial weld failure, etc.).	7	0	1	0
D. VALVE CONDITION (1971-1975)				
1. Number of cylinders requiring valve replacement.	13	28	60	86
2. Number of clyinders with valve and/or vessel threads partially stripped.	0	5	0	0
3. Number of clyinders with valve crossthreaded.	0	7	0	0
4. Number of cylinders with valve not completely closed.	0	0	0	0
5. Number of clyinders with valve loose or insufficient threads engaged.	0	0	7	19
6. Number of cylinders received with valve damaged (example, valve bent and fresh metal exposed at coupling, etc.).	0	14	1	5

TABLE 1. Data Bank-Package Closure Experience Obtained by Survey[a] (For Period 1971-1975) (cont'd)

E. PLUG CONDITION (1971-1975)				
1. Number of cylinders requiring plug replacement.	0	0	0	0
2. Number of clyinders with plug loose or with insufficient threads engaged.	0	0	0	0
3. Number of vessels with plug and or vessel threads partially stripped.	0	0	0	0
4. Number of vessels with plug crossthreaded.	0	0	0	0
5. Number of clyinders received with plug damaged from rough treatment during handling or shipping (example, plug bent and fresh metal exposed at coupling, etc.).	0	0	0	0
F. OVERPACK CONDITIONS (1971-1975)				
1. Number of cylinders received in overpack.	2480	3164	878	0
2. Number of cylinders received without overpack when required.	0	0	0	0
3. Number of cylinders received with gross damage to overpack.	0	0	0	0
4. Number of clyinders received without sealing gasket in overpack.	0	0	0	0
5. Number received with deteriorated gasket.	3	1	0	0
6. Number received with closure bolts loose.	~40	~40	0	0
7. Number with missing closure bolts:				
a. All closure bolts missing	0	0	0	0
b. Some closure bolts missing	~20	~16	0	0
8. Number received with damaged overpack mating surface.	7	5	0	0
G. TRANSPORTATION MODE				
Approximate Percentage of Cylinders Received By:				
1. Rail	0	3	12	14
2. Truck	88	97	88	62
3. Piggy-Back (Truck on Rail car)	12	0	0	24
4. Other (please specify)	0	0	0	0
TOTAL	100%	100%	100%	100%

H. DO FUTURE PLANS (NEXT 10 YEARS) INCLUDE FACILITIES TO HANDLE 10 AND OR 14-TON UF_6 CYLINDERS IF SUCH FACILITIES DO NOT CURRENTLY EXIST? Yes = 3 No = 7

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

COMMENTS ______________________________

than the radiotoxicity. Although enrichment levels greater than 3.5-4.0% were not considered in this analysis, the study addressed both chemical and radiological health effects.

Meteorological information was obtained by averaging actual data from 26 reactor sites throughout the country. Population distribution information was obtained by dividing the U.S. into four population zones and assigning a representative population distribution to each zone, using census data extrapolated to 1980. The distance traveled in each zone was then estimated.

The products of the UF_6 release, HF and UO_2F_2, were assumed to be neutrally buoyant when airborne. In releases involving fire, the products were assumed to be carried aloft and released from the fire plume (elevated release). In instances where solid chunks of UF_6 lay on the ground and slowly hydrolized over a period of time (4 hours), it was assumed that only the HF became airborne; all UO_2F_2 was assumed to remain on the ground. Accepted dispersion models were used to determine areas of potentially fatal concentrations. A key assumption was that all individuals located within an area exposed to a fatal gas concentration would be killed.

In the case of a release of UF_6 resulting from a transportation accident, the assumption of no evacuation of the area near the release site would be overly conservative. Because of the nature of the HF gas generated during the release (concentrations well below those assumed fatal cause extreme irritation to eyes and nose) only those unable to evacuate themselves from the area would be in danger. For this reason, a 95% evacuation level was assumed in this study. The effects of this assumption will be discussed later.

RISK EVALUATION OF UF_6 SHIPMENTS

Because of the complex nature of the shipping system model, the risk analysis was divided into four parts, each part corresponding to one of the four shipping package configurations. The risk involved with shipping each of the four cylinder configurations was determined and is presented in Table 2. These risks were then summed to determine the overall transportation system risk.

