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The Probability of Spent-Fuel Transportation Accidents

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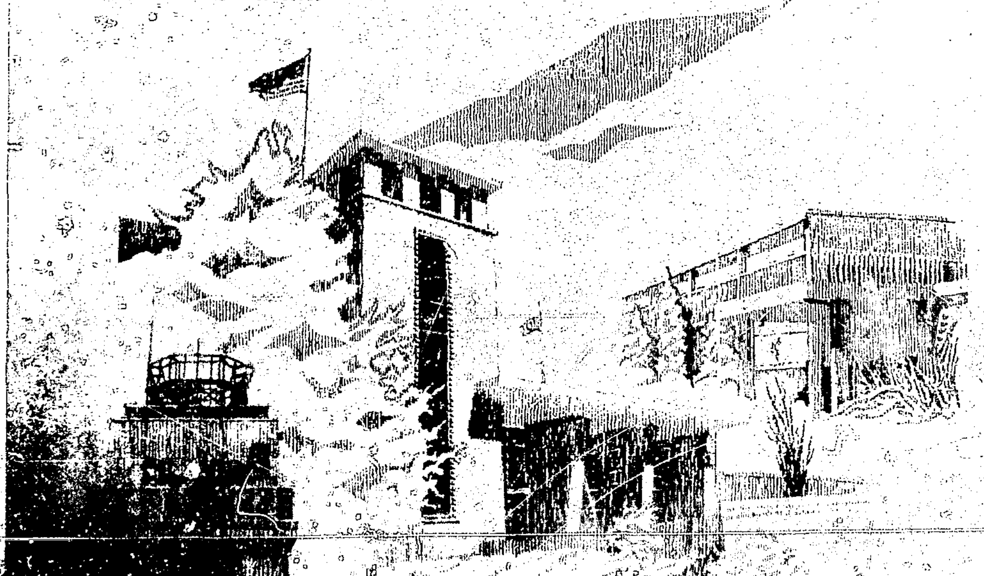

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THE PROBABILITY OF SPENT FUEL TRANSPORTATION ACCIDENTS

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Abstract

The transported volume of spent fuel, incident/accident experience and accident environment probabilities were reviewed in order to provide an estimate of spent fuel accident probabilities. In particular, the accident review assessed the accident experience for large casks of the type that could transport spent (irradiated) nuclear fuel. This review determined that since 1971, the beginning of official U. S. Department of Transportation record keeping for accidents/incidents, there has been one spent fuel transportation accident. This information, coupled with estimated annual shipping volumes for spent fuel, indicated an estimated annual probability of a spent fuel transport accident of 5×10^{-7} spent fuel accidents per mile. This is consistent with ordinary truck accident rates. A comparison of accident environments and regulatory test environments suggests that the probability of truck accidents exceeding regulatory test for impact is approximately 10^{-9}/mile.

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THE PROBABILITY OF SPENT FUEL TRANSPORTATION ACCIDENTS

Introduction

Spent fuel shipments are a small fraction of those needed to support the nuclear fuel cycle and a very small fraction of all radioactive material shipments, but because of the relative radiotoxicity of the constituents of spent fuel, its transportation usually occupies a prominent place in any discussion of transportation operations for radioactive materials. The purpose of this report is to provide a concise statement about the probability of spent fuel transportation accidents. The information provided in this report will deal with the number of shipments of radioactive material that occur in the United States in a single calendar year. Having stated the volume of radioactive material (RAM) shipments, an examination will be made of the actual accident experience in the United States involving radioactive materials in transport. Spent (irradiated) fuel is a sub-set of all the radioactive materials which are transported in support of nuclear fuel cycle operations. The magnitude of annual spent fuel transport accident experience and estimated annual shipping distances will be combined to determine an estimated probability of occurrence for spent fuel transport accidents.

The transport experience for spent fuel presented in this report is related to actual U. S. spent fuel transport experience. However, in reality there have not been large quantities of spent fuel assemblies actually transported from the reactors to other destinations. As will be shown, the number of assemblies shipped per year (average 300 assemblies/year) has been a function of U. S. waste management policies and programs. Until 1976, when a moratorium was imposed on the commercial reprocessing of spent fuel, it was assumed that commercial spent fuel reprocessing would eventually take place. Whether commercial reprocessing will take place in the future is not known at this time. The spent fuel in the reactor spent fuel storage pools will eventually have to be moved to some other location or the reactors will have to cease operating. What the exact magnitude of spent fuel shipping volume will be in the next few years is not known with precision. Transportation parameters such as shipping volumes, distances, locations of offsite away from reactor (AFR) storage locations (if developed), and location of spent fuel repositories (if developed) all affect the projected number of spent fuel transport accident occurrences that can take place. Recognizing that the data set is not as complete as one would desire it to be, a discussion of spent fuel transport experience will now be presented.

