A Historical Review of the Safe Transport of Spent Nuclear Fuel

Fuel Cycle Research & Development

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Added Section 3, *Past Incidents in Transporting SNF and HLW,* and made changes to the executive summary, introduction, and conclusions sections to reflect this addition.

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EXECUTIVE SUMMARY

This report is a revision to M3 milestone M3FT-16OR090402028 for the former Nuclear Fuels Storage and Transportation Planning Project (NFST), “Safety Record of SNF Shipments.” The US Department of Energy (DOE) has since established the Office of Integrated Waste Management (IWM), which builds on the work begun by NFST, to develop an integrated waste management system for spent nuclear fuel (SNF), including the development of a large-scale transportation system for the safe transport of SNF to storage or disposal facilities.

The US does not currently operate a large-scale transportation system for SNF, but there is extensive experience worldwide in transporting SNF safely. This report contains a review of publicly available information on SNF transportation worldwide. Estimates were developed to ascertain the number of fuel assemblies, the number of tons of SNF shipped, and the number of shipments made between 1962 and 2016 worldwide. Data are not available for all countries, and statistics are also incomplete for many of the countries that have supplied information, so all quantities shown are lower bounds. However, from this review, it can be concluded that:

- At least 25,400 shipments of SNF have been made worldwide, but likely more than 44,400. It is likely that significantly more cask shipments have been made for all forms of SNF considered. The shipments within and into the US account for approximately 10 to 17 percent of this total.
- The quantity of SNF shipped worldwide to date is at least 87,000 metric tons of heavy metal (MTHM) and likely more than 109,000 MTHM. This is considered a lower bound since many of the data sources did not report on the heavy metal quantities shipped. Of the quantities reported here, the US accounts for only about 5 to7 percent of the total.

Additionally, the study identified that at least 130 cask shipments of vitrified high-level radioactive waste (HLW) containing more than 2,350 canisters of HLW have been reprocessed at the plant in La Hague, France, and shipped back to the countries where the SNF originated.

Review of the data sources shows that all of these shipments were undertaken without any injury or loss of life caused by the radioactive nature of the material transported. In general, there have been few transportation accidents worldwide in the history of transporting SNF, and none have had significant radiological consequences. This report investigates incidents in SNF and HLW transportation for which information could be found. These incidents may be classified as transportation accidents, instances of equipment contamination which occurred during transport of SNF, problems with or failure of conveyances, or disruptions to the transport of radioactive material.

Accidents have been infrequent in SNF and HLW transportation, and most have been minor accidents such as low-speed derailments or minor traffic accidents. Instances of radioactive contamination on SNF and HLW casks and the vehicles that carry them have occurred more frequently than transportation accidents, but these instances were still infrequent when compared to the overall number of shipments which were made in several countries over the years. Contamination was found on shipments within the US in the 1970s and 1980s and in Europe in the 1990s. After many studies, improvements in operating procedures at nuclear facilities, and enhanced regulatory oversight and enforcement of contamination limits, instances of radiological contamination of equipment have become less frequent.

Although uncommon, disruptions to shipments have occurred recently in Germany. Thousands of people have attended nonviolent and violent protests, resulting in shipments being delayed. Although there have not been any radiological effects as a result these protests, injuries have occurred, shipments have been delayed, and millions of dollars in extra costs have been incurred.

There have been very few incidents in the history of SNF transportation due to (1) the robust regulatory requirements in place for SNF shipping packages, commonly called *casks*, and (2) the high degree of

expertise of the package designers, manufacturers, and SNF shippers. However, a cask's performance during a transportation accident, including its ability to contain radioactive contents and to provide adequate shielding and criticality safety, has always been a subject of concern to shippers, regulators, and the general public. This report examines an actual accident involving a loaded SNF cask that occurred during a shipment in the US in 1971. It was a severe accident in which a truck overturned and then the cask being transported on the truck separated from the trailer. To the knowledge of the authors, it was the most severe accident ever to occur during a shipment of SNF. However, the cask was only superficially damaged; it succeeded in containing all of the radioactive material, and furthermore, the SNF element inside the cask was undamaged. Photographs of the accident scene, the cask damage, the recovery of the cask from the accident site, and the SNF element are included in this report, along with a photograph of the cask upon its return to service after inspection and refurbishment.

Following the case study of the accident involving SNF, this report presents a review of the US Nuclear Regulatory Commission (NRC) documents analyzing the risks inherent to SNF transportation. The NRC has conducted four studies attempting to quantify the risks in transporting SNF using the best available data, assumptions, and models. In every reinvestigation of SNF transportation risk assessment undertaken by the NRC, the radiological risks of SNF transportation have been estimated to be low in comparison to the risks inherent in truck and rail transportation. Furthermore, the collective dose received by the general public from SNF and HLW shipments is four orders of magnitude smaller than the naturally occurring background dose received by the same population in the same period of time.

As computational analysis methods have improved, estimated risks of SNF transportation have decreased. In the earliest risk assessment reports, it was assumed that casks would rupture in accidents and release all of their contents since the mechanisms for cask failure could not be modeled. As methods improved, it became possible to model strains on cask components and SNF rods, as well as the effects of high temperatures on containment seals and cask shielding. As more detailed and realistic simulations were performed, it became possible to reduce the uncertainty associated with risk analysis, thereby providing more reliable estimates of the actual risks involved in transportation.

Since the first investigation of SNF transportation risk by the NRC, regulations on casks have always been found adequate to protect the health and safety of the public in the event of a transportation accident. The hypothetical accident conditions described in the regulations are, in fact, much more severe than the majority of potential transportation accidents.

This report shows that transportation of SNF has been accomplished routinely and safely in many countries around the world, including the US, for decades.

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ACRONYMS

AGR	Advanced Gas Reactor
AEC	US Atomic Energy Commission
AEC-ORO	AEC Oak Ridge Office
AEE	Atomenergoexport
BNFL	British Nuclear Fuels Limited
CEGB	United Kingdom Central Electricity Generating Board
CFR	Code of Federal Regulations
COGEMA	Compagnie Général des Matières Nucléaires
DOE	US Department of Energy
DOT	US Department of Transportation
DSIN	Directorate for the Safety of Nuclear Facilities
EDF	Electricite de France
EMAD	Engine Maintenance Assembly and Disassembly
EPRI	Electric Power Research Institute
FCRD	Fuel Cycle Research and Development
FRA	Federal Railroad Administration
FRR SNF	Foreign Research Reactor Spent Nuclear Fuel Program
GKN	Gemeinschaftskernkraftwerk Neckar
GTRI	Global Threat Reduction Initiative
HEU	highly enriched uranium
HLW	high-level radioactive waste
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
IRSN	Institut de radioprotection et de sûreté nucléaire (French Institute of Radiation Protection and Nuclear Safety)
LNFC	Lanzhou Nuclear Fuel Complex
LWR	light water reactor
MTHM	metric tons of heavy metal
NAC	Nuclear Assurance Corporation
NFST	Nuclear Fuels Storage and Transportation Planning Project
NFT	Nuclear Fuel Transport Co., Ltd.
NMED	Nuclear Materials Events Database
NPP	nuclear power plants

NRC	US Nuclear Regulatory Commission
NNSA	National Nuclear Security Administration
OCRWM	Office of Civilian Radioactive Waste Management
ORNL	Oak Ridge National Laboratory
PATRAM	Packaging and Transportation of Radioactive Materials
PNTL	Pacific Nuclear Transport Limited
PWR	pressurized water reactor
RAMRT	Radioactive Material Routing Report
RAMTED	Radioactive Material Transport Event Database
RMIR	Radioactive Materials Incident Report
RRRFR	Russian Research Reactor Fuel Return Program
SAGSTRAM	Standing Advisory Group on the Safe Transport of Radioactive Material
SMAC	Shipment Mobility/Accountability
SNF	spent nuclear fuel
SNL	Sandia National Laboratories
UK	United Kingdom
WVDP	West Valley Demonstration Project

1. INTRODUCTION

The US Department of Energy (DOE) tasked the former Nuclear Fuels Storage and Transportation Planning Project (NFST) with laying the groundwork for interim storage of spent nuclear fuel (SNF) and high-level radioactive waste (HLW), including associated transportation. DOE has since established the Office of Integrated Waste Management to develop a waste management system for SNF and HLW, including the development of a transportation system. The US does not currently operate a large-scale transportation system for SNF and HLW, but there is extensive experience worldwide in transporting SNF and HLW safely.

This report reviews publicly available information on SNF transportation worldwide. Based on this review, estimates are made of the number of fuel assemblies shipped, the number of tons of SNF shipped, and the number of shipments made between 1962 and 2016 worldwide. Data are not available for all countries, and statistics are incomplete for many countries that have supplied information, so all quantities shown are considered lower bounds. However, it is clear that tens of thousands of tons of SNF have been transported safely in tens of thousands of shipments worldwide over the past fifty years.

In addition, this report catalogs past transportation incidents involving the transportation of SNF and HLW. In general, there have been few transportation accidents in the history of transporting SNF, none of which have significant radiological consequences. There has never been an injury-causing release of radioactive material in a transportation incident involving SNF or HLW. The transportation incidents described in this report may be classified as transportation accidents, instances of contaminated equipment transporting SNF, problems with or failure of conveyances, and disruptions to transporting radioactive material.

There have been very few incidents in the history of SNF transportation due to (1) the robust regulatory requirements in place for SNF shipping packages or casks, and (2) the high degree of expertise of the package designers, manufacturers, and SNF shippers. However, a cask's performance during a transportation accident, including its ability to contain radioactive contents and to provide adequate criticality shielding and safety, has always been a subject of concern to shippers, regulators, and the general public. This report examines an actual accident involving a loaded SNF cask that occurred during a shipment in the US in 1971. It was a severe accident in which a truck overturned and then the cask being transported on the truck separated from the trailer. To the knowledge of the authors, it was the most severe accident ever to have occurred during a shipment of SNF. However, the cask was only superficially damaged, and it succeeded in containing all of the radioactive material; the SNF element inside the cask was undamaged.

Following the case study of an accident involving SNF, this report presents a review of the US Nuclear Regulatory Commission (NRC) documents that analyzing the risks inherent to SNF transportation. The NRC has conducted four studies attempting to quantify the risks in transporting SNF using the best available data, assumptions, and models. Each NRC study has estimated the risks to be lower than the previous study, as models and estimates have become more realistic, and fewer overly conservative assumptions were made to account for gaps in data.

This report shows that transportation of SNF has been accomplished routinely and safely in many countries around the world, including the US, for decades. It is proposed that this report be used as the starting point for a database of SNF and HLW transportation incidents worldwide to be maintained continuously. By learning from past incidents, shippers of SNF and HLW can continue to make safe shipments while avoiding mistakes made in the past. Furthermore, it will be beneficial for all stakeholders to have an accurate and balanced source of information regarding the transportation of SNF and HLW.

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2. SHIPMENTS OF SNF AND HLW IN THE US AND WORLDWIDE

This section summarizes the estimates of SNF and HLW made in the US and worldwide. These are indeed "estimates" because there is no comprehensive, reliable source of this information. The estimates are derived from reports of past efforts made to quantify these shipments, as well as various documents available in the popular scientific literature listing specific shipments or shipment campaigns.

2.1 Estimates of Worldwide Shipments of Radioactive Material in Type B Packages Published in 1986

The first attempt to make a comprehensive worldwide assessment of radioactive material shipments, including SNF and HLW shipments, was undertaken by the International Atomic Energy Agency (IAEA) with the assistance of consultants from various countries. This effort was undertaken by the IAEA based on a recommendation from the first meeting of the Standing Advisory Group on the Safe Transport of Radioactive Material (SAGSTRAM). The group determined that it was not viable to seek such data on a continuing basis, so they made a one-time effort to take a snapshot of what was then being shipped throughout the world.

In 1980, a request went out to all IAEA member states for "summary information based on the best data available to or collected by the competent authorities over an initial one-year reporting period." The effort summarized in a Packaging and Transportation of Radioactive Materials (PATRAM) paper (Pope and McClure 1986) indicated that 49 countries responded to the request, but data from only 35 countries were found to be useful. In addition, 12 countries acknowledged receipt of the request but then did not reply. Many responding countries acknowledged that the data provided were not complete. For example, it was found that of the 35 countries responding:

- 21 provided data on international shipments, but 10 of these data sets were judged to be incomplete, and
- 31 provided data on their domestic shipments, but 12 of these were judged to be incomplete.