Risk spectrum curves for the four individual container configurations are shown in Figure 2 along with the risk spectrum for the entire shipping system for the reference year. Because the shipment of UF_6 in 14-ton cylinders by rail contributes the greatest portion to the total system risk (especially in the high consequence portion of the spectra), the total and 14-ton risk curves are virtually identical. Figure 3 shows the UF_6 shipment risk spectrum in perspective with other risks, including those from previous risk assessment studies in this series.[1,2,3]

TABLE 2. Summary of UF_6 Shipping Risks

Shipping Container	Transport Mode	Probability of Accident (events/year)	Probability of Release (events/year)	Probability or Significant Release (events/year)	Probability of Release Resulting In $\geq$ 1 Death
2.5-ton (30B) With Overpack	Truck	1.1	1.0×10^{-2}	1.7×10^{-3}	4.7×10^{-7}
10-ton (48X)	Truck	9.6×10^{-1}	1.1×10^{-1}	4.1×10^{-4}	2.3×10^{-5}
10-ton (48X) With Overpack	Rail	1.4×10^{-2}	2.80×10^{-5}	1.80×10^{-5}	1.0×10^{-8}
14-ton (48X)	Rail	5.7×10^{-1}	8.7×10^{-2}	1.0×10^{-3}	4.7×10^{-5}

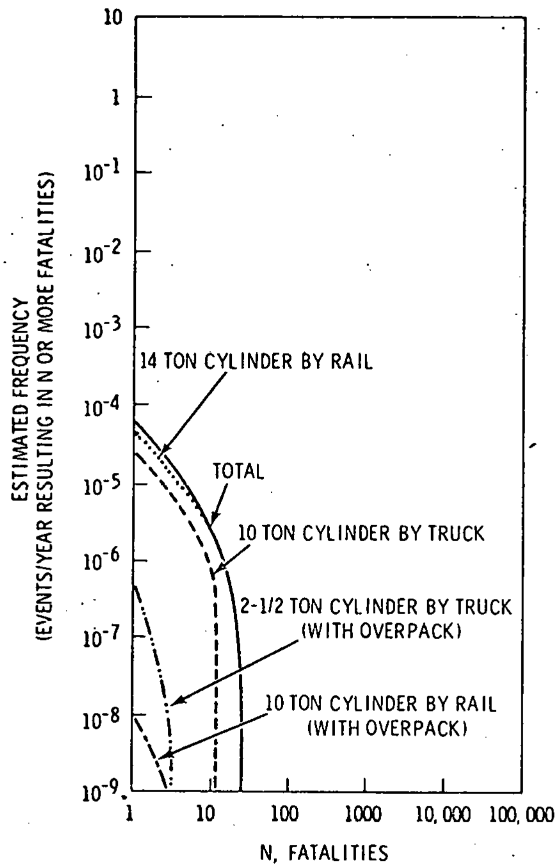

FIGURE 2. Risk Spectra for Individual Transport Modes and Total for Shipping System

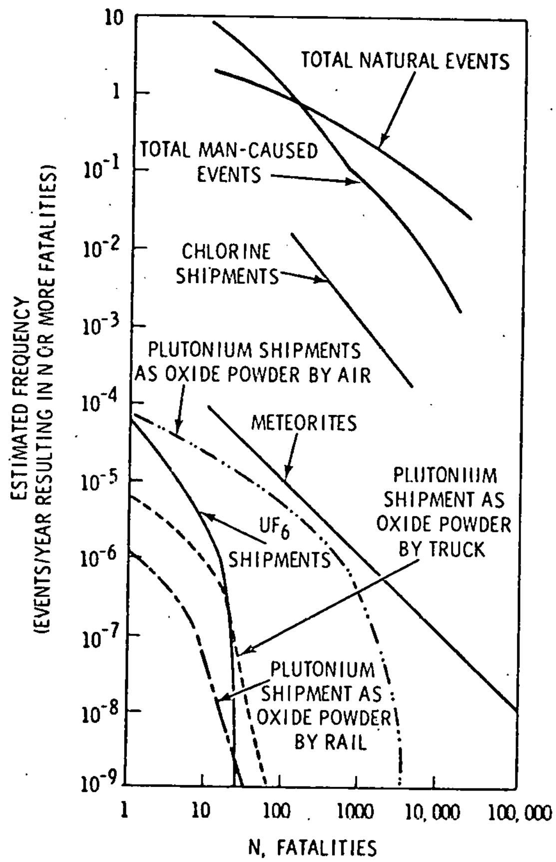

FIGURE 3. Risk Spectrum for Shipment of UF_6 and Other Risk Spectra

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

MAJOR CONTRIBUTORS TO OVERALL RISK

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

For all cylinder configurations, only release sequences in which the cylinder failed explosively in a fire presented the potential for producing fatalities. These release sequences correspond to the third and fourth release fraction groups described earlier. In all other release sequences, materials released were either dispersed and diluted so thoroughly that a lethal level could be found only at the source point, or the materials were not dispersed from the accident at all. Furthermore, only HF gas was found to have the potential to produce fatalities. Radiation doses from UO_2F_2 were found to be insignificant and concentrations of UO_2F_2 were insufficient to present a chemical hazard when compared to the chemical effects of HF gas. A personnel hazard exists only in an area 2 km or less from the accident site. (The radius of the zone of lethal concentration can be as small as 20 m depending on the type of release and the weather conditions at the time of the accident).