Spent Fuel Transportation Experience in the United States

It is estimated that approximately 500 billion packages of all types of commodities are shipped in the United States each year,[1] and approximately 100 million (0.02 percent) of the total estimated shipments involve hazardous materials such as flammables, explosives, poisons, corrosives, and radioactive materials. The most recent estimate of radioactive materials shipments in the U. S., on an annual basis,[2] indicates that there are approximately 2 million shipments of radioactive material packages per year. About one-third of the radioactive material packages which are shipped annually contain such small quantities of radioactive materials that they are exempt from the packaging and labeling requirements of the Department of Transportation (DOT) regulations.

A summary of the radioactive material shipments for 1975 is shown in Table I, listed by shipment type according to the primary use of the radioactive material (i.e., limited, medical, industrial, fuel cycle, and waste).

The first point that needs to be established is the shipping volume of spent fuel in the U. S. on an annual basis. This has been examined[3] and is summarized in Table II.

Detailed information was not available for the analysis in Reference 3 so that one could not state with certainty whether the spent fuel assemblies were pressurized water reactor (PWR) or boiling water reactor (BWR) assemblies. In addition, the transport mode (i.e., truck or rail) was not specified. Very few of the shipments were known to be rail shipments, most of the shipments were by truck. Current truck cask designs can transport only 1 PWR or 2 BWR assemblies per truck shipment. From Table II, if one assumes that all the spent fuel shipments were made by truck and there was one fuel element per shipping cask, then average annual shipments of 300 would constitute only .08 percent of all the annual total of fuel cycle and waste packages shown in Table I. Having established, through available records, that spent fuel shipments comprise a very small fraction of projected annual radioactive material shipments, there is some basis for assuming that a transportation accident involving spent fuel would indeed be a low-probability event. The accident records for transportation accidents which have involved radioactive materials will now be examined.

TABLE I

Summary of Radioactive Material Shipping (1975)[1]

Shipment Type	Packages per Year	Kilometers per Year	Percent of Total (packages)
Limited (exempt)	7.03×10^5	1.19×10^9	32
Medical	9.10×10^5	1.12×10^9	42
Industrial	2.15×10^5	3.01×10^8	10
Fuel Cycle	2.04×10^5	2.09×10^7	9
Waste	1.52×10^5	3.22×10^6	7
	2.19×10^6	2.64×10^9	100

TABLE II

Summary of Spent Fuel Shipments in the United States[3]

Year	Assemblies Shipped
1964	264
1965	39
1966	165
1967	269
1968	67
1969	217
1970	180
1971	561
1972	93
1973	267
1974	137
1975	492
1976	712
1977	675
1978	512
1979	147
Total	4797

Average shipment = 300 assemblies per year

A Review of US Radioactive Material Accident/Incident Experience

In 1971 a regulatory requirement was instituted by the Material Transportation Bureau, US Department of Transportation (49 CFR, 171.15) which required the reporting of a hazardous material transportation incident. The regulations for filing hazardous Material Incident Reports (HMIRs) require reporting of circumstances during the course of transportation (including loading, unloading, and temporary storage) in which, as a direct result of hazardous material, there are deaths, injuries requiring hospitalization, carrier or other property damage exceeding $50,000, fire, breakage or spillage occurs involving etiologic agents, and, in the case of radioactive materials, there is suspected contamination.

The Transportation Technology Center at Sandia National Laboratories has acquired all the current radioactive material files of the DOT HMIR system and in addition has obtained similar accident/incident information from the U S Nuclear Regulatory Commission. A summary of this composite accident/incident data file is shown in Table III.