Also, it was noted that the data provided were from countries representing only ~26 percent of the world's population, 55 percent of the world's gross domestic product, and 80 percent of the then-installed nuclear power generating capacity.

In addition, the time periods reported varied significantly. Some respondents did not specify the time period of shipments, while others provided data for varying periods from 1979 through 1982.

The data request omitted key pieces of information that would have helped with the current analysis. Namely, it did not ask respondents for the number of SNF and/or HLW shipments, but only asked that shipments be specified by package type. Recognizing that all SNF and HLW shipments would occur in Type B packages, Table 2-1 provides a rough estimate summary of what was shipped annually in Type B packages for the 1979 to 1982 timeframe by the top 16 countries reporting. Thus, the number of SNF and HLW shipments according to this assessment would be less than the values shown in the table.

The data in Table 2-1 were reported in terms of *package shipments*, which is defined for the purpose of the IAEA study as a "single package transported by a single mode of transport from an origin to a destination." In addition, the number of shipments reported in Table 2-1 for Type B(U) and Type B(M) packages has been combined into the number of annual shipments in a Type B package.

The total estimated Type B package shipments per year was estimated to be approximately 255,000. However, a good majority of those shipments came from three countries (Canada, the United Kingdom, and the United States), all three of which were at that time major suppliers of high activity sources for agriculture, industry, and medicine, thus requiring the use of Type B packages. Therefore, the total SNF and HLW shipments would likely have been a small fraction of the Type B shipments reported.

Table 2-1. Estimated number of annual shipments in Type B packages during 1979–1982*.

Country reporting	Estimated annual Type B package shipments
Australia	0
Canada	~78,800
Finland	250
France	1,200
Federal Republic of Germany**	5,600
Hungary	1,840
Ireland	7,550
Italy	6,700
Japan	510
Norway	250
Poland	5,430
South Africa	1,900
Spain	1,320
Sweden	250
United Kingdom	~47,800
United States of America	~96,000
Total estimated annual Type B package shipments	**~255,000**

*Adapted from Table V, Pope, 1986.
**Otherwise known at that time as "West Germany".

A lesson learned from this effort was that it is difficult, if not impossible, to obtain a comprehensive, accurate assessment of the worldwide shipments of radioactive material. However, by considering reports and symposia presentations made voluntarily by governments, organizations, agencies, and companies, it is possible to gain insight into the types and quantities of shipments of radioactive materials, specifically of SNF and HLW, at different times. The next section reviews some of the specific data obtained from such reports and presentations. It is followed by an analysis of the IAEA's second attempt to gain a global perspective of shipping rates in 2001.

2.2 Typical Detailed Reports of SNF Shipments Reported from the 1960s to 2016

The typical SNF data presented in this section may overlap with data from various reports, so care must be taken when attempting to add the data for a comprehensive, US and/or world view. The data may not fully represent all shipments from a given entity, and the time periods for each data source often vary or may not be specified. The following summarizes typical results from presentations made by various entities primarily at the PATRAM symposium up to 2010 and from other sources as available.

2.2.1 SNF Shipments Reported at PATRAM 1983

Between 1962 and 1982, the United Kingdom Central Electricity Generating Board (CEGB) transported 7,000 shipments of SNF from its various Magnox and Advanced Gas Reactor (AGR) Nuclear Power Plants (NPPs) to the Sellafield site for reprocessing (Mummery 1983). All shipments were made by rail using the CEGB-designed cuboid casks (known in the UK as *flasks*).

From 1966 through 1982, 4,451 metric tons of heavy metal (MTHM) in the form of spent natural uranium fuel was transported from various reactors in France to the Marcoule and La Hague Reprocessing Plants. The casks used for these shipments weighed approximately 54 metric tons each (Lenail 1983).

During 1971–1972, approximately 1,000 irradiated materials test reactor fuel (MTR) elements were shipped from Canada to the European reprocessing plants at Mol, Belgium (Mangusi 1983). These shipments involved road and sea transport.

From 1973 through 1982, 1,685 MTHM (>5,000 fuel elements) of spent light water reactor (LWR) fuel were transported from various European and Japanese NPPs to the La Hague Reprocessing Plant in France (Lenail 1983). The shipments were made by road, rail, and sea using casks ranging in weight from 38 to 110 metric tons each.

- The number of road transports ranged from 9 to 90 per year, with a total of 566 road shipments for the time period.
- The number of sea transports between 1979 and 1982 (including road or rail transport at the beginning and end of the shipments) ranged from 29 per year to 106 per year, with a total of 266 shipments for the time period.
- Since most casks in these shipments weigh 80 metric tons or more, most shipments were made by rail, with road transportation used for the last 40 km distance from the Valognes terminal to La Hague. A total of 2,476 rail shipments during this leg of transport had occurred up to 1982.

From about 1977 through 1982, approximately 175 shipments of more than 3,000 irradiated material test reactor (MTR) fuel elements were completed from various locations such as South Africa and Europe to either the Savannah River Site (SRS) or the Idaho National Laboratory (Mangusi 1983). These shipments, which involved both road and sea transport, resulted in more than 100,000 highway miles of transit.

In late 1979, multiple shipments of SNF were made in the US using legal weight truck casks from the Turkey Point NPP to Battelle Memorial Laboratory in Ohio and the Nevada Test Site in Nevada. A total of 13 SNF assemblies were shipped (Sherman 1983).

From 1979 to 1982, Japan made 34 shipments of 67 casks (with more than one cask per shipment) containing spent LWR fuel. These shipments were made from seven Japanese NPPs to the Tokai Reprocessing Plant (Onodera 1983). The shipments were primarily by sea, and a total of 198 MTHM was transported.

2.2.2 SNF Shipments Reported at PATRAM 1986

From 1964 to 1984, 4,141 commercial SNF assemblies had been transported by road in the US (McClure 1987).

At PATRAM 1986, Lenail and Curtis updated the shipment data they had presented at PATRAM 1983 (Sect. 2.2.1) (Lenail 1987). It was reported that from 1966 through 1985, 3,755 cask shipments of SNF had been completed to the Marcoule and La Hague reprocessing plants in France. These shipments occurred by road, rail, and sea, and they had originated from European countries and Japan. Specifically:

- 4,780 MTHM of gas-cooled reactor fuel comprising 1,580 cask shipments were completed to La Hague from 1966 through 1985.
- 2,440 MTHM of gas-cooled reactor fuel comprising 510 cask shipments were completed to Marcoule from 1975 through 1985.
- 4,120 MTHM of LWR fuel comprising 1,540 cask shipments were completed to La Hague from 1973 through 1985.

- 10.6 MTHM of fast breeder reactor fuel comprising 125 cask shipments were completed to La Hague from 1968 to 1985.

Thus, from 1966 through 1985, a total of 3,755 cask shipments comprising 11,351 MTHM of SNF were made to the Marcoule and La Hague reprocessing plants.

From 1971 through mid-1986, 135 MTHM of SNF was transported from the Beznau I and Beznau-II NPPs in Switzerland to Sellafield in the UK (Dommann 1987). Shipments of SNF began from the Mühleberg NPP in 1975, with 134 MTHM transported to the La Hague reprocessing facility, and beginning in 1982, 100 MTHM of SNF were transported from the Mühleberg NPP through mid-1986. Also, shipments of SNF began from the Gösgen NPP in 1982, with 93 MTHM transported to the La Hague reprocessing facility through mid-1986. These shipments were made using a combination of road and rail. Figure 2.1 includes a photograph of the typical processing of large SNF casks between rail vehicles and a purpose-designed oceangoing vessel at the Barrow-in-Furness port facility in the UK.

Between 1981 and 1985, three shipments of SNF were made from the Loviisa NPP in Finland to V/O Atomenergoexport (AEE) in the Soviet Union (Koskivirta 1987). The shipments, which were accomplished in the USSR by a combination of road and rail, were in 90 metric-ton Soviet-designed TK-6 casks. Each cask is capable of carrying approximately 3.6 MTHM.

During 1983, six sea-borne shipments of SNF were made between various Swedish NPPs and the La Hague reprocessing plant in France (Gustafsson 1987). The total quantity of SNF shipped in that year was 57 MTHM. The purpose-built vessel used for the Swedish shipments was the M/S Sigyn (see Fig. 2.2).

Road shipments began in 1983 between various NPPs in the US and the West Valley Demonstration Project (WVDP), the Test Area North at the Idaho National Engineering Laboratory (INEL, currently "Idaho National Laboratory" [INL]), and Chem-Nuclear's waste disposal facility at Barnwell, SC (Mangusi 1987). These shipments involved the use of two TN-8L casks and two TN-9 casks. The shipments were made from the Surry, Oyster Creek, and Dresden NPPs. By May 1986, 175 MTHM of SNF had been transported.

Beginning in November of 1984 and ending in October 1985, 124.4 MTHM of SNF was transported from the Monticello NPP to the Morris, Illinois storage facility (Voiland 1987). These shipments, all made by rail, were made using the IF-300 rail cask. A total of 19 two-cask shipments were used in the campaign, which moved 684 BWR SNF elements to the Morris facility.

During 1985 and early 1986, shipments of 252 MTHM of LWR (1,270 SNF elements) and BWR SNF have been made from Swedish NPPs to the Swedish AFR facility CLAB facility in Sweden, comprising 82 cask shipments, 80 percent of which were by sea, and the remaining 20 percent were by road (Gustafsson 1987).

Fig. 2-1. Processing of casks between railcars and purpose-built vessel at Barrow-in-Furness (photo by coauthor R. B. Pope during June 2002 IAEA appraisal of the safety of the transport of radioactive material for the UK (IAEA 2002).

Fig. 2-2. M/S Sigyn, specially designed Swedish vessel for SNF and HLW transport. (Posiva 2016).

2.2.3 SNF Shipments Reported at PATRAM 1989

Shipment of Magnox SNF began in the United Kingdom in the 1962–1963 timeframe (Mummery 1983, Mummery 1989). Through 1989, more than 10,000 cask movements have occurred from both the Magnox and AGR power stations to the Sellafield plant. Shipments had been primarily by rail, but some segments of the shipments (up to 13 miles in length) were by road.

Between 1973 and 1988, British Nuclear Fuels PLC in conjunction with Pacific Nuclear Transport Limited transported more than 570 casks (called *flasks* in the UK) of LWR fuel on 79 sea voyages from Japan to the United Kingdom (Gowing 1989). Each shipment involved land transport by road or rail at the beginning and end of the sea transport.

In 1982, preparations began for shipment of 322 fuel elements from the Italian Garigliano NPP to the shutdown reactor at Saluggia in the Turin Province (Orsini 1989). The shipment campaign, which involved road transport of 46 cask shipments in an AGN1 cask, was completed in December 1987.

For the period 1986–1988, Electricite de France (EDF) personnel reported that 3,894 SNF assemblies had been transported from various pressurized water reactor (PWR) NPPs in France to La Hague (Gouin 1989).

During the period 1986 through 1989, 1,574 spent research reactor fuel (SRRF) elements were shipped from Taiwan to the United States (Cashwell 1989). These shipments were carried out by a combination of land and sea transport, with the destination site being the SRS in South Carolina and the INEL in Idaho. The last leg of these shipments was completed by rail.

During 1986 to 1989, approximately 75 percent of the damaged core of the Three Mile Island (TMI)-2 NPP was transported by rail from the TMI NPP in Pennsylvania to INEL (Reno 1989). A total of 40 cask loads of material was shipped.

In 1986, 76 fuel assemblies were transported by road from the Surry NPP in Virginia and the Engine Maintenance Assembly and Disassembly (EMAD) facility at the Nevada Test Site (NTS) to INEL (Reno 1989). Sixty of the assemblies were from the Surry NPP, whereas the remaining 17 assemblies emanated from the EMAD but originated from the Turkey Point NPP.

In 1987, two SNF assemblies and part of a third assembly were transported from Battelle Columbus Division near Columbus, Ohio to INEL by road (Reno 1989). For the purpose of this document, it has been assumed that this was accomplished with one cask shipment.

In 1988, 104 cask shipments were received at the CLAB facility in Sweden (Gustafsson 1989) as follows:

- 76 cask shipments of PWR and BWR fuel from NPPs,
- 9 cask shipments of core components,
- 8 cask shipments of MOX fuel from West Germany, and
- 11 cask shipments of fuel from the Åegsta NPP that had been shipped and stored at Studsvik.

