Conf-731105--6

23,754

PROBABILITY AND CONSEQUENCES OF ACCIDENTS IN THE NUCLEAR FUEL CYCLE*

L. B. Shappert**
W. A. Brobst†
J. W. Langhaar††
J. A. Sisler†

To be presented at the ASME Winter Meeting, Detroit, Michigan,
November 11-15, 1973

To be submitted for publication in Nuclear Safety

---

*Research sponsored by the U.S. Atomic Energy Commission.

**Oak Ridge National Laboratory, Oak Ridge, Tennessee (Operated by Union Carbide Corporation under contract with the U.S. Atomic Energy Commission).

†USAEC.

††E. I. du Pont de Nemours and Company, Wilmington, Delaware.

fey

DRAFT

PROBABILITY AND CONSEQUENCES OF ACCIDENTS IN THE NUCLEAR FUEL CYCLE

SAFETY PHILOSOPHY

The safety philosophy involving the shipment of radioactive materials, as reflected in the regulations,[1,2] is based on two main considerations. These are:

(a) to protect the employees, transport workers and the public from external radiation in the transport of radioactive material under normal conditions, and

(b) to assure that the packaging for radioactive materials is designed and constructed so that, under both normal and accident conditions, the radioactive material is unlikely to be released from the packaging.

The objectives of the first consideration are met by limitations on the radiation levels on the outside of packages of radioactive material and stowage and segregation provisions.

The objective of the second consideration is achieved through design standards on packaging and implementation of a quality assurance program, including proof-testing and independent reviews, to assure conformance, to correct problems, and to help assure continued satisfactory performance over the lifetime of the package under normal and accident conditions.

Every package must be designed and its use monitored to prevent release of radioactive materials not only during normal conditions of transport, but also under other postulated abnormal circumstances developed through analyses and defined in the regulations.

The industry bears the primary responsibility for assuring safety in the packaging and transport of radioactive materials. The industry's activities are regulated by the Atomic Energy Commission (AEC) and the Department of Transportation (DOT). The regulatory functions include review of designs, quality assurance programs, testing, and use of packaging for radioactive materials.

FUEL CYCLE

The cycle is shown in Fig. 1, which details the necessary steps required to produce fuel assemblies of the proper design and fissile material content for a reactor. Between each operation in the fuel cycle, material must be transported; this is done in containers or packaging designed specifically to protect both the material shipped and the public.

Projected Shipments in the Fuel Cycle

The number of shipments involving material in the nuclear fuel cycle is directly affected by the growth of the nuclear power industry. The derived projection[3] of the U. S. generating capacity of nuclear plants in the year 1980 is presented in Table 1, along with the capacity which was available in 1970. The corresponding projection of the characteristics and annual number of shipments of nuclear fuel materials and wastes are presented in Table 2.

Table 2 does not project shipments of fresh or spent Liquid Metal Fast Breeder Reactor (LMFBR) or Gas Cooled Reactor (GCR) fuel since these reactors are not expected to be operational until after 1980.