RISK SENSITIVITY STUDIES

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

For this risk assessment, the area presenting the greatest uncertainty is evacuation of people from the vicinity of the accident. Hydrogen fluoride gas in concentrations far below that necessary to cause physical damage is highly irritating to the eyes and nose. To test the effects of evacuation on the risk of shipping UF_6, sensitivity studies assuming no evacuation, 90% evacuation, and 99% evacuation were carried out. The results of these sensitivity analyses are compared graphically with the base case (which assumed 95% evacuation) in Figure 4.

The sensitivity of the risk to the presence of fire in a rail accident was tested. All of the cars in a train are not expected to be exposed to the fire, because of the size of the train relative to the fire size. Accident environment data indicate that the car carrying UF_6 cylinders would be directly exposed to the fire in 14% of all rail accidents involving fire. To test this assumption, a sensitivity study was carried out in which it was assumed that in 100% of all rail accidents involving a shipment of UF_6, the cylinders would be exposed to the fire (a highly conservative assumption). The results are shown in Figure 4.

A sensitivity study was carried out to determine the effects of packaging errors on the risk. The case was evaluated assuming no packaging errors were present during the shipment. The results of the sensitivity analysis show that the risk is insensitive to packaging errors.

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

To determine the effects of multiple container fire failures on the risk of transporting UF_6, a special sensitivity study was carried out. Assumptions on fire magnitude and location were used to determine the probability of a certain number of cylinders being exposed to the fire. Analyses were made from one cylinder to all cylinders in a shipment exposed and failing. Consequences were evaluated in the same manner as for the base case. The results of this supplemental sensitivity study are shown in Figure 5 along with the results of the evaluation of the base case.

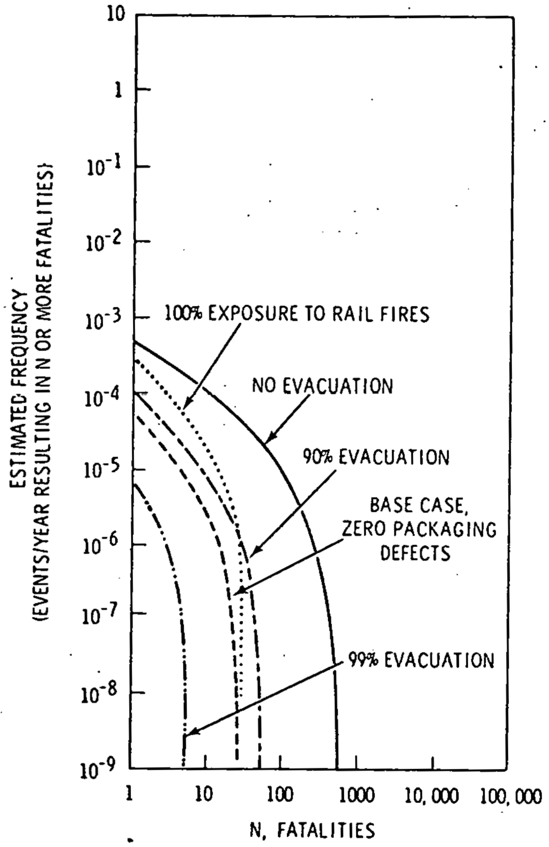

FIGURE 4. Risk Spectra for Sensitivity Cases

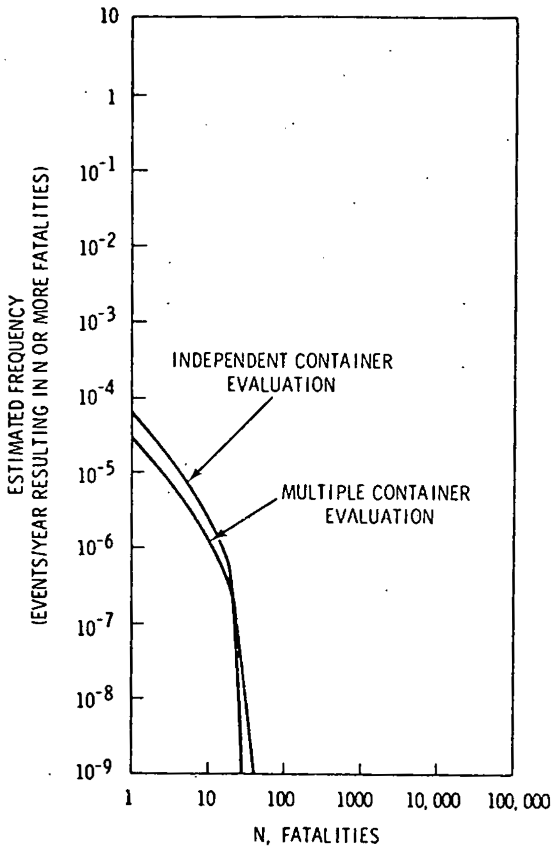

FIGURE 5. Risk Spectrum Evacuation of Single and Multiple Container Failure

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