In 1989, a USSR paper reported that LWR SNF from WWER-1000 NPPs in the Soviet Union and the Ukraine had been transported by rail to reprocessing plants in the Soviet Union (Kondratyev 1989). Between 1985 and 1989, 12 trips were made (7 from the Novo-Voronezh NPP, 3 from the South Ukrainian NPP, and 2 from the Kalinin NPP). Based on the description of the casks used and the shipments made, approximately 117 MTHM had been shipped from these three sites.

2.2.4 SNF Shipments Reported at PATRAM 1992

From 1962 through 1992, the United Kingdom's Nuclear Electric/CEGB had transported more than 21,000 MTHM in approximately 13,000 cask (flask) shipments (Pannett 1992).

Between 1978 and 1992, SNF shipments occurred by sea from various Japanese NPPs to the Tokai-mura facility in the Ibaraki Prefecture of Japan (Nagano 1992). During this period, 564 MTHM had been transported in 204 cask shipments.

At PATRAM 1992, the shipment of SNF in Sweden was updated (Dybeck 1992). From 1985 through 1992, 1,600 MTHM had been transported to CLAB.

During 1991, 114 shipments of irradiated material were made between Germany and other countries, and 7 shipments were made domestically within Germany (Alter 1992).

2.2.5 Total Shipments of SNF to La Hague up to 1992

In a PATRAM 1992 presentation (Bernard 1992), it was reported that up until the date of the symposium in September 1992, 19,000 MTHM in 5,500 cask shipments had been received at the La Hague reprocessing facility in France, and an additional 13,000 MTHM from 110 NPPs in some 3,000 cask shipments were expected to be made.

2.2.6 Estimated Total Shipments of SNF within the US to 1991

Also during PATRAM 1992, a paper was presented (Pope 1992) summarizing the results of a study conducted for the Office of Civilian Radioactive Waste Management (OCRWM) in an attempt to understand and quantify the shipments of SNF in the United States for the period of 1964 through September 1991. The paper showed that approximately 2,700 power reactor SNF rail and truck cask shipments had occurred during the previous 28 years. In total, approximately 2,000 MTHM had been shipped.

The data sources used in this study were DOE’s Shipment Mobility/Accountability (SMAC) database and the US Department of Transportation (DOT) Radioactive Material Routing Report (RAMRT).

The summary table from this reference document is reproduced here as Table 2-2.

Table 2-2. Summary of Commercial SNF Shipments, by Mode, in the United States from 1964 to 1991. (Source: Pope 1992).

	Road (truck)	Rail (train)	Totals
Number of assemblies	4706.93	4673.71	9380.64
Percentage of assemblies	50	50	100
Number of shipments	2351	248	2599
Percentage of shipments	90	10	100
Number of loaded casks	2351	348	2699
Percentage of loaded casks	87	13	100
Tonnage of SNF (MTU)	983.473	988.501	1971.974
Percentage of tonnage	50	50	100
Average tonnage of SNF per loaded cask (MTU/cask load)	0.42	2.84	N/A

In summary, the PATRAM 1992 report (Pope 1992) showed that, in the US during that 28-year period:

- ~9,380 SNF assemblies had been transported in the US,
- these assemblies were transported in 2,699 cask shipments,
- all these shipments occurred by road (~90 percent) and rail (~10 percent), and

- the total mass of SNF transported was ~1,972 MTHM.

For the United States, eight documents are cited in Sects. 2.2.1 through 2.2.4, but these incrementally represent fractions of those shipments accounted for in the comprehensive summary in Sect. 2.2.6. Thus, the data shown in Table 2-2 (Pope 1989) represent the best estimate of SNF shipped from commercial NPPs within the US during 1962–1989.

In addition, two documents cited report a total of approximately 4,570 MTR, and other research reactor fuel elements were shipped from foreign countries to the US during 1977 to 1989 (Mangusi 1983, Cashwell 1989).

Thus, combining the data for commercial NPPs with the incremental data for research reactors, at least 14,250 SNF assemblies have been transported within or into the US.

2.2.7 SNF Shipments Reported at PATRAM 1995

From 1970 to 1994, more than 4,550 MTHM were shipped in 1,904 casks (flasks) by 1,562 individual shipments in Germany (Fasten 1995). Figure 2.3 compares the number of shipments made within Germany with those exported and those transiting the country by year. It was reported that

> *Most of the spent fuel from the German nuclear power plants was transported to the reprocessing plants in France and in the United Kingdom. Some spent fuel was shipped also to Belgium (nine shipments in 1970), to Denmark (one shipment in 1983) and to Sweden (twelve shipments in 1977, 1987, and 1988). The transport of spent fuel from the former GDR to Russia (from nuclear power plants Rheinsberg and Greifswald) was carried out in 1972 to 1985. They were stopped in 1985, because the intermediate storage facility in Greifswald started operation.*

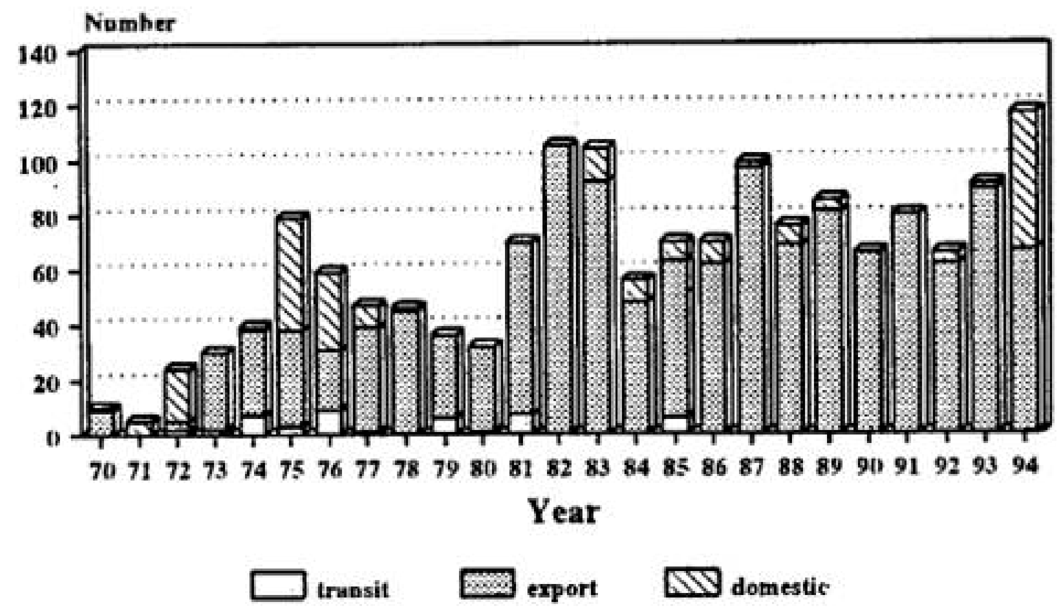

Fig. 2-3. Number of SNF shipments within, from, and transiting Germany, 1970 –1994 (Fasten 1995).

Data on nuclear material shipments made from 1990 through 1994 in Germany were summarized at PATRAM 1995 (Alter 1995). During that period, 336 shipments were made to reprocessing facilities in France and the UK, amounting to 365 cask shipments (302 to La Hague and 65 to Sellafield). Also, with the closing of the Kalkar fast-breeder reactor, 57 shipments involving 305 casks were shipped between 1992 and 1995 to interim storage at the Ahaus facility.

2.2.8 SNF Shipments Reported at PATRAM 1998

Shipments of plutonium (quantity unspecified) in the 1992–1993 timeframe (Nagakura 1998, Aoki 1995) were also reported. This plutonium, which resulted from the reprocessing of Japanese SNF “in foreign countries” (i.e., France and the UK), had been shipped by sea from Europe to Japan. Similarly, two shipments of 68 HLW canisters of vitrified HLW resulting from that reprocessing campaign had been made from France to Japan between 1995 and 1997 (Nagakura 1998, Nambu 1998).

During late 1997 and early 1998, three truck shipments of DOE-owned aluminum-clad SNF were made between Oak Ridge National Laboratory (ORNL) and SRS in a BMI-1 cask (Shappert 1998). The three shipments, which were undertaken as part of the Reduced Enrichment Research and Test Reactor (RERTR) Program, contained a total of 18.6 kg of (~0.019 MTHM).

During the period 1972 to 1997, 1,422 rail shipments of SNF occurred in Germany (Alter 1998). The origins and destinations of these shipments were not specified.

From the period 1990 through 1995, 312 SNF assemblies were shipped in 78 “transportation cycles” (i.e., package shipments) using a 37 metric ton, road-transported KSC-4 shipping cask in the Republic of Korea (Lee 1998).

In 1997, 76 MTR fuel assemblies loaded into two IU04 casks were transported by road and rail from Italy to France, then by maritime vessel to the United States, and then by rail within the US to SRS as part of the RERTR Program (Gila 1998).

2.2.9 SNF Shipments Reported at PATRAM 2001

Data presented at PATRAM 2001 (Mori 2001) for SNF transport within Japan are compared here with data from a series of papers presented at earlier PATRAM symposia (Nagakura 1998, Aoki 1995, Nagano 1992). SNF transports within Japan through 2001 appear to have resulted in approximately 196 cask shipments; this generally agrees with the numbers shown earlier in Sect. 2.2 (Onodera 1983). The quantities shipped as specified in Mori 2001 and Nambu 1998 showed that from 1978 through 2001, approximately 900 MTHM were shipped domestically in Japan by a combination of short land transport (road and rail) at origin and destination, with intervening sea transport. The total number of maritime voyages of SNF was approximately 200. However, the combination of these Japanese papers results in significant differences in the quantity of SNF shipped, ranging from as low as ~900 to as much as ~2,100 MTHM. Thus, the various sources of Japanese shipping data have been rationalized into a single set of data as discussed in Sect. 2.3.

Sea transport for Japanese domestic shipments was accomplished with the “Hinoura Maru” (see Fig. 2.4). An example of land transport of SNF in Japan is shown in Fig. 2.5.

Magnox SNF fuel assemblies were shipped from the Tokai NPP in Japan to the Sellafield reprocessing plant in the UK (Ohtaka 2001). From 1969 through 2001, 71 maritime shipments consisting of 130,000 SNF elements containing 1,500 MTHM were shipped from the Tokai station. In addition (Ohtaka 2001), through 2001, approximately 2,000 SNF assemblies had been transported by maritime vessel from the BWR Tokai-2 NPP to Sellafield or La Hague.

Shipments of MTR and TRIGA SNF from Europe, South America, Australia and Japan to the United States have occurred as part of the Foreign Research Reactor Spent Nuclear Fuel (FRR SNF) program (Schmidt 2001). These international shipments to SRS and Idaho Falls were accomplished using the MV Arneb maritime vessel. Seven shipments were made by 2001, with 1400 MTR SNF assemblies shipped to SRS and 202 TRIGA SNF assemblies shipped to Idaho. Figure 2.6 shows one of the casks used in these shipments, and Fig. 2.7 shows the MS-ARNEB at a port facility.

Fig. 2-4. The Japanese Hinoura Maru (Mori 2001).

Fig. 2-5. Example of SNF land transport in Japan (Mori 2001).

Fig. 2-6. TN 7-2 transport cask loaded on a road vehicle used for transport of research reactor SNF (Schmidt 2001).

Fig. 2-7. MS-ARNEB vessel with a security vehicle at a port facility (Schmidt 2001).

A paper presented at PATRAM 2001 discussed experience with shipments of a dual-purpose cask (Roland 2001), the TN 52L, which was the "first dual-purpose high capacity spent fuel cask ever to have been transported internationally." The TN 52L weighs 118 metric tons loaded. Figure 2.8 shows the cask being loaded onto a heavy-haul road vehicle, and Fig. 2.9 shows the cask during road transit. However, the reference document does not specify the quantity of shipments made.

Fig. 2-8. TN 52L dual-purpose SNF cask being loaded onto a heavy-haul road vehicle (Roland 2001).

Fig. 2-9. TN52L dual-purpose SNF cask during transit on heavy-haul road vehicle (Roland 2001).

Another paper presented at PATRAM 2001 outlined experience with the on-site loading and storage of dual-purpose casks in Europe (Sicard 2001). From 1995 to 1999, a total of 10 TN24 D casks were loaded at the DOEL NPP in Belgium, and from 1996 to 1999, a total of 8 TN 24 XL casks were loaded at DOEL.