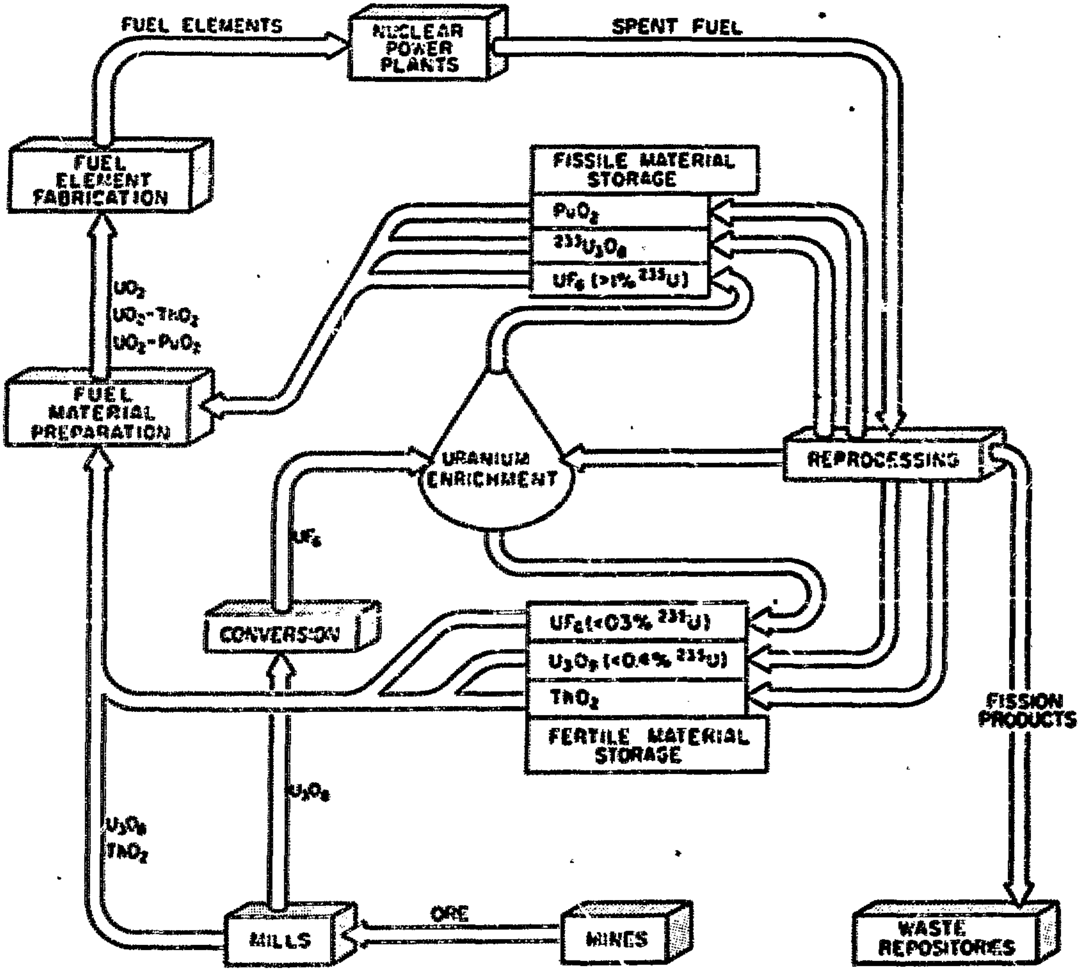
Table 1. Projected Generating Capacity [GW(e)]* of Nuclear Power Plants in the United States[3]

Year	Total Capacity GW(e)
1970	6.1
1980	131.6

---

*Gigawatts are equivalent to a million kilowatts.

ORNL DWG. 71-8610



THE NUCLEAR FUEL CYCLE

Summary of

Table 2. Projected Shipments of Nuclear Fuel Materials and Wastes Within the United States in the Year 1980

Material	Annual Load MTU	Annual No. of Shipments Year 1980
U_3O_8	22,700	1786
UF_6 (Natural)	21,900	2549
UF_6 (Enriched)	6,000	815
UO_2	4,400	940 ~~121~~
Fresh fuel	4,300	785
Spent fuel (truck)	1,700	3700
Spent fuel (rail)	1,100	375
	ft^3	
High level waste	2,790	20 ~~1466~~
Intermediate level waste	114,000	1520
Alpha waste	307,000	270

It is assumed that only one PWR or 2 BWR spent fuel assembl~~y~~ies can be transported in a cask designed for truck shipment, while a rail cask could carry an average of seven, PWR or 18 BWR assemblies.

Modes of Transportation

The four main modes of commodity transport in the United States are truck, rail, aircraft, and barge. All can be used for the transport of radioactive material but truck is used most frequently. Many of the packages, particularly those which carry unirradiated material, are of convenient size and weight for truck shipment.

The method of shipment for spent fuel casks, which are quite ~~massive~~ heavy because of the dense shielding required to reduce the radiation to acceptable levels, is currently being studied by fuel reprocessing companies, utilities, and other interested groups. Because shipping charges are generally related to the weight being shipped, economics dictates the cask should be as large as possible within the constraints imposed. In addition, fewer of the large casks with greater payloads need to be shipped.

Although constraints frequently involve weight limitations imposed by the mode of shipment, other problems affect the choice of the mode of shipment. For example, rail transport is most useful for shipments of concentrated, heavy loads such as casks of spent fuel or high-level waste. However, not all reactor sites are equipped with rail sidings. A fuel reprocessor in the Southeast evaluated the transportation situation in his market area and found that only about two thirds of the nuclear utility sites have rail service.[4] Thus, truck transport is required for shipping spent fuel for at least part, if not all, of the distance from these reactors to the reprocessing site.

be advantageous for shipment of heavy cargo such as [illegible]

Barge transport appears to ~~have great potential insofar as safety is concerned~~.[5] However ~~Unfortunately~~, this mode of transportation is not available at all reactor sites, although most are built on waterways of some sort. ~~Barges' greatest advantage would involve the shipment of massive weights such as spent fuel casks~~. Speeds are slow, but barges can operate 24 hr a day if required.