Table III makes the distinction between a transportation accident, a handling accident and other reported incidents in the data base. The reasoning for this distinction is as follows. A reported incident is judged to be a transportation accident if there are accident conditions sustained by the vehicle transporting the radioactive material. Obviously such conditions may be very mild (i.e., a fender bender) or the accident conditions may be very severe (e.g., a head-on collision involving the transport vehicle). Since the reporting requirements also specify that loading, unloading

TABLE III

Accident/Incident Report Summary
(U. S. Experience 1971-80)[4]

Transportation Accidents	85
Handling Accidents	110
Reported Incidents	464
Event Total	659

and storage operations are in the jurisdiction of the HMIR system, an accident category called handling accidents has also been defined. For example, if handling accident conditions occur, such as the accidental drop or crush of a package in a warehouse or a package is run over by a fork lift, then this type of condition typifies the handling accident situation as opposed to accident conditions during actual transport operations.

Because of the wide range of circumstances for reporting a hazardous material incident, a third reporting category has been defined for the purposes of analysis. If a reported hazardous material incident does not involve transport accident or handling accident conditions, then it is categorized as a reported incident. Reported incidents meet the regulatory requirement for reporting hazardous material incidents but do not involve accident conditions (e.g., decontaminated casks sometimes show evidence of surface leaching of small amounts of radioactive contamination). Subsequent decontamination operations easily remove the small amounts of contamination but the mere encounter of such circumstances is cause for reporting the event.

Transportation Accident Summary -
Accidents with Release of Radioactive Materials

There are two accident situations which will now be examined, transportation accidents with radioactive releases and transportation accidents without releases of radioactive materials. This section will deal with the former case. The latter case will be examined in the next section. If one examines the 85 accident events (involving 711 packages) in Table 3 and studies the accidents which actually released radioactive material from the packages, the results can be summarized as shown in Table IV.

Table IV introduces a new piece of radioactive material packaging nomenclature, that of the Type A package. All radioactive material packagings are divided essentially into two groups, Type A packagings and Type B packagings. The DOT and NRC packaging and transport regulations specify that all radionuclides (except exempt quantities) shall be transported in one of these two packaging classifications. The regulations further specify that if the radioactive material quantity is greater than exempt magnitudes but equal to or less than a Type A quantity, then the radioactive material shall be shipped in a Type A packaging. The magnitudes of Type A quantities vary with the radiotoxicity of the various radionuclides. The essence of the regulation is that Type A quantities are very limited in magnitude, so limited in fact that the Type A packaging is environmentally tested and licensed to what is considered the "normal conditions of transport," that is, not to include accident conditions. Since Type A packagings can be in transport accidents, the primary protection of a Type A packaging comes from the quantity limitation imposed on the radioactive contents (i.e., the Type A quantity).

TABLE IV

Transportation Accident Summary - Accidents with Release of Radioactive Material

RAM Packages Involved in Accidents	RAM Released	Release Description		Description of Material Released
Packaging Failures* (with release)	38 Type A ------->	5 Release Events -->	3 Urban ->	•Uranium ore •Sand (LSA) •RAM (not otherwise specified)
			2 Non-Urban ->	•Uranium oxide
Packaging Failures* (no release)	3 Type A			
Packagings in Accidents with No Failures	660 Type A 10 Type B			
	711			

*The 41 packaging failures involved 38 Type A packages which released radioactive material.

Similarly, Type B packagings can transport larger than Type A quantities of radioactive material. Accordingly, Type B packagings are environmentally tested and licensed to the "normal conditions of transport" and to "hypothetical accident conditions." The hypothetical accident conditions will be discussed at greater length later in this report. Spent fuel shipments fall into the category of Type B (Large Quantity) packagings.

The point of Table IV is that all the transportation accident events where there have been releases of radioactive contents were Type A packagings. It should be noted that in all the transport accidents there was a total of 711 packages being transported. Only 41 packages were damaged, only 38 packagings released their contents in 5 separate and distinct release events. All of the packagings which released contents were Type A packagings. The two release events involving uranium oxide were the September 1977, Springfield, CO, accident which released 12,000 pounds of uranium oxide from 55 gallon steel drums and the March 1979 accident at Wichita, KS, which released 1800 pounds of uranium oxide from 55 gallon steel drums. These quantities are large but such information must be coupled with the fact that uranium oxide is a low-specific-activity material and, hence, produced little environmental or human radiological hazard.