Although not transported off site, they are configured so that such transportation can occur. The TN 24D can accommodate 28 PWR SNF assemblies, and the TN 24XL can accommodate 24 PWR SNF assemblies. It was further reported that higher-performance dual-purpose casks had been developed and were in the process of being delivered to the DOEL NPP. All of the casks have a Type B(U)F certification for transport.

Two shipments of SNF assemblies were undertaken in the TN 52L dual-purpose cask, each containing 52 BWR SNF assemblies. These shipments were made from the Leibstadt NPP in Switzerland to La Hague during the 1999–2000 timeframe. Also, a TN 97L dual-purpose cask with 97 BWQR SNF assemblies was transported from the Liebstadt NPP to the Swilag storage facility in Switzerland (Sicard 2001).
Figure 2.10 shows the TN 97L loaded on a heavy-haul road transport vehicle.

Fig. 2-10. The TN 97L dual-purpose cask loaded on a heavy-haul road transport vehicle (Sicard 2001).

2.2.10 Estimated Total Worldwide Shipments of SNF Reported at PATRAM 2001

A paper was presented at PATRAM 2001 (Pope 2001), a "Worldwide Assessment of the Transport of Nuclear Fuel and High-Level Waste." This paper summarized the results of informal contacts made by the IAEA

> *with many of the countries and organizations that have been involved in transporting irradiated nuclear fuel and high-level wastes, requesting information on shipments completed to date, and future shipment plans for these two types of radioactive material. Although the data provided are incomplete, the results are enlightening regarding the quantities of these materials that have been transported*.

This effort resulted in contacting personnel in 16 countries and extracting data from literature from published sources from nine countries. It also made use of an IAEA survey of worldwide experience in wet and dry SNF storage. The survey included an assessment experience in SNF shipping. As noted in the preceding quote, the resulting data were recognized as not being complete.

The PATRAM 2001 paper included summary tables of the following:

- SNF shipping experience at Sellafield in the UK as reported by BNFL/PNTL covering both LWR and non-LWR fuels
- LWR SNF shipping experience at La Hague
- Non-LWR shipping experience in France
- SNF shipping experience in Belgium
- SNF shipping experience in Canada
- SNF shipping experience in the Czech Republic
- SNF shipping experience in Finland
- SNF shipping experience and plans in Germany
- SNF shipping experience in Hungary
- SNF shipping experience in Italy
- SNF shipping experience in Japan
- SNF shipping experience in the Netherlands
- SNF shipping experience in the Russian Federation
- SNF shipping experience in Slovakia
- SNF shipping experience in Spain
- SNF shipping experience in Sweden
- SNF shipping experience in the Ukraine
- SNF shipping experience in the United States

Compilation of these data resulted in concluding that approximately 73,000–98,000 MTHM in the form of SNF were transported throughout the world up until approximately the beginning of 2001. These shipments constituted approximately 24,000–43,000 flask/cask shipments by all surface modes of transport (i.e., road, rail and sea). The data obtained in this study are summarized in Table 2-3.

In addition, data were collected for shipments of vitrified HLW from La Hague to Belgium, Germany, and to Japan. These data show that 520 MTHM of HLW in eight shipments involving 16 cask shipments had been completed.

2.2.11 Estimated SNF Shipments in the United States through 2001 – Reported at PATRAM 2001

The data collected by the IAEA as reported at PATRAM 2001 (Pope 2001) are summarized in Table 2-4. These data resulted from combining data from Pope 1991 and NRC 1998.

2.2.12 SNF Shipments Reported at PATRAM 2004

In 2003, China made its first shipments of SNF from Guangdong NPP (Daya Bay) Unit-1 to the Lanzhou Nuclear Fuel Complex (LNFC) reprocessing facility (Meinert 2004). A Nuclear Assurance Corporation (NAC) cask design, the NAC-SSTC, weighing 125 tons (113.6 metric tons), was used. Figure 2.11 is a photograph of the cask on its transport skid, and Fig. 2.12 is a photograph of this cask in transit. Although the cask was very large, it was transported approximately 4,000 km (2,480 miles) from the NPP to the reprocessing facility by road. As of September 2004, five cask shipments had been completed, with 130 SNF assemblies shipped.

An update on the shipments of SNF from Germany to La Hague and of HLW shipped from La Hague to Germany was provided at PATRAM 2004 (Alter 2004). The first shipments of SNF to La Hague began in 1973. As of September 2004, approximately 5,400 MTHM of SNF had been transported in 127 cask shipments to La Hague, and 39 cask loads of vitrified HLW had been shipped from La Hague to the storage facility at Gorleben. All of these shipments were by rail.

The HLW shipments were made by special train in Germany, which consisted of

- 4 diesel 6-axle, 2,400 kW locomotives each with a weight of 120 tons,
- 12 special 8-axle heavy-goods railway cars for 12 CASTOR casks, each car with a total weight of 160 tons, and
- 12 accompanying railway cars for police-guards.

The total length of the special train was 649 m, with a total weight of 2,912 metric tons. Because of social unrest, 18,485 police-guards were involved in the final transport in November 2003.

Table 2-3. Summary of findings from the 2001 IAEA survey of SNF and HLW shipments (Pope 2001).

Shipments	Estimated quantity	Estimated number of casks
LWR/Magnox/AGR to Sellafield and La Hague	50,000–75,000[a]	18,500–37,100[a]
FBR France (domestic)	11	125
Non-LWR originating in France	10,507	m/a
Canada (domestic)	100	187
Czech Republic (to/from Slovenia)	242	65
Finland to USSR/Russian Federation	233	65
Germany (domestic to storage)	>25	66
Hungary (originating)	258	72
Italy (domestic)	81	52
Japan (domestic)	161	50
Russian Federation (domestic)	3,500	500
Slovakia (originating)	380[b] (239–380)	700[c] (635–700)
Sweden (domestic)	3,300	1,100
Ukraine (originating)	1,300	300
United States of America	2,274	3,025
HLW from La Hague	520	8
APPROXIMATE TOTALS	**73,000–98,000**	**24,000–43,000**

[a] Uncertainty results from range of data from two sources of data for shipments of non-LWR fuels within the UK
[b] 141 MTHM of these could have been those shipped back to the Czech Republic
[c] 65 of these cask shipments could have been those shipped back to the Czech Republic

Table 2-4. Estimated SNF shipments in the United States, 1964–1997 (Pope 2001).

Time period	Mass of SNF shipped (MTHM)		Number of cask shipments		Totals		Source of data
	Road	Rail	Road	Rail	Mass of SNF (MTHM)	Number of cask shipments	
1964–1978	472.5	348.1	1565	126	820.6	1691	(Pope 1991)
1979–1997	356.3	1096.6	1181	153	1452.9	1334	(NRC 1998)
Total: 1964–1997	**828.8**	**1444.7**	**2746**	**279**	**2273.5**	**3025**	

Fig. 2-11. NAC-STC on transport skid in China (Meinert 2001).

Fig. 2-12. NAC-STC cask in transit by highway in China (Meinert 2001).

From 1995 to 2004, 20 shipments of HLW were made from La Hague to Japan, Germany, Belgium and Switzerland (Lancelot 2004), as follows:

- Japan: 9 shipments comprised of 19 casks containing 28 canisters of HLW and 18 casks containing 20 canisters of HLW for a total of 892 canisters
- Germany: 6 shipments comprised of 39 casks containing 28 canisters of HLW for a total of 1,092 canisters
- Belgium: 7 shipments comprised of 7 casks containing 28 canisters of HLW for a total of 196 canisters
- Switzerland: 4 shipments comprised of 4 casks containing 28 canisters of HLW for a total of 112 canisters

Relative to the shipments of HLW from La Hague to Germany, strong opposition by elements of the public resulting in "heavy and violent demonstrations with the intent to stop and to delay the trains transporting the flasks" caused the latter shipments to be made with a large consist of railcars/casks under large police protection (Verdier 2004). The latter shipments were undertaken with 12 casks each. Figure 2.13 is a photograph of the heavy-haul road transport of one of the CASTOR HLW casks traveling from La Hague to the railhead at Valognes, France. Figure 2.14 is a photograph of the train consist showing the cask railcars and accompanying passenger cars for security personnel. Figure 2.15 is a photograph of a typical scene showing demonstrators impeding the progress of the train.

Fig. 2-13. Heavy-haul road transport of HLW cask between La Hague and Valognes, France (Verdier 2004).

Fig. 2-14. Train consist containing 12 cask railcars and associated security personnel cars (Verdier 2004).

Fig. 2-15. Demonstrators on rail tracks during rail transport in Germany (Verdier 2004).

From 1978 through the end of FY2003, the Japanese company Nuclear Fuel Transport Co., Ltd. (NFT) transported 950 MTU of SNF from Japanese NPPs to the PNC Reprocessing Facility at Tokai, and from 1998 to 2003, NFT transported 780 MTHM of SNF in 139 cask shipments to the SNF storage pool at the JNFL Rokkasho Reprocessing Facility (Kaneko 2004).

Unique shipments of SNF occurred between 1983 and 1986, when 625 SNF assemblies involving 257 individual cask shipments were returned to the originating utilities from the West Valley Demonstration Project (Tyacke 2004). The 125 SNF assemblies at West Valley were later shipped to the Idaho National Engineering and Environmental Laboratory (INEEL, aka INEL and INL) in July 2003. Figure 2.16 is a photograph of a loaded West Valley transport cask, and Fig. 2.17 is a photograph of two casks used to transport the SNF to Idaho.

Fig. 2-16. Loaded West Valley cask with impact limiters and tie rods installed (Tyacke 2004).

Fig. 2-17. Two loaded West Valley casks parked inside INEEL secured area (Tyacke 2004).

2.2.13 SNF Shipments Reported at PATRAM 2007

At the time of PATRAM 2007, 532 SNF research reactor assemblies had been returned from Japan to the United States (Tamura 2007).

2.2.14 SNF Shipments Reported at PATRAM 2010

An update showed that 3,160 MTHM of SNF were shipped from Japanese NPPs to the Rokkasho reprocessing plant through 2009 (Saegusa 2010).

As of 2010, 61 SNF cask shipments had been made from the Caorso NPP in Italy to La Hague, amounting to 190 MTHM of BWR SNF (De Gasbarro 2010). The transfer of casks used from heavy-haul road to rail at the Caorso multimodal transfer point in Italy is shown in Figure 2.18.

Fig. 2-18. Transfer of rail cask from heavy-haul road vehicle to railcar at the Caorso Multimodal Transfer point in Italy (Di Gasbarro 2010).

On 29 June 2009, as part of the Russian Research Reactor Fuel Return (RRRFR) Program supported by the DOE National Nuclear Security Administration (NNSA) and the Global Threat Reduction Initiative (GTRI), 27.3 kg (0.027 MTHM) of 70 highly enriched uranium (HEU) SNF assemblies (enriched to 36.6 percent) were transported by air from Romania to Russia in a Type B(U) package (Bolshinsky 2010a). The shipments were made in 18 Russian TUK-19 casks aboard a Volga-Dnepr Airlines AN-124-100 commercial cargo aircraft. Figure 2.19 shows a TUK-19 cask, Fig. 2.20 shows three casks loaded into a cargo container for shipment, and Fig. 2.21 shows the AN-124-100 aircraft (Bolshinsky 2010b).

Fig. 2-19. Russian TUK-19 cask (Bolshinsky 2010b).

Fig. 2-20. Three TUK-19 casks loaded in a freight container prior to air transport (Bolshinsky 2010b).

Fig. 2-21. AN-124-100 aircraft used for transport of TUK-19 casks (Bolshinsky 2010b).

2.2.15 SNF Shipments Reported at PATRAM 2013

Through 2013, under the framework of the RRRFR, more than 50 shipping operations were completed, returning research reactor fuel to Russia from thirteen countries: Belarus, Bulgaria, Czech Republic, Hungary, Kazakhstan, Latvia, Libya, Poland, Romania, Serbia, Ukraine, Uzbekistan and Vietnam (Budu 2013). These shipments used 20 Russian TUK19 casks and 16 Czech Skoda VPVR/M casks. Some of these shipments were follow-on air shipments that were made based on the experience gained in the shipment of HEU SNF by air from Romania in June 2009. Seven additional air shipments of research reactor SNF had been completed by 2013 using the same cask/air transport system: one shipment from Libya in 2009, four shipments from Romania in 2012, and two shipments from Uzbekistan in 2012. However, the paper does not delineate the quantities of SNF transported in any of these shipments.