Air freight is used infrequently for shipping radioactive material in the fuel cycle since the speed available from air freight is not a significant factor in these movements and, therefore, the extra expense is [illegible] ~~difficult to justify~~.

PROBABILITY OF ACCIDENTS

The probabilities of accidents by truck, rail, and barge are derived below from statistics of accidents[6] supplied by the U. S. Department of Transportation (DOT) for 1969 and 1970.[7,8,9] The conditions likely to be encountered in the accidents in terms of velocity of impact of the vehicle and incidence and duration of fire were developed from analyses made by Leimkuhler,[10] various statistics on frequency of fires, and information in the 1969 and 1970 accident statistics referred to above.

Accidents occur in a wide range of frequencies and severities. Most accidents occur at low vehicle speeds; the severity of accidents is greater at higher speeds but the frequency decreases as the severity increases. Accidents generally involve some combination of impact, puncture, and fire effects.

Accident Statistics for Trucks

In 1969, large motor carriers[7] reported a total of 38,813 accidents involving death, injury, or property damage in excess of $250 million. The accidents included 19,682 injuries, 1,497 fatalities, with an overall accident rate of 2.46 accidents per million vehicle miles. For hazardous materials shipments, the accident rate was 1.69 per million vehicle miles. Fire occurred in 1.57% of the reportable accidents.[11]

In truck accidents, severe damage to the package may be encountered in all types of accidents. Impacts which are likely to be most damaging are those on stationary, rigid objects, such as concrete abutments or bridge structures. In collisions with an object, yielding or crushing of the vehicle or the object with which the vehicle collides reduces the impact received by the package. Roll-overs usually occur at higher speeds, and must be considered as potential contributors to major damage of a package.

A study in 1960[10] showed the following percentages of accidents for the four ranges of truck speeds given. We have assumed those percentages apply to the four ranges of speeds used in our analysis of 0-30, 30-50, 50-70, and > 70 mph.

Table 3. Type of Accident for Trucks vs. Speed at Time of Occurrence

	Speed in MPH			
Type of Accident for Trucks	0-32	32-52	52-72	> 72
All accidents	23.7%	56.0%	19.8%	0.5%
Collisions with autos and buses	34%	42%	23%	1%
Collisions with other trucks	25%	72%	3%	0.1%
Overturns and other collisions	8%	69%	23%	0%

Truck fire data[7] indicate that fire is involved in about 0.8% of truck-truck collisions, 0.3% of the truck-auto collisions, 0.6% of truck-fixed object collisions, 2% of the truck-train collisions, and 1% of the roll-over/run-off accidents.

It is assumed that only in truck-truck accidents is there a credible likelihood that fires would occur which last more than 1/2 hour, and then only when one of the trucks is carrying significant amounts of flammable liquids as cargo (e.g., tank trucks of gasoline or liquefied petroleum gas; or van trailers carrying barrels of paint).

Of the fires which do occur, it has been estimated[12] that 1% of the fires last more than one hour, 10% last between 1/2 hour and one hour and the balance, 89%, last less than 1/2 hour.

Accident Statistics for Railroad Cars

In 1969, for a total number of car miles of about 61 billion, the rail industry[8] reported a total of 8,543 accidents involving death, injury, or property damage in excess of $750, of which 4,971 were other than grade-crossing accidents. The accidents included 23,356 injuries, 2,299 fatalities.

The average train length is about 70 cars. The overall accident rate is 0.14 train accidents per million car miles. The accident rate for other than grade-crossing accidents is 0.08 train accidents per million car miles. Each accident involves an average of 10 rail cars, so the accident rate per car for other than grade-crossing accident would be about 0.8 car accidents per million car miles.

Twenty-one percent of the reportable accidents were collisions, 70% were derailments, and 9% were other types of accidents. About 1.5% of the rail accidents involved fire, most of them occurring in serious derailments in overland movements.

Reports of accidents that occur at various speeds indicate that 58.5% of all train accidents occur at a speed less than 30 miles an hour, 32% occur at a speed between 30-50 miles an hour, 9.4% occur between 50-70 miles an hour, and 0.1% occur at speeds exceeding 70 miles an hour.