Transportation Accident Summary
Accidents with No Release of Radioactive Materials

An examination of Table IV will provide the information for the final step of analysis, that of examining the severity and nature of the accident which involves spent fuel. In Table IV, 660 Type A and 10 Type B packages were noted to be exposed to transport accident conditions but did not release their radioactive contents. We shall now examine those accidents in this set of events which involve large casks of the type which might transport spent fuel. A summary of these events is shown in Table V. Table V indicates that accidents have involved various cask types and materials being transported. In fact, only one of the accidents involved spent fuel being transported. The detail in Table V is presented to indicate that transportation accidents have occurred. An important additional note is that none of the events shown in Table V produced releases of radioactive material and consequently there were no environmental or health effects to the general population from these events. The driver of the truck in the spent fuel accident was killed, but this was not due to the radioactive material but to the mechanical severity of the truck overturning.

The environmental threat to the packagings indicated in Table V involved primarily impact conditions and one case of impact followed by fire. A reading of the original accident reports and their attachments does not allow a great deal of precision to be applied to change of velocity estimates in order to quantify the impact conditions. A reasonable estimate might include vehicle velocity changes in the 30-80 mph range.

TABLE V

Summary of Transport Accident Conditions
Type B Packages - Radioactive Material (RAM)

Package	Date	Mode	Package Contents	Accident Conditions	Environmental Threat
6000 lb cask	4/71	Rail	UF_6	Derailment	Impact
49000 lb cask	12/71	Truck	Spent Fuel	Truck overturned	Impact
32000 lb cask	6/72	Truck	UF_6	Truck overturned	Impact
15200 lb cask	3/74	Rail	RAM-LSA	Derailment	Impact
38000 lb cask	8/74	Truck	RAM-Waste	Trailer overturned	Impact
[illegible]00 lb cask	8/75	Truck	Y235,Y238 Pu239	Tractor-trailer ran off road and overturned	Impact
[illegible] lb cask	10/75	Truck	RAM-LSA	Truck ran off road and overturned	Impact
30000 lb cask	4/76	Truck	LSA-Waste	Vehicle struck overpass	Impact
28000 lb cylinders	3/77	Rail	UF_6	Derailment, close contact with burning ammonium nitrate	Impact-Fire
6800 lb cylinders	1/79	Truck	UF_6	Vehicle rear ended	Impact

Accident Rates - Spent Fuel Transportation Accidents

The determination of an accident rate for spent fuel transportation accidents presumes an accurate knowledge of the number of annual transport miles for spent fuel shipments. Such information is not known with great precision. If the shipments in Reference 3 are actually charted between origin and destination, an estimate of approximately 200,000 miles (320,000 km) per year can be obtained. These shipping estimates are summarized in Figure 1. It should be noted that there have not been great numbers of spent fuel shipments to date. The shipment numbers discussed earlier in this section represent the transport of some spent fuel for reprocessing and the transshipment of spent fuel between reactor spent fuel pools to provide space for spent fuel which will be discharged in the future. At the present time, the main inventory of spent fuel is still resident in the reactor spent fuel pools. Future shipment patterns depend almost entirely on policies to be announced by the U S government.

The actual recording of accident and incident information commenced in 1971 by the US Department of Transportation. Spent fuel shipments in the US commenced in 1964. If one applies the annual average (estimated) of 200,000 miles of spent fuel shipments to 1971 and later years and uses the occurrence of one spent fuel accident, the accident rate is:

1971 through 1980 inclusive, 10 years at 2×10^5 miles per year

Total miles = 2.0×10^6 miles (3.22×10^6 km)

$$\text{Accident rate} = \frac{1}{2.0 \times 10^6} = 5.0 \times 10^{-7} \text{ spent fuel accidents/mile} \qquad (1)$$

The calculated accident rate assumes that the spent fuel shipments are made by truck. Most spent fuel shipments have been made by truck, very few have been made by rail according to Nuclear Assurance Corp. of Atlanta, GA. There have been no spent fuel accidents in rail transportation.

The Severity of Spent Fuel Transportation Accidents

The information presented in this analysis has emphasized the actual transportation accident/incident experience that has occurred for radioactive materials since 1971, the origin date of the Department of Transportation's Hazardous Material Incident Report (HMIR) system.

The historical perspective that a review of radioactive material transportation accident/incident experience offers is one that shows that the radioactive material transport record is really quite good. The interested and concerned members of the public and the nuclear industry can and should make the distinction between a transportation or handling accident, as described in this analysis, and the other conditions which regulations prescribe for reporting of hazardous material incidents which do not involve transportation (i.e., loading, unloading, or storage of radioactive materials). Such distinctions are made to provide a more accurate picture of past accident/incident experience.