Related to the shipments described by Budu, et al. 2013, two shipments of SNF were made in the SKODA VPVR/M casks in 2007 and 2013 (Pdolaha 2013). The first shipment consisted of 576 SNF assemblies in 16 casks. The second shipment consisted of 112 SNF assemblies in six casks. The SKODA VPVR/M cask and its associated basket are shown in Fig. 2.22.

Fig. 2-22. SKODA VPVR/M cask and cask basket (Pdolaha 2013).

Pdolaha 2013 summarizes the SNF shipments completed between December 2007 and July 2013 as shown in Table 2-5. The table also shows that under the RRRFR, at least 100 cask shipments of research reactor SNF were made consisting of 3,432 SNF assemblies. These shipments used all modes of transport: air, highway, rail, and sea.

Moses 2013 states that approximately 2.2 MT of Russian-origin HEU fresh fuel and SNF were shipped in the following countries:

- 24 shipments of HEU fresh fuel from 13 countries: Serbia, Romania, Bulgaria, Libya, Latvia, Czech Republic, Uzbekistan, Poland, Germany, Vietnam, Hungary, Ukraine, and Belarus
- At least 25 shipments of HEU SNF from Uzbekistan, the Czech Republic, Latvia, Bulgaria, Hungary, Romania, Ukraine, Libya, Kazakhstan, Belarus, Serbia, and Poland, Vietnam

Table 2-5. Shipments of SNF completed under the RRRFR through July 2013 (Pdolaha 2013).

Country (Facility)	Shipment Date	No. of casks used	SNF Data	No. of shipped FA (basket cells)	Transport Route
Czech Republic 1	Dec 2007	16	HEU: IRT-2M LEU: IK-10	576	Road, rail
Bulgaria (IRT-2000)	Jul 2008	3	HEU: S-36 LEU: EK-10	108	Road, rail, river
Hungary 1 (BRR)	Oct 2008	16	HEU: VVR-M VVR-M2 LEU: EK-10	576	Road, rail, sea
Poland 1 (EWA)	Sept 2009	16	HEU: VVR-M2	864	Road, rail, sea
Poland 2 (EWA)	Feb 2010	8	HEU: VVR-M2		Road, rail
Ukraine 1 (VVR-M)	May 2010	7	HEU: VVR-M2	252	Road, rail
Belarus (PAMIR-630D, IRT-M	Oct 2010	4	HEU	144	Road, rail, sea
Serbia (RA)	Nov 2010	16	HEU: TVR-S	576	Road, rail, sea
Ukraine 2 (VVR-M)	Mar 2012	4	HEU: VVR-M2	98	Road, rail
Poland 6 (EWA)	Oct 2012	3	LEU: IK-10	90	Road, rail, sea
Czech Republic 2 (LVR-15)	Mar 2013	6	HEU: IRT-2M	112	Road, rail, sea
Vietnam (DNRR)	July 2013	1	HEU: VVR-M2	36	Road, air, rail

Table 2-5 does not include all of the countries listed by Moses. Specifically, shipments made as part of the RRRFR program from Uzbekistan, Latvia, Romania, Libya, Kazakhstan, and Belarus are not listed in the table.

In addition, Moses states

> *the USDOE Domestic and Foreign Fuel Return Programs completed shipments from thirty-nine (39) countries to return US origin fuel to either the Savannah River National Laboratory (South Carolina, USA) or the Idaho National Laboratory (Idaho Falls, Idaho). The countries include:*

- *Argentina, Australia, Bangladesh, Brazil, Canada, Chile, Columbia, Congo, Denmark, Germany, Ghana, Greece, Indonesia, Iran, Iraq, Italy, Jamaica, Japan, Mexico, Netherlands, Nigeria, Pakistan, Peru, Philippines, Portugal, Romania, Slovenia, South Africa, South Korea, Spain, Sweden, Switzerland, Syria, Taiwan, Thailand, Turkey, United Kingdom, Uruguay, and Venezuela.*

2.2.16 Additional data on SNF Shipments from non-PATRAM Sources

Treating Table 2-5 as the most nearly complete summary of available data on research reactor fuel transported under the RRRFR program as of July 2013, other non-PATRAM documents provide additional input to these and later shipments. On October 23, 2008, the World Nuclear News (WNN 2008) provided insights that 765 kg (0.77 MTHM) of HEU SNF had been removed to Russia at that time. Beyond the July 2013 date, the following documents provide further information regarding the RRRFR shipments:

- On April 5, 2013, the IAEA (Tozser 2013a) announced that 760 kr (0.76 MTHM) of HEU SNF had been removed in 11 shipments from the Czech Republic to Russia.
- On November 5, 2013, the IAEA (Tozser 2013b) announced that 203.7 MTHM of SNF had been successfully removed from Hungary to Russia.
- On September 29, 2015, the NNSA announced (NNSA 2015) that the final 5 kg (0.005 MTHM) of HEU SNF that existed in Uzbekistan had been successfully removed as part of the RRRFR. It is further noted that 2,200 kg (2.2 MTHM) of Russian-origin fuel had then been returned from 28 countries to Russia.

2.3 Rationalizing the Data from Section 2.2.

Sections 2.1 and 2.2 illustrate that a large body of SNF shipping data is available, beginning with papers presented at PATRAM 1983, with shipping data beginning as early as 1962 (Mummery 1983, Shuler 1989). Unfortunately, these individual submittals of data are incomplete and often inconsistent. Without careful consideration, the data could be misinterpreted because some of the data from the various sources can be duplicative. Thus, in attempting to rationalize the data from Sect. 2.2 to gain a comprehensive understanding of SNF shipments made in the US and worldwide, duplicate counts of inputs have been removed. It must also be noted that very few of the data sources cited in Sect. 2.2 provide all the data elements that would present an accurate and complete picture. Those elements are:

- time span of data provided (in many cases, both the start and end dates for the data were specified, but in some cases only the end date for the data was specified),
- shipment origins and destinations (in many cases, both the origins and destinations were specified, but in some cases only the origin or destination was specified and in a few cases only the country in which the shipments were made was specified), and most importantly,
- the number of cask shipments, number of fuel assemblies, and quantity of SNF in terms of MTHM. (In all but one case, only one or two of the three data elements are specified, where only one paper describing shipments involving Sweden [Gustafsson 1987] provides all three data elements).

Section 2.3.1. provides a rationalized view of the shipments made in the US of (1) NPP SNF, (2) industrial and academic research reactor SNF shipments made within the US under the regulatory purview of the NRC, and (3) SNF shipments of research reactor fuel brought into the US as part of the FRR SF program. In preparing this summary assessment, it was discovered that there are no sources of data providing a fully comprehensive view of NPP SNF shipments in the US to the present. The combination of the study reported at PATRAM 2001 (Pope 2001), along with NRC data from 1979–2007 (NRC 2010) provide the most comprehensive view for the US. The NRC 2010 report includes research reactor shipments within the US. Furthermore, few shipments of NPP SNF have occurred in the US in the last decade, so the rationalized summary for the US in Sect. 2.3.1. considers these important points.

Section 2.3.2. provides a rationalized view of the worldwide shipments of NPP SNF excluding those within the US. Unfortunately, there are no single data sources available that can provide a relatively comprehensive view of NPP SNF shipments throughout the world to the present. Indeed, the most recent attempt to produce such an assessment occurred at the end of the 1990s (Pope 2001). Section 2.3.2. builds on that data by considering other documents identified since that time.

Section 2.3.3. provides a summary view of worldwide research reactor SNF shipments except for those shipments entering the US under the FRR SF program, which are accounted for in Sect. 2.3.1.

Section 2.3.4. provides a summary view of the shipments of HLW that have been reported.

2.3.1 Rationalized SNF Shipping Data for the United States for NPPs and Research Reactors

Ten documents relating to specific shipments of NPP SNF were cited in Sect. 2.2. These shipments were for SNF assemblies transported between various NPPs and other facilities (e.g. Morris, Barnwell, the West Valley Demonstration Project, and the DOE facilities at SRS, Idaho, and Nevada). These documents are related to shipments made from 1964 through 1998, so it must be assumed that the data reported in 2001 (Pope 2001) plus the data from the NRC (NRC 2010) provide the most comprehensive view of shipments of NPP SNF in the US available at this time.

Table 2-4 provides the best estimate of shipments in the US that was available through 1997. These data include consideration of NUREG-0724, Rev. 13 (NRC 1998), which provided data on shipments of SNF from 1979 to 1997. This NUREG which was cited in the IAEA study of worldwide SNF shipments as published in 2001 (Pope 2001).

The NRC has issued updates to this NUREG twice since 1998. The latest version is NUREG-0725, Rev. 15 (NRC 2010). Chapter 3 of this NUREG document provides statistics for highway and railway shipments of SNF from 1979 to 2007:

> *descriptive statistics on the shipments that have occurred since the NRC began approving spent fuel shipments in 1979, through 2007. It includes only shipments of academic, industrial, and utility irradiated reactor fuel subject to NRC regulation. The NRC does not regulate DOE shipments; therefore, the statistics reported here do not include them.*

Because the NRC data are for both power reactor fuel and research reactor fuel and do not include data on the FRR SF program shipments, these latter data on research reactor shipments into the US have been compiled from sources cited in Section 2.2. Therefore, part of the DOE SNF shipments are included in this overview, but SNF shipments made by DOE and/or the US Navy (other than those identified as FRR SF program shipments) are not included. These FRRSF program shipment data are summarized in Table 2-6.

Schmidt notes that “NCS was involved in the management of the shipments from Europe, South America, Australia and Japan,” so there is the potential for duplication of some of the data in Table 2-6, specifically with the data for shipments from Italy (Gila 1998) and Japan (Tamura 2007). Thus, these data are discounted in the totals shown, but the total for number of fuel assemblies shipped is shown with a greater than symbol indicating that some of the Japanese data may apply.

Table 2-7 summarized the estimated shipments of SNF in the US, including (1) shipments of NPP SNF, (2) those shipments research reactor fuel for which NRC has regulatory authority, and (3) those shipments arriving in the US of research rector SNF resulting from the FRR SF program.

Shipments within the US and into the US containing NPP and research reactor SNF are estimated as follows:

- well in excess of 4,300 cask shipments (this number is assumed to be very low due to the scarcity of data as shown in Table 2-6 for this data element),
- much greater than 4,800 SNF assemblies shipped, and
- greater than 5,900 MTHM shipped.

Table 2-6. Summary of research reactor shipments of SNF performed under the FRR SF Program.

Time period	Origins	Destinations	Number of cask shipments	Number of fuel assemblies	MTHM	Reference
1977–1982	South Africa and Europe	SRS and Idaho	>175		>3,000	(Mangusi 1983)
1986–1989	Taiwan	US		1,574		(Cashwell 1989)
1997	Italy	SRS		76		(Gila 1998)
To 2001	Europe, South America, Australia, Japan	SRS and Idaho		1,602*		(Schmidt 2001)
To 2007	Japan	US		532		(Tamura 2007)
TOTALS			**>>175**	**>4,800**	**>3,000**	

* Includes 1,400 MTR assemblies and 202 TRIGA assemblies

Table 2-7. Estimated SNF shipments in the United States for NPP and research reactor SNF, 1964–2010.

Type of SNF	Time period	Origins	Destinations	Number of cask shipments	Number of fuel assemblies	MTHM
NPP	1964–1978	US NPPs	Various sites	1,691		821
NPP and research reactor	1979–2007	US research reactors	Various sites	2,470		2,093
Research reactor	1977–2007	Foreign facilities	SRS and Idaho	>175	>4,800	>3,000
TOTALS				**>4,300**	**>>4,800**	**>5,900**

2.3.2 Rationalized Worldwide SNF Shipping Data Excluding Data for the United States for NPPs

The data presented in Table 2-3 for this assessment of worldwide shipments of NPP SNF for the period to approximately the beginning of 2001 provide the starting point for rationalizing the worldwide shipment data. The summary values were reduced to discount the number for the US shipments and the shipments of HLW. Therefore, the following estimates of the number of cask shipments and quantity of SNF (in MTHM) shipped to approximately the beginning of 2001, except for those shipments undertaken in the US, are:

- ~21,000 to 40,000 cask shipments, and
- ~70,000 to 92,000 MTHM.