Fires other than those involving ruptured tank cars of flammable liquids are unlikely to last longer than 1/2 hour, due to lack of sufficient fuel. Data relating major fires to train speed are sparse. It is estimated that 1.5% of all rail accidents involve fire of which 85% last less than 1/2 hour, 14% last between 1/2 hour and 1 hour, and 1% of the fires last more than 1 hour.

Accident Statistics for Barges

Records for fiscal year 1970 for domestic waterborne traffic[9] show a total of 506 billion ton-miles of water traffic with 548 cargo barge accidents reported. Data are not available to indicate the fraction of those ton-miles due to barge traffic. We estimated the total barge ton-miles to be 380 billion. According to the Coast Guard report, miscellaneous types of vessels, including cargo barges, were involved in accidents which resulted in 33 injuries ~~and~~ plus 33 fatalities during that period.

The available data cannot be analyzed in the same way as the data for rail or truck transport. On the basis of discussions with the U. S. Coast Guard, it is estimated assumed that the average net (cargo) weight of a typical barge is about 1,200 tons. The total number of barge-miles would then be about 310 million. This yields an accident rate of about 1.8 accidents per million barge miles.

There are no data on the duration of fires in barge accidents so we have used the rail figures of 85% of all fires lasting less than 1/2 hour, 14% lasting between 1/2 and 1 hour, and 1% lasting more than 1 hour.

ACCIDENT SEVERITY CATEGORIES

The following information has been extracted in part from the Environmental Survey of Transportation of Radioactive Materials to and from nuclear power plants.[12] This report, the subject of an AEC rulemaking hearing held April 2, 1973 in Washington, D. C., presents an analysis of the impact on the environment from the transportation of nuclear fuel and solid wastes to and from a reactor in accordance with current regulatory standards and requirements. In it an attempt is made to realistically consider the severity of accidents that can occur in the transport environment and the consequences of those accidents.

Table 4 presents categories of accidents that can occur in the transport environment. The categories are defined in terms of velocity of vehicle impact and incidence and duration of fire.

Table 4. Definition of Accident Severity Categories

Accident Severity Category	Vehicle Speed at Impact (mph)	Fire Duration (hr)
1. Minor	0-30	0-1/2
	30-50	0
2. Moderate	0-30	1/2-1
	30-70	0-1/2
3. Severe	0-50	> 1
	30-70	1/2-1
	> 70	0-1/2
4. Extra Severe	50-70	> 1
	> 70	1/2-1
5. Extreme	> 70	> 1

Although barge speeds seldom exceed 15 mph, for the purposes of this analysis minor cargo damage is assumed to occur at speeds less than 30 mph, moderate damage at 30 - 50 mph and severe cargo damage above 50 mph.

Accident Probability

The probabilities of an accident in each of the five accident severity categories and for each of the three modes of transport has been calculated on the basis of the data presented earlier.

The differences between the truck, train, and barge accident probabilities in terms of accidents per mile in each of the severity categories are small. Therefore, for purposes of estimating the risks in this analysis, a single value rounded off to one significant figure is taken for all three modes of transport as shown in Table 5.

Table 5. Accident Probabilities for Truck, Rail, and Barge per Vehicle* Mile for the Accident Severity Categories

Minor	Moderate	Severe	Extra Severe	Extreme	Total
2×10^{-6}	3×10^{-7}	8×10^{-9}	2×10^{-11}	1×10^{-13}	2.3×10^{-6}

* for trains, each car is considered a vehicle.

Numbers of Accidents

If these accident statistics are applied to the numbers of shipments estimated to occur in the nuclear fuel cycle, (see Table 2) and if the average distance over which these shipments are sent is estimated, the probability of accidents, by severity category, can be estimated. Results of such an evaluation are shown in Table 6 for the total number of shipments in the nuclear fuel cycle in the year 1980.

Table 6. The Estimated Total Number of Accidents Occurring in the Nuclear Fuel Cycle in 1980 by Severity Category

Total number of Shipments	Total Shipping Distance, Miles x 10^{-6}	Number of Accidents		
		Minor	Moderate	Severe
23,850 [illegible]	~~11.90~~ 9.53	23.8 19.0	~~3.6~~ 2.6	0.1 [illegible]7
		Extra Severe	Extreme	
		[illegible]7 .00002	.0000001 9	

Consequences of Accidents

The most likely result of an accident that would lead to significant radiological consequences is ~~loss of~~ containment. release of radioactive material.