The overall truck accident rate has been determined[5] to be approximately 2.5×10^{-6} truck accidents per mile. The analysis in this section has shown spent fuel truck transport accidents to be approximately 5.0×10^{-7} accidents per mile.

One bit of perspective can be offered by examining the severity (or intensity) of the truck and rail accidents and to relate the severity of the impact and fire environments to the severity of the regulatory (licensing) tests imposed packaging designs. These comparisons are made in Figure 1.

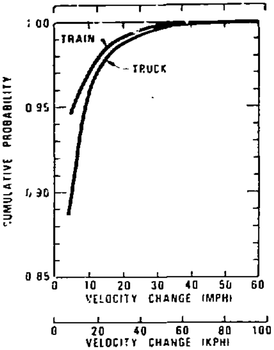

Figure 1. Cumulative probability of velocity changes due to impact, given a reportable truck accident or a reportable train accident.

Using impact as an example, one can observe in Figure 1 from a probability viewpoint that the regulatory tests cover a large range of accident conditions (given the occurrence of an accident). There is one point in Figure 1 that is very subtle; the velocity change of 30 mph (44 fps) in the hypothetical conditions (49 CFR 173.398) is associated with an unyielding target specification. Unyielding targets represent specialized laboratory conditions for target hardness and provide an upper bound for package damage. Such conditions are not real in the ordinary sense of the term and occur very infrequently if at all. In fact, the one spent fuel accident in Table V involved the truck overturning into relatively soft soil.

If one uses the derating scheme in Appendix H of Reference 1, the impact velocity of a package onto an unyielding target can be related to an equivalent velocity onto a yielding target. The relationship is

$$\frac{v_y}{v_{un}} = \left[\frac{1-\nu_y^2}{1-\nu_{un}^2}\right]\left[\frac{E_{un}}{E_y}\right]^{1/3} \qquad (2)$$

un,y, unyielding and yielding target designators

ν, Poisson's ratio　　　v = impact velocity

E, Modulus of Elasticity

A maximum value for the velocity ratio V_y/V_{un} can be obtained for soft soil versus an unyielding target[1] and

$$\frac{V_{\text{soft soil}}}{V_{\text{unyielding}}} = 7 \tag{3}$$

Thus, an unyielding target, a 30 mph (44 fps) impact would be roughly equivalent to an impact onto soft soil at

$$V_{\text{soft soil}} = (7)(44) = 308 \text{ fps}$$

$$308 \text{ fps} = 210 \text{ mph} \quad . \tag{4}$$

An impact into soft soil requires a very high velocity for an equivalent damage situation. Performing such calculations provides an indication as to why the Type B packages have sustained accident environments very handily and have not released their radioactive contents. The 308 fps impact velocity also allows one to move further to the right (in the direction of increasing impact velocity) on the asymptotic curve of Figure 1, hence the range of accidents covered are even greater than indicated in Figure 1. These relative response arguments for the impact environment are summarized in Reference 6 and depicted graphically in Figure 2. Figure 2 represents a reproduction of Figure 1 with the superposition of the target hardness zones representing moderately hard and relatively soft targets.

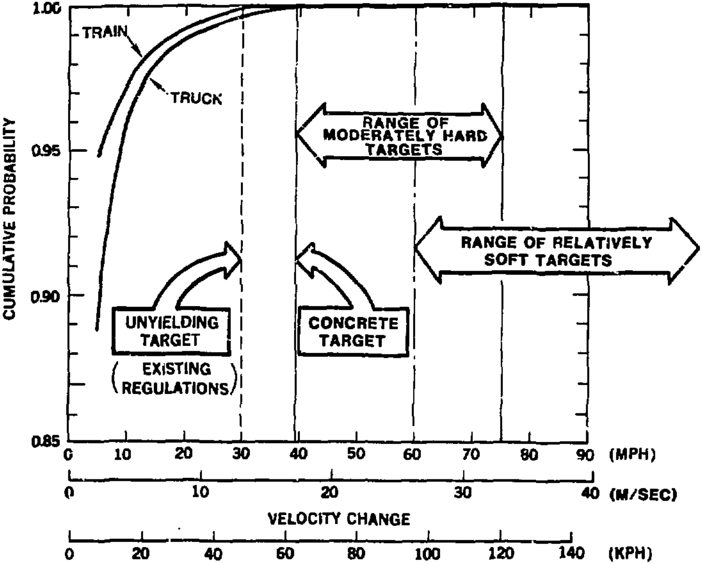

Figure 2. Damage equivalence diagram - impact environment.