Additional international shipments, as determined using the references cited, are summarized in Table 2-8. These include shipments identified from individual documents that do not appear to be included in Table 2-3.

Table 2-8. Global assessment NPP SNF shipments (excluding shipments in the US).

Time period	Origins	Destinations	Number of cask shipments	Number of fuel assemblies	MTHM	Reference
1962–2000	Multiple countries	Multiple countries	~21,000–40,000		~70,000 to 92,000	Table 2-3
2003–2004	China	China	5	130		(Meinert 2004)
To 2010	Republic of Korea	Republic of Korea	78	312		(Lee 1998)
To 2010	Japan NPPs	Tokai and Rokkasho reprocessing plants	~150	~4,000	740–1,800	(Nagano 1992, Mori 2001, Kaneko 2004, Saegusa 2010)
2009–2010	Caorso NPP in Italy	La Hague		61	190	(De Gasbarro 2010)
1999–2000	Leibstadt NPP, Switzerland	Swilag facility, Switzerland		97		(Sicard 2001)
1985–1989	Ukraine and USSR NPPs	USSR reprocessing plants			>117	(Kondratyev 1989)
1973–2000	Europe and Japan	La Hague			>8,900	(Lenail 1983, Gouin 1989, Sicard 2001)
TOTALS			**~21,000 to 40,000**	**>>4,500**	**~80,000–103,000**	

Thus, the estimated number of cask shipments and quantity of SNF (in MTHM) shipped to the present time, except for those shipments undertaken in the US, are:

- ~21,000 to 40,000 cask shipments (in rounded numbers, the additional data in Table 2-8 did not change this estimate), and
- ~80,000 to 103,000 MTHM.

2.3.3 Summary of Shipments of Research Reactor SNF Other Than Those under the US FRR SF Program

Shipments of research reactor fuel have occurred between various countries other than into the US as part of various international agreements, including the RRRFR program.

Table 2-9 summarizes the data that have been identified relating to these types of shipments.

Table 2-9. Global Assessment of non-US Research Reactor SNF Shipments.

Time period	Origins	Destinations	Number of cask shipments	Number of fuel assemblies	MTHM	Reference
1971–1972	Canada	Belgium		~1,000		(Mangusi 1983)
2009	Romania	Russia	18	70	0.027	(Bolshinsky 2010)
2007–2013	Czech Republic	Russia		688	0.76	(Budu 2013, Pdohla 2013, Tozser 2013a)
2008–2013	Multiple countries	Russia	85	2,744	>204	(Pdohla 2013, Tozser 2013b)
2015	Uzbekistan	Russia			0.005	(NNSA 2015)
TOTALS			**>103**	**>4,500**	**>205**	

2.3.4 Summary of HLW Shipments

Approximately 2,350 canisters of vitrified HLW were shipped from the La Hague reprocessing plant to Belgium, Germany, Japan, and Switzerland (Nagakura 1998, Nambu 1998, Alter 2004, and Lancelot 2004). These canisters were shipped in at least 130 different cask shipments.

2.4 Summary of SNF and HLW Shipment Assessment

The preceding provides an overview summary of shipments of SNF and HLW made in the US and worldwide. The assessment, which made use of more than 50 references readily available in open literature, was undertaken to provide the best estimate possible of shipments of nuclear power plant SNF assemblies, research reactor SNF assemblies, and vitrified radioactive HLW.

However, it must be emphasized that because of the nature of the data and information available, the values presented are estimates. Data from different types of source material were in different formats and were sometimes incomplete in terms of the data elements desired, and there was the potential for double counting information. Thus, extensive effort was made to avoid such double counting while striving to provide estimates that establish lower bound values for shipment quantities.

Based on this assessment, it can be concluded that:

a) The number of cask shipments worldwide is well in excess of 25,400–44,400. It is likely that significantly more cask shipments have been made for all forms of SNF considered. The shipments within and into the US account for approximately 10 to 17 percent of this total.

b) Significantly more than 14,000 SNF assemblies have been shipped. This number is considered very low since the data sources most frequently did not provide the number of SNF assemblies shipped.

c) Also, the quantity of SNF shipped is well in excess of 87,000–109,000 MTHM. Again, many of the data sources did not report on the heavy metal quantities shipped. For the quantities reported here, the US accounts for only about 5–7 percent of the total (many of the shipments in the US have been in small, highway-transported casks).

In addition, the study identified that at least 130 cask shipments of vitrified HLW with more than 2,350 canisters of the HLW have been shipped from the reprocessing plant in France to the countries of the SNF's origin.

In reviewing all data sources, it is also emphasized that all of these shipments were undertaken without injury or loss of life due to the radioactive nature of the material transported.

3. PAST INCIDENTS IN TRANSPORTING SNF AND HLW

Shipments of SNF and HLW have occurred for more than 50 years. During this time, tens of thousands of tons of material have been transported in tens of thousands of shipments. The vast majority of these have been completed safely, with very few incidents worldwide. Indeed, there has been no transportation accident involving SNF or HLW in which a release of radioactive material has caused any significant negative effect to the public or the environment. This safety record has been made possible by establishing robust regulatory requirements for the casks used in transport, studying past shipments and incidents, and improving equipment and procedures to lessen the probability and impacts of future events. This section contains a compilation of transportation incidents involving SNF and HLW in the US and worldwide. Efforts have been made to compile a thorough list of incidents in transporting SNF and HLW; however, no claim is made that this list contains all such occurrences.

3.1 United States

In the US, data on transportation incidents involving radioactive material are collected by the US Department of Transportation (DOT) and the US Nuclear Regulatory Commission (NRC). Sandia National Laboratories (SNL) began maintaining the Radioactive Materials Incident Report (RMIR) database in 1981. RMIR includes transportation incidents involving radioactive material dating back to 1971 (McClure et al. 1997). Information was collected from DOT and NRC reports, state radiation control offices, DOE reports, and media reports. The RMIR database was maintained until 2004; the DOT continues to maintain a database of transportation incidents for hazardous materials, and the NRC maintains a database of incidents involving radioactive material not limited to transportation. Reporting requirements for the DOT and NRC ensure that RMIR has a complete record of notable incidents between 1971 and 2004. DOT requires reporting when a person has an injury requiring hospitalization or dies, when property damage of $50,000 or more results from the incident, when there is fire, leakage, or suspected contamination, or when there are other circumstances which the carrier believes should be reported to DOT. NRC requires reporting of any theft, loss, or release of radioactive materials, or instances of exposure to radiation.

NRC maintains the Nuclear Materials Events Database (NMED). Since the RMIR database records end in 2004, NMED records from 2005–2014 were investigated for any incidents since. No records were found involving SNF or HLW transportation. Prior to 1971, there is no official record of transportation incidents involving SNF.

The regulations on packaging and transportation of radioactive material given as 10 Code of Federal Regulations (CFR) Part 71 were published on July 22, 1966 (Hafner 2014). Prior to this, transport safety regulations for radioactive material transportation in the US were in place through initially the Bureau of Explosives, and later through the Atomic Energy Commission and DOT. Although some changes have been made over the years, packages certified under the early transport safety regulations and then under 10 CFR Part 71 have been designed with the goal of ensuring the safe transportation of SNF and HLW ever since.

Incidents involving the transportation of SNF and HLW in the US fall into two main categories: (1) transportation accidents and (2) instances of radioactive contamination on transportation casks used in SNF shipments.

3.1.1 Transportation Accidents

A paper presented at PATRAM in 1970 reported that 14 transportation accidents had occurred in AEC shipments in the US between 1949 and 1969 (Mc Cluggage 1971), although details were not provided in the report.

Between 1971 and 2004, four transportation accidents involving loaded SNF casks have occurred. All details are taken from RMIR (SNL 2005).

December 8, 1971: A truck carrying a loaded SNF cask veered off the road to avoid a head-on collision. The truck left the road, the driver was killed in the accident, and the cask was thrown clear of the trailer and into a ditch. The cask suffered damage to two bolts, the paint, and the thermal insulation but released no radioactive material. A report detailing the accident was prepared by Oak Ridge National Laboratory (Chandler 1972). The cask damage was repaired, and the cask was placed back into service January 12, 1972.

February 9, 1978: A trailer carrying spent mixed oxide fuel buckled under the weight of the cask; there was no damage to the cask and no release.

December 9, 1983: A truck carrying a loaded SNF cask was involved in an accident when the tractor separated from its intermediate axles but remained connected to the trailer; there was no damage to the cask.

March 24, 1987: A train carrying core debris from the Three Mile Island-2 reactor struck an automobile at a crossing. The driver of the automobile was injured and taken to a hospital, the locomotive suffered minor damage, the train was delayed 45 minutes, but the casks were not damaged and did not release any of the contents.

Since the RMIR was discontinued in 2004, one additional accident took place involving a loaded SNF cask:

October 25, 2007: The caboose and buffer car of a train carrying SNF derailed while moving at 4 or 5 mph at the Shearon Harris nuclear power plant in Wake County, North Carolina (WRAL, 2007)

Four additional transportation accidents occurred with empty SNF casks between 1971 and 2004. Details are taken from RMIR (SNL 2005).

March 29, 1974: A derailed tank railcar struck a flatcar carrying an empty SNF cask; the cask was not damaged, and the accident did not lead to contamination.

August 13, 1978: An empty SNF cask broke through a trailer bed while traveling; there was no injury or contamination. The overpack and base plate of the cask were damaged but the accident report does not mention whether any contamination occurred.

January 9, 1988: A rail track switch in the wrong position caused a set of wheels to derail while a railcar was being moved. An empty cask being transported by the railcar was not affected.

December 14, 1995: A railcar on a train carrying two empty SNF casks derailed; no damage or injuries resulted.

Since the discontinuation of RMIR, three additional accidents have taken place involving empty SNF casks.

September 22, 2005: A railcar carrying an empty SNF cask derailed and tipped over after it was hit by another railcar in a railyard in a low speed collision (WBFO 2005). The railcar was righted after approximately 36 hours.

August 29, 2008: A trailer carrying a new empty SNF transportation cask came to a stop to avoid leaving the road in California en route to the Humboldt Bay shutdown nuclear power plant. There were no injuries. The road was blocked more than 24 hours while the cask was recovered and the trailer was removed from the road (Walters 2008).

May 6, 2014: A truck and a train carrying an empty SNF cask collided at a grade crossing. There were no injuries, but the truck, which was carrying a cargo of pineapples, became stuck on the tracks and was damaged (Guerra 2014).

The fact that no radioactive material was released from a cask that was thrown from its vehicle in an accident so severe that the driver was killed is a testament to the safety of the packages used to transport

SNF and HLW. The safe performance of packages in accidents has been a crucial part of the safety record in transporting this material.

3.1.2 Radioactive Contamination

Most incidents involving the transportation of SNF in the US have been instances of cask surface contamination. RMIR contains some details about 53 of these events. Table 3-1 presents a list of incidents involving excess surface contamination on loaded or empty casks or transportation equipment (e.g., shipping pallet, lifting yoke, trailer), along with the contamination measurements when provided in the incident report listed in RMIR (SNL 2005). The regulatory limit for non-fixed radioactive contamination on the surface of a package is defined in 49 CFR Part 173.443(a) as 4 Bq/cm^2 for beta and gamma emitters and low-toxicity alpha emitters, and 0.4 Bq/cm^2 for alpha emitters not considered to be low-toxicity. The international transport safety standards published by the IAEA specify the same limits for non-fixed contamination on a package (IAEA 2012). Some instances of surface contamination had readings within regulatory limits; the reason these were included in RMIR is not clear. However, they are included in this report for the sake of completeness, as events in which radioactive contamination is suspected require reporting to the DOT and thus inclusion in RMIR.

The phenomenon of casks failing to meet contamination limits upon arrival at their destinations when they had met regulations prior to the shipment is often referred to as “weeping.” Cask weeping occurs after a cask has been placed in a contaminated environment such as a spent fuel pool and becomes contaminated with what initially is determined to be fixed contamination but with time and exposure to transport and environmental conditions, the contamination becomes non-fixed. A common contaminant is the fission product ^{137}Cs, which can adhere and become fixed (adsorbed) in the cask surface. Exposure to moisture, rain, or humidity during transport can cause the contamination to become non-fixed to the cask so that a cask which complied with non-fixed contamination regulations at the beginning of transit may fail upon arrival (IAEA 2005). A provision in 49 CFR 173.443(b) allows for the non-fixed contamination levels to comply with regulations as long as that contamination is within the levels given in 49 CFR 173.443(a) at the beginning of the shipment and is not over 10 times greater than those limits by the time the cask reaches its destination.