The probability that a package will be breached as a result of an accident is higher as the accidents become more severe but ~~the probabilities that the more severe accidents will occur become very small~~. On the other hand, [illegible] accidents are uncommon. R 13,14

Various factors limit the effect accident conditions will have on a package.[13,14] In relatively minor accidents, serious damage to packages can occur due to impacting on sharp objects or by being struck by other cargo. Conversely, in extreme accidents, damage to some packages may be minimal. In some cases, the packages may be thrown free of the impacting vehicles or be so located in the vehicle that they are unaffected by the impact or the fire that ensues. Package damage depends on the form and amount of energy sustained by the package and the ability of the package to withstand those forces. The form and amount of the energy transmitted to the package in an accident depends on several factors which vary according to the accident circumstances.

The ability of a package to withstand accident forces depends on the design of the package and the quality assurance exercised in its manufacture, use, and maintenance.

DOT and AEC regulations specify certain package accident damage tests[15] which R 15 provide a means for reproducing in the laboratory or in the field the same general type and degree of damage a package might reasonably be expected to sustain in a severe transportation accident. Any package which can be shown to meet these standards

[illegible]

is called a "Type B" package and can be expected to withstand [illegible] accidents without leakage or significant shielding loss. The tests do not in themselves represent a transportation accident. [illegible]

There are four such tests. They are a 30-foot freefall onto a flat unyielding surface, a 40-inch freefall onto a steel plunger, a thermal test and immersion in water. To better understand the design requirements imposed by the accident damage test criteria, the 30-foot freefall and the thermal test are discussed in some detail.

Although the velocity at the time of impact in the drop test is about 30 mph, the test requires dropping the package, including the protective shield if it is part of the package, on ~~an~~ [illegible] unyielding surface. In very few accidents does the vehicle [illegible] impact with a substantially unyielding surface. In a real accident, the forces the package sustains are mitigated by the angle of impact of the vehicle, the crushing of the vehicle, which could absorb much of the impact, and the fact that, for impacts of heavy objects such as transporting trucks, the object with which the truck collides in most cases yields and thus absorbs some of the impact.

With respect to fire, the package must be designed to withstand the thermal environment in which the package is subjected to the heat input from a radiant environment having a temperature of 1475°F and an emissivity of 0.9 for 30 minutes.

In estimating the probability of various degrees of damage, account is taken of the fact that severe transportation fires seldom last more than 1/2 hour, except in ships and storage depots[16] because either the fuel is exhausted or the fire is extinguished by fire fighting crews. Since the temperature rise in real fires are gradual rather than instantaneous and under very unusual circumstances will more than 50% of a package surface be in contact with flame, it is highly unlikely that a transport fire lasting up to one hour would produce damage more severe than that resulting from the thermal test. Even in a longer fire, the package may be in a location where the fire has little or no effect on it.

For the above reasons, it is concluded that a package designed to meet the thermal test requirements in the regulations as a Type B package ~~is likely to~~ could withstand ~~the most frequently encountered~~ practically all fire conditions in transportation accidents.

Estimates of Releases in Accidents

Estimates of the amount of radioactive material released in the unlikely event that a container is breached are given below, taking into account engineering assessments of a variety of package designs, actual accident experience, the properties of the fuel and radwaste, and experience in shipment, reactor operation, and storage. In the case of Type B packages, accidents which exceed the design basis accidents are very unlikely.

The mechanical and physical effects the accident forces would have on the contents, i.e., the fuel rods and solidified or compacted waste, and on the rate and amount of release when a breach of containment occurred, were considered in estimating the release in each type of accident. Consideration also was given the influence of the accident forces on dispersion of the released material. The consequences in terms of potential doses to people were calculated for the estimated releases of krypton-85, iodine-131, and non-volatile fission products. Average distributions of weather and population densities for a release on land were used in the calculations.

Some accidents in transportation may produce stresses on packages more severe than the stresses the packages are designed to withstand. The consequences of such accidents could be serious but the probability of occurrence of such accidents is extremely low. Quality assurance for design, manufacture, and use of the packages; continued surveillance and testing of packages and transport conditions; conservative design of packages; and the low probability of occurrence make the environmental risk from such accidents extremely low.