In Reference 1 it is suggested that on a US area basis unyielding targets occur about 1 percent of the time, "hard" targets about 14 percent, and "soft" targets about 85 percent. The probability of encountering an unyielding or hard target is somewhat higher in the vicinity of roadways, but a detailed investigation has not been made. Thus, the probability of a truck accident which exceeds the impact environment posed by the regulatory test is approximately 10^{-9} accidents/mile. Similarly, the probability of exceeding the fire environment posed by the regulatory test is between 10^{-10} and 10^{-4} accidents/mile (Figure 3).

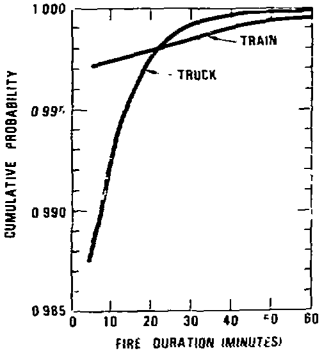

Figure 3. Cumulative probability of fire durations, given a reportable truck accident or a reportable train accident.

The important feature of the relative response argument is that a complete impact accident scenario includes impact velocity change and target hardness definition. Considering the unyielding target hardness conditions for packaging licensing, impacts into softer target media can produce less package damage than from the regulatory licensing tests.

Summary

One should note the distinction made between a transportation accident and a reported incident that is made in this report and in Reference 4. The necessity for such a distinction is that events that are determined to be accidents (from a careful study of the accident/incident reports) are counted and totaled in order to calculate accident rates. For purposes of this analysis a very liberal interpretation of what constitutes a transport accident has been taken so as to include almost any transport related event which anyone might judge to be an "accident". However, a careful study of the detailed DOT HMIR's and similar information from the NRC indicates that many reported events are not transport accidents. Any casual inclusion of all reported events in the accident rate calculation destroys the numerical accuracy and hence the validity of the accident rate.

If one reviews transportation accidents involving radioactive materials it can be determined that there have been transportation accidents with releases of radioactive materials but these releases have been from Type A packages which contain very limited quantities of materials.

For the more accident resistant packages, Type B packages, there have been accident occurrences but there have been no releases of radioactive contents from Type B packages.

An examination of the records has uncovered only one spent fuel transport accident. This event occurred on December 8, 1971, near Oak Ridge, TN. In this event, the truck driver lost control of the vehicle in trying to avoid a collision. The spent fuel cask was thrown from the truck during the accident; there was no release of radioactive contents from the cask. The driver of the vehicle was fatally injured due to the mechanical forces of the accident.

This single spent fuel transport accident has been used to calculate a spent fuel accident rate. The calculated spent fuel accident rate is based upon an estimated 200,000 spent fuel transport miles per year (320,000 km) for the nine years of 1971-1979. The calculated spent fuel accident rate is approximately 5.0×10^{-7} spent fuel accidents/mile (3.1×10^{-7} spent fuel accidents/km). The spent fuel transport accident occurrence rate, which is based on the fact that essentially all spent fuel to date has been transported by truck, is an order of magnitude smaller than the 2.5×10^{-6} truck accidents per mile (1.56×10^{-6} truck accidents/km), Reference 5. The calculated spent fuel accident rate is an approximate value for two reasons: (1) the annual number of spent fuel shipment miles is an estimated value and (2) most of the spent fuel is being held in the reactor storage pools instead of being transported away from the reactors.

Finally, information is contained in this report which allows one to assess, at least in a crude fashion, the likelihood that a spent fuel cask will be in an accident which will cause cask failure. This analysis suggests that accidents with the potential for release occur about once in every 500 million miles travelled. Cask impacts onto yielding targets produce large target deformations and relatively small deformations of the cask. Any scenario of a transport accident should provide a complete description of target conditions and likelihood of target impacts rather than only state the cask impact velocity magnitudes. The coupling of the cask impact velocity change with target hardness allows a quantitative assessment of cask impact velocity conditions onto yielding impact targets.

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