It should be noted that in all of these contamination incidents, contamination was confined to the cask or transportation equipment, and it did not spread past the vehicle to the public or to the environment. From 1979 to 2007, 1,553 SNF shipments subject to NRC regulation were made in the US, not including DOE shipments not subject to NRC regulation (Garrett et. al. 2010). Table 3-1 lists 31 incidents included in RMIR (SNL 2005) between 1979 and 2007 involving loaded or empty SNF casks. Based on this information, surface contamination of the cask was an issue in no more than 1% of shipments (assuming that there were at least as many shipments of empty casks as loaded casks) during this time period.

Table 3-1. Dates of instances of non-fixed radioactive contamination on SNF packages in the US [RMIR (SNL 2005)].

Date of surface contamination incident	Contamination (if given) (Bq/cm^2)
01/24/74	*
02/26/74	*
04/29/74	*
12/11/74	*
12/23/74	*
01/13/75	*
02/27/77	1.83

Table 3-1. Dates of instances of non-fixed radioactive contamination on SNF packages in the US [RMIR (SNL 2005)] (cont.).

04/13/77	7.03
05/03/77	14.72
05/12/77	24.05
05/16/77	0.27
07/26/77	5.3
08/03/77	9.9
08/23/77	7.83
02/16/78	10.53
02/27/78	7.00
05/16/78	6.38
07/24/78	8.34
07/29/78	17.00
08/01/78	9.67
08/07/78	19.82
11/27/78	*
03/28/79	27.87
04/02/79	3.85
04/02/79	13.00
04/03/79	17.50
04/04/79	4.29
04/05/79	4.04
07/23/80	3.83
08/25/80	6.50
02/02/81	*
05/30/81**	80.0
05/31/81**	*
06/02/81**	50.0
06/02/81**	133.33
08/25/83	4.67
09/30/83	*
10/21/83	9.35
01/07/84	*
01/25/84	32.52
02/24/84	4.05
01/11/85	16.67
02/03/85	*
07/08/85	10.00
02/28/86	*
07/29/86	111.167

Table 3-1. Dates of instances of non-fixed radioactive contamination on SNF packages in the US [RMIR (SNL 2005)] (cont.).

07/29/86	*
08/19/86	*
10/15/91	16.67
11/22/91	14.67
08/14/92	16.67
06/14/93	4.77
07/19/93	4.33

*Contamination measurement not available.
**These shipments used the same cask; the NRC suspended shipments with this cask following these instances of contamination.

In order to reduce the time needed to decontaminate casks, and in an effort to reduce personnel radiation exposure and prevent instances of surface contamination exceeding regulatory limits, the Electric Power Research Institute (EPRI) performed a study on factors affecting cask surface contamination. EPRI found that certain cask finishes such as machined or electropolished surfaces could lead to a reduced number of instances of contamination and could also reduce the amount of time required for decontamination. Protective coatings and cleaning agents were also studied. The results were summarized in a report (EPRI 1985).

Since 1971, radioactive contamination has occurred twice beyond the cask, but neither event was caused by external surface contamination. Details are taken from RMIR (SNL 2005).

> July 4, 1976: A pinhole leak in the outside jacket of an SNF cask was discovered while in transit by road. That leak allowed the loss of liquid, but it was reported that the liquid was not contaminated. The report estimated the activity of the SNF in the cask was 50,000 Ci. The shipment was allowed to proceed once it was determined that it posed no risk to the public.
>
> January 27, 1984: An empty cask produced a slow drip while in storage. The amount released was given as 0.001 μCi in the report.

3.2 International

The list of transportation incidents that occurred outside the US is not exhaustive, but efforts were made to locate as many incidents as possible.

3.2.1 Canada

Although Canada plans to transport SNF and HLW in a future campaign for its disposition in a repository yet to be sited, Canada does not have much past history with transporting SNF. Limited quantities are shipped infrequently (fewer than 10 shipments annually are typical) and have been completed safely and securely by road (Stahmer 2009).

3.2.2 Japan

Since NPPs in Japan do not have direct rail access, and all are located along the coastline, SNF shipments are made over water by vessel. Successful shipments of SNF have been made to Europe for reprocessing since 1969, and vitrified HLW has been shipped to Japan from Europe since 1995 (Pacific Nuclear Transport Limited [PNTL] 2012). All shipments have been made without release of radioactive material.

3.2.3 Russia

The authors were unable to identify any publicly available official reports on transportation incidents or accidents in Russia involving SNF or HLW. However, a report of a fire on a storage barge for SNF based at Primorye in 1999 was found. According to the report, the barge was damaged, but none of the SNF it was storing was affected (Kudrik 1999).

3.2.4 United Kingdom

In the United Kingdom (UK), Public Health England's Centre for Radiation, Chemicals and Environmental Hazards maintains the Radioactive Material Transport Event Database (RAMTED), which contains information on transportation accidents and incidents involving radioactive material dating back to 1958. Incidents are included in RAMTED when they involve (1) a road accident severe enough to cause a fire, turn the vehicle on its side, or damage the package; (2) for rail, an instance where the rail axles or brakes overheat and smoke, causing the train to stop; or (3) when an SNF cask (referred to as an "irradiated nuclear fuel flask" in the UK) is reported to have surface contamination exceeding regulatory limits (Hughes et al. 2006).

In 2006, a summary report was written reviewing 806 events and their consequences for the period 1958–2004 (Hughes et al. 2006). Annual reports have been written each year since, with the most recent report published describing incidents in 2012. From 1958 to 2004, 187 events involving SNF casks were recorded in RAMTED, with the most frequent type of incident (33%) being related to surface contamination of the cask. Three instances of fire on the locomotive were reported, but the cask was not affected in any of these cases. During this time period, the only incident involving SNF transportation in which any dose was received was in 1996, when a contaminated spacer from an SNF cask was accidentally carried into the cab by a driver and left for several hours. No member of the public received any dose from this, and the whole-body dose to the driver was assessed at 0.0065 mSv. Although this report enumerates 257 incidents involving Type B packages and their consequences—notably that 27 packages suffered damage although there was no increase in dose rate or loss of containment in any of these incidents—it is not specified which of these incidents involved SNF casks and which involved Type B packages containing other materials. For proper context on the scale of SNF and HLW transportation in the UK, a 2001 paper (Pope et al. 2001) reported that over the 30–35 years before the paper's publication, approximately 13,820 cask loads of SNF had been transported to the Sellafield site from within the UK, power plants in Europe, and power plants in Japan.

From 2005 to 2012, additional details have been published about the specific incidents involving SNF transportation in annual reports. These incidents are listed here with a brief description; additional information may be found in the references.

July 2005: A person climbed onto a moving train transporting an empty SNF cask; the cask was not affected (Hesketh et al. 2007).

October 2005: Brakes failed on railcars carrying SNF casks as they were parked overnight; the casks were not affected (Hesketh et al. 2007).

October 2005: Surface contamination was found on a railcar; radiological consequences were determined to be negligible (Hesketh et al. 2007).

May 2006: A train carrying an empty SNF cask collided with a car at a grade crossing; the cask was not affected (Hughes and Harvey 2007).

October 2006: Smoke from the locomotive of a train carrying an SNF cask set off a smoke detector and the train was stopped; the cask was not affected (Hughes and Harvey 2007).

May 2007: An empty SNF cask was found to have surface contamination above regulatory limits upon arriving at a power plant (the origin and destination were not published in the report); the dose consequences were determined to be trivial (Harvey and Hughes 2009).

December 2007: Some SNF casks may have been operated with incorrect components; shipments were suspended by the affected company until March 2008, when an investigation was completed and corrective action was taken (Harvey 2009).

January 2008: Following the prior incident, SNF cask shipments were voluntarily suspended by another company pending an investigation to ensure the correct lid bolts were being used (Harvey 2009).

April 2008: SNF cask shipments were temporarily suspended (after resuming in March as noted above) following an inspection of a cask not using the specified valves (Harvey 2009).

June 2008: Related to the events in December 2007 and April 2008, the company determined that it had used an obsolete design specification for the previous procurement, leading to the improper specification being used for valves and washers (Harvey 2009).

July 2008: An SNF cask was found to have surface contamination on the lid above the regulatory limit eight days after cask receipt (Harvey 2009).

August 2008: An SNF cask was found to have surface contamination on the lid above regulatory limits (Harvey 2009).

September 2008: During a routine inspection of two SNF casks leaving a nuclear site, two screws on a water level valve assembly were loose on one of the casks (Harvey 2009).

October 2008: Related to the January 2008 incident, shipments from a nuclear company to a fuel handling plant were suspended after deficiencies were found in the company’s procedures: the company was unable to demonstrate that spare components on SNF casks complied with specifications; operations were affected at two power plants, but no exposures resulted (Harvey 2009).

January 2009: An SNF cask was found on arrival at a power plant to have one bolt on the lid out of 16 loose; in response, lid tightening procedures were reviewed and updated at all nuclear sites (Harvey 2010).

February 2009: Six SNF casks were found to have noncompliant lid seal member bolts during cask checks; this was found to be due to an error when purchasing spare parts (Harvey 2010).

March 2009: An SNF cask was found on arrival at a nuclear site to have one bolt out of 28 not tightened sufficiently; shipments from the power plant which had sent the cask were suspended until an investigation was completed (Harvey 2010).

March 2009: An SNF cask was found to be noncompliant during routine maintenance due to the seal weld related to the cask valve being incorrectly tested (Harvey 2010).

April 2009: During processing of an SNF cask, the blanking plugs for the water valves and the lid chock locking bolts were found to be only hand tight; faulty packaging procedures at the consignor site were found to be the problem (Harvey 2010).

June 2009: An SNF cask was found to be missing the four washers for the four water level valve retaining bolts, and it was also found that that these washers had been missing for three shipments and the cask had passed the leak test seven times; washers were refitted before further shipments were made with the cask (Harvey 2010).

September 2009: An SNF cask was tilted during loading onto a flatrol (railcar) at a power plant, causing the crane to stop; there was no evidence of damage to the cask (Harvey 2010).

October 2009: On arrival at a reprocessing facility from a power plant, an SNF cask was found to have one lid bolt not adequately tightened; shipments from that power plant were suspended pending an investigation (Harvey 2010).

February 2010: An SNF cask transported from a power plant to a nuclear site was found to be missing a lid valve bolt on arrival; the lid had been otherwise properly closed (Harvey and Jones 2011).

March 2010: A shipment of HLW from the UK to an unspecified foreign country was found to be out of position with the holding channels of the transportation cask; this was believed to be due to an anomaly in the loading instructions (Harvey and Jones 2011).

March 2010: A pin hole leak due to a weld defect was found on an SNF cask, not related to the cask body; the entire cask fleet was investigated for other defects (Harvey and Jones 2011).

April 2010: An SNF cask outer lid seal was found to be dislocated from the seal groove upon arrival at a nuclear facility; the seal was within tolerance (Harvey and Jones 2011).

May 2010: A cask was received at a power plant with a screw tightened to the incorrect torque (Harvey and Jones 2011).

May 2010: A cask was found to have two brass plugs missing from the lid valve at a nuclear site; the plugs have no safety significance (Harvey and Jones 2011).

May 2010: An empty SNF cask was received at a power plant with a water level valve clamp fitted in the wrong direction; the functionality remained the same, although not within operating manual specification (Harvey and Jones 2011).

June 2010: Upon inspection, stains from liquid contamination were found on a weld on the radioactive warning label plate of an SNF cask (Harvey and Jones 2011).

August 2010: Similar to an incident in May, an SNF cask was received at a power plant with the water level valve clamp fitted in the incorrect direction (Harvey and Jones 2011).

February 2011: An SNF cask arrived at a power plant with two lid-chock locking bolts looser than recommended (Harvey and Jones 2012).

June 2011: A defect was found in a valve seal for an SNF cask during manufacture; the cask owner investigated to determine if the defect was confined to the individual case (Harvey and Jones 2012).

July 2011: Shipments were suspended until cask integrity could be assured; concerns had been raised over the thickness and diameter of steel cover plates (Harvey and Jones 2012).

August 2011: An SNF cask was received with a faulty valve seal; the seal was not related to containment (Harvey and Jones 2012).