As an example of a postulated extra-severe accident involving an irradiated fuel cask, it is postulated that a rail cask containing 3.2 MT of irradiated fuel cooled 150 days is in an accident involving a severe impact and fire which causes a breach in the containment. If 10% of the rods were perforated and 100% of the coolant released, as much as 1.9×10^3 Ci of Kr-85, 0.01 Ci of I-131 and 130 Ci of gross fission products could be released.

The consequences of this type of accident were estimated assuming a ground-level release under average weather conditions with all of the krypton and iodine and 1% of the available gross fission products being dispersed in the air. Such an extra-severe accident will involve many rail cars and, likely, fire. Because of these conditions, persons are not expected to be closer than 50 meters downwind from the accident, the direction in which the highest exposures would occur.

A cumulative whole-body dose of about 0.4 man-rem from the Kr-85 would be received by the million people nearest the accident, assuming 10^4 persons per square mile. Persons 50 meters downwind could receive an average dose of 0.4 rem from the gross fission products.

The magnitude of exposure to individuals as a result of the extremely severe accident described here may be compared with the Federal Radiation Council's recommended maximum annual whole-body case of 0.5 rem in one year for individuals in uncontrolled areas.

The contamination on the ground, assuming the coolant is released as vapor and the contamination dispersed, would be severe over an area of about 3000 sq ft, requiring decontamination according to standards[17] ~~9~~ of the Environmental Protection R 17 17 Agency, and minor over an area of about 0.1 sq mile, requiring further consideration as to whether specific action would be required. For a high population density of 10,000 persons per square mile, an average of only one person must be evacuated in the 3,000 sq ft area that is contaminated; the cost of evacuation and contamination cleanup is estimated to be $10,000 to $50,000. These costs are not total, but are only those associated with the radioactivity carried. Those costs such as damage to the vehicle, roadbed, rerouting traffic, police work, etc. which would be associated with an accident involving, say, heavy machinery, is not included.

REFERENCES

1. Code of Federal Regulations, Title 10, Part 71.
2. Code of Federal Regulations, Title 49, Part 173-178
3. Nuclear Power 1973-2000, WASH 1139(72) Dec. 1, 1972.
4. A. T. Peyton, Jr., Transportation of Spent Nuclear Fuel, Conference on Transportation of Radioactive Material Held in Charlottesville, Virginia on 26-27 October, 1970, PB 197-556, p. 122.
5. Big Load Afloat, The American Waterways Operators, Inc., 1250 Connecticut Avenue, Suite 502, Washington, D. C.
6. William A. Brobst, The Probability of Transportation Accidents, 14th Annual Explosives Safety Seminar, New Orleans, Louisiana, November 10, 1972.
7. Federal Highway Administration, "1969 Accidents of Large Motor Carriers of Property," December 1970. This covers interstate motor carriers of property having annual operating revenues of $300,000 or more.
8. Federal Railroad Administration Accident Bulletin No. 138, "Summary and Analysis of Accidents on Railroads in the U.S.," 1969.
9. U.S. Coast Guard, "Statistical Summary of Casualties to Commercial Vessels," December 1970.
10. F. Leimkuhler, Trucking of Radioactive Materials; Safety vs Economy in Highway Transport, the Johns Hopkins Press, Baltimore, 1963.
11. Federal Highway Administration, "1969 Analysis of Accident Reports Involving Fires," December 1970.
12. WASH-1238, Environmental Survey of Transportation of Radioactive Materials to and from Nuclear Power Plants, prepared by the Directorate of Regulatory Standards, USAEC (December 1972).
13. "The Transport of Radioactive Materials. Interim Recommendations for the Application of Environmental Tests to the Approval of Packaging," Messenger and Fairbairn, AHSB-S-R-19, 1963.
14. Examination of the International Atomic Energy's Regulations for the Safe Transport of Radioactive Materials EUR 3485 e,f Vol. I "Technical Packaging Requirements; An Analysis of the Criteria and Tests, Together with a Study of Practical Means of Compliance," Final Report, 1968.
15. 49 CFR Section 173.398; 10 CFR paragraph 71.36.

16. William A. Brobst, Transportation Accidents: How Probable?, Nuclear News Vol. 16/No. 7, May 1973.

17. Federal Radiation Council Report No. 7, "Background Material for the Development of Radiation Protection Standards; Protective Action Guides for Strontium 89, Strontium 90, and Cesium 137," May 1965.