August 2011: An SNF cask was received from a power plant with one of the lid bolts not adequately torqued; further checks were recommended to ascertain the presence of excess anti-seize compound that may have caused the bolt to become loose (Harvey and Jones 2012).

September 2011: An HLW shipment of three casks from the UK to its country of origin (unspecified) was found to have an under-tightened bolt keeping the trunnion cap on one out of the three packages; the shipment continued once it was tightened properly (Harvey and Jones 2012).

October 2011: Upon receipt in an unnamed foreign country, 5 of 28 containers of HLW were found to have surface contamination levels in excess of that country’s regulatory requirements; two were rechecked and cleared, while the other three required decontamination (Harvey and Jones 2012).

November 2011: At a power plant, an SNF cask was found to have a defect in a weld on the cover plate; it was sent to a facility for further investigation and repair, although no leak was identified (Harvey and Jones 2012).

November 2011: An SNF cask received at a nuclear facility was found to be missing the water level valve, and padlocks of the cover plate of the purge valve were not locked; however, as the railcar carrying the cask was padlocked, there was little safety implication (Harvey and Jones 2012).

November 2011: One of 16 lid chock locking bolts was found loose on an SNF cask at receipt; this caused negligible risk (Harvey and Jones 2012).

December 2011: A train carrying SNF casks hit part of a tree on the railway line; the locomotive was exchanged at the next stop, there was no derailment, and the casks were not affected (Harvey and Jones 2012).

January 2012: An SNF cask was received from a power plant with a lid-chock locking bolt loose (Jones and Harvey 2014).

Reports for transportation incidents in the UK since 2012 are not yet available. Many of those detailed above from 2005–2012 may seem insignificant, but they are included to show common incidents involving SNF transportation in the UK. Most of the incidents in recent years are due to bolts being inadequately tightened and some casks being shipped with excess surface contamination. Instances of the replacement parts for casks not meeting specifications also contributed to the list of incidents. It appears that most of the incidents reported were the result of human error, where workers involved in prepared casks for shipment did not follow prescribed procedures. There were few actual transportation accidents, and none of those led to cask damage or release of radioactive material. Lessons which can be learned from experience in the UK would be to ensure adequate cask decontamination and adhere strictly to procedures for all loading operations and replacement parts procurement.

3.2.5 Continental Europe

More SNF and HLW has been shipped within and to France than any other country in continental Europe. In 2001, it was estimated that 5,760 casks of SNF originating from LWRs in France, the rest of continental Europe, and Japan had been transported to La Hague facility for reprocessing (Pope et al. 2001). According to the same 2001 reference document, SNF has been shipped in Belgium, the Czech Republic, Finland, Germany, Hungary, Italy, the Netherlands, the Russian Federation, Slovakia, Spain, Sweden, and Ukraine. The paper does not include information about transportation incidents except to state that all shipments before 2001 within and from Italy had taken place without accident.

Incidents surrounding the transportation of SNF and HLW in continental Europe may be categorized as transportation accidents, radioactive contamination, or protests surrounding shipments.

3.2.5.1 Transportation Accidents

There have been several accidents involving SNF casks in continental Europe. The Institut de radioprotection et de sûreté nucléaire (IRSN, or the French Institute of Radiation Protection and Nuclear Safety), a public reference organization in France, published a fact book (IRSN 2010) listing three accidents:

June 1987: An SNF cask was superficially damaged but did not release any material when the trailer carrying it swerved into a ditch near Lailly-en-Val, France. The cask was recovered after approximately 30 hours, as it was stuck in the soil near the trailer.

November 1991: An SNF cask was dropped onto a docked ship when the hoisting equipment holding it broke; the cask suffered superficial damage, and there were no radiological consequences.

February 1997: A convoy of three railcars transporting SNF casks to Germany derailed in a rail yard; the track and axles of one railcar were damaged, but the casks were not affected.

Further details about the February 1997 derailment were included in a paper by Rancillac and Sert (1999), which noted that the derailment was caused by a rail breaking while the train was traveling at

28 km/h (17 mph). One of the railcars tipped during the accident, but after 36 hours, the shipment was able to continue once it was determined that it could proceed safely.

At least two additional transportation accidents have taken place since that publication was released:

July 12, 2013: A train derailment occurred near Bessines sur Gartempe, France. The railcars came to a stop after traveling 100 yards; the cause of the derailment was a track problem. It was unclear if the train was carrying SNF at the time (Nuclear Street 2013).

December 23, 2013: A railcar left the track while carrying an SNF cask while travelling at less than 20 km/h (12 mph). Radiological surveys confirmed that the cask continued to conform to regulatory limits for radiation dose rates and contamination. However, a point on the railcar was found to have radiological contamination. The railcar was subsequently decontaminated, and another railcar was used to complete the shipment. In post-accident analysis, the railcar was not found to be deficient in design, manufacturing, or maintenance. The reasons for the derailment were unclear at the time the report was written. While this accident did not have significant consequences since the railcar did not overturn and no damage was done to the SNF cask, the railyard where it occurred is surrounded by a densely populated residential area, with an estimated 250,000 people living within 2.5 km (1.5 mi) of the location. For this reason, the rail accident received broad media coverage at the time (IRSN 2014).

3.2.5.2 Radioactive Contamination

In May 1998, SNF shipments were suspended for six months in France following the Directorate for the Safety of Nuclear Facilities (DSIN) becoming the Competent Authority for SNF shipments in France. It was known in the industry and by authorities that SNF shipments received at the Valognes railway terminal in France (the arrival point for SNF from France and other continental European countries being sent to La Hague facility for reprocessing by the Compagnie Général des Matières Nucléaires [COGEMA]) that from 1988 to 1998, around 20% of the arriving SNF casks and vehicles had levels of surface contamination in excess of the 4 Bq/cm^2 regulatory limit. SNF shipments were suspended at the same time in Belgium, Germany, Switzerland, and the Netherlands until surface contamination issues could be addressed (Brachet 2000).

Upon investigation, it was determined that there was no health-related radiological consequence of the contamination on the shipments (Common Report 1999). Furthermore, the contamination was due to a combination of poor quality control procedures on the part of the shippers and inadequate controls and enforcement on the part of the regulators (Price 2000).

Detailed information on instances of cask contamination are contained in a report (Common Report 1999) written by the competent authorities of France, Germany, Switzerland, and the UK. Tables 3-2 and 3-3 and Figures 3-1 and 3-2 illustrate the extent of the contamination issue and are taken directly from the referenced report. Table 3-2 quantifies the extent of surface contamination on SNF casks and vehicles from NPPs in France to the Valognes rail terminal from which they are sent onward to the reprocessing plant at La Hague. Table 3-3 contains information on the number of shipments and levels of contamination on casks and vehicles received at Valognes from continental European countries outside of France. Figure 3-1 displays statistics on the frequency of instances of radioactive contamination on empty SNF casks (“flasks”) and vehicles (“wagons”) from the COGEMA terminal at Valognes and also from British Nuclear Fuels Limited (BNFL) in the UK. Figure 3-2 displays statistics on the frequency of radioactive contamination on loaded shipments arriving at the COGEMA terminal at Valognes and also those arriving at BNFL.

Table 3-2. Instances of contamination on SNF shipments received at Valognes from nuclear power plants within France (Common Report 1999).

Year	No. of flasks arriving Valognes	Number of contaminated flasks Assessment expressed as an average of contaminated points			
		Total	4-50 Bq.cm⁻²	50-150 Bq.cm⁻²	>150 Bq.cm⁻²
1998	68	12	9	2	1
1997	207	55	51	4	0
1996	198	54	46	7	1
1995	153	48	34	13	1
1994	183	31	24	6	1
1993	179	45	30	11	4
1992	132	53	44	8	1
1991	98	14	9	4	1
1990	137	29	25	3	1
1989	143	28	15	13	0
1988	120	15	6	3	6
Year	**No of flasks arriving Valognes**	**Number of contaminated wagons and trailers Assessment expressed as an average of contaminated points**			
		Total	**4-50 Bq.cm⁻²**	**50-300 Bq.cm⁻²**	**>300 Bq.cm⁻²**
1998	68	1	0	0	1
1997	207	43	10	22	11
1996	198	44	15	15	14
1995	153	44	11	27	6
1994	183	24	3	10	11
1993	179	19	1	13	5
1992	132	29	6	19	4
1991	98	13	1	8	4
1990	137	24	3	15	6
1989	143	20	1	5	14
1988	120	17	2	5	10

Table 3-3. Instances of contamination on SNF shipments received at Valognes from nuclear power plants in continental Europe outside of France (Common Report 1999).

Year	No. of flasks arriving Valognes	Number of contaminated flasks Assessment expressed as an average of contaminated points			
		Total	4-50 Bq.cm⁻²	50-300 Bq.cm⁻²	>300 Bq.cm⁻²
1998	19	2	2	0	0
1997	70	5	5	0	0
1996	92	4	4	0	0
1995	85	4	2	0	2
1994	103	4	1	3	0
1993	108	5	4	1	0
1992	102	9	4	2	3
1991	113	9	6	2	1
1990	101	8	3	4	1
1989	134	16	7	7	2
1988	104	11	7	1	3

Table 3 3. Instances of contamination on SNF shipments received at Valognes from nuclear power plants in continental Europe outside of France (Common Report 1999) (cont.).

Year	No. of flasks arriving Valognes	Number of contaminated wagons and trailers Assessment expressed as an average of contaminated points			
		Total	4-50 Bq.cm^{-2}	50-300 Bq.cm^{-2}	>300 Bq.cm^{-2}
1998	19	3	0	0	3
1997	70	15	0	8	7
1996	92	8	1	3	4
1995	85	12	2	3	7
1994	103	10	0	6	4
1993	108	10	1	3	6
1992	102	20	3	10	7
1991	113	6	0	4	2
1990	101	14	0	4	10
1989	134	12	0	4	8
1988	104	10	0	1	9

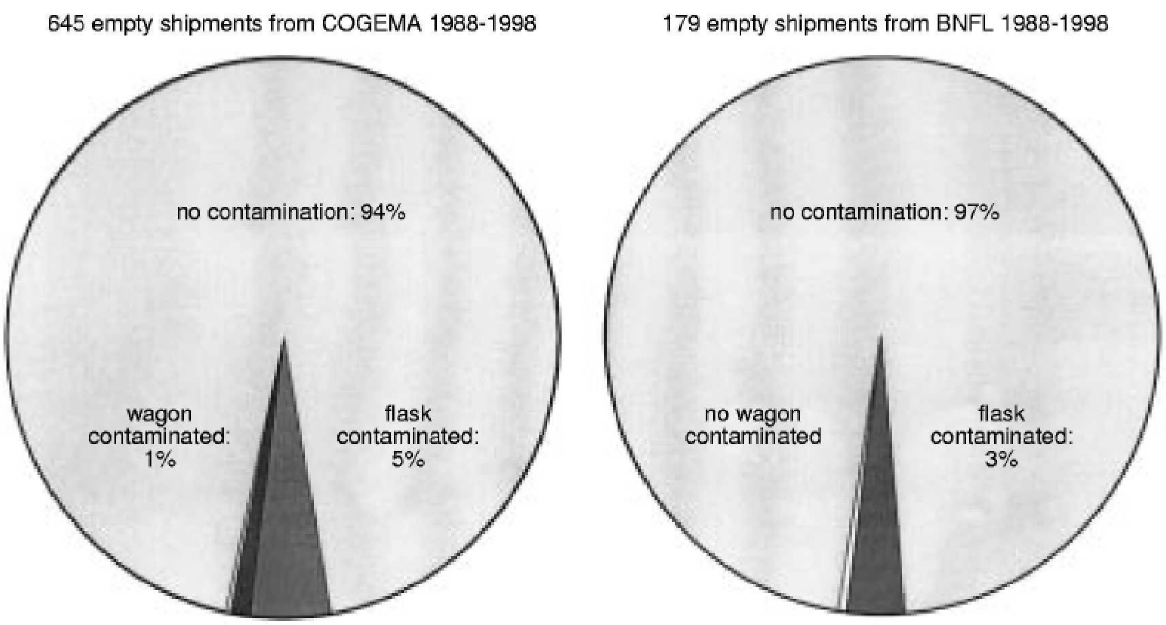

Fig. 3-1. Frequency of contamination instances on empty SNF cask shipments from Valognes and BNFL (Common Report 1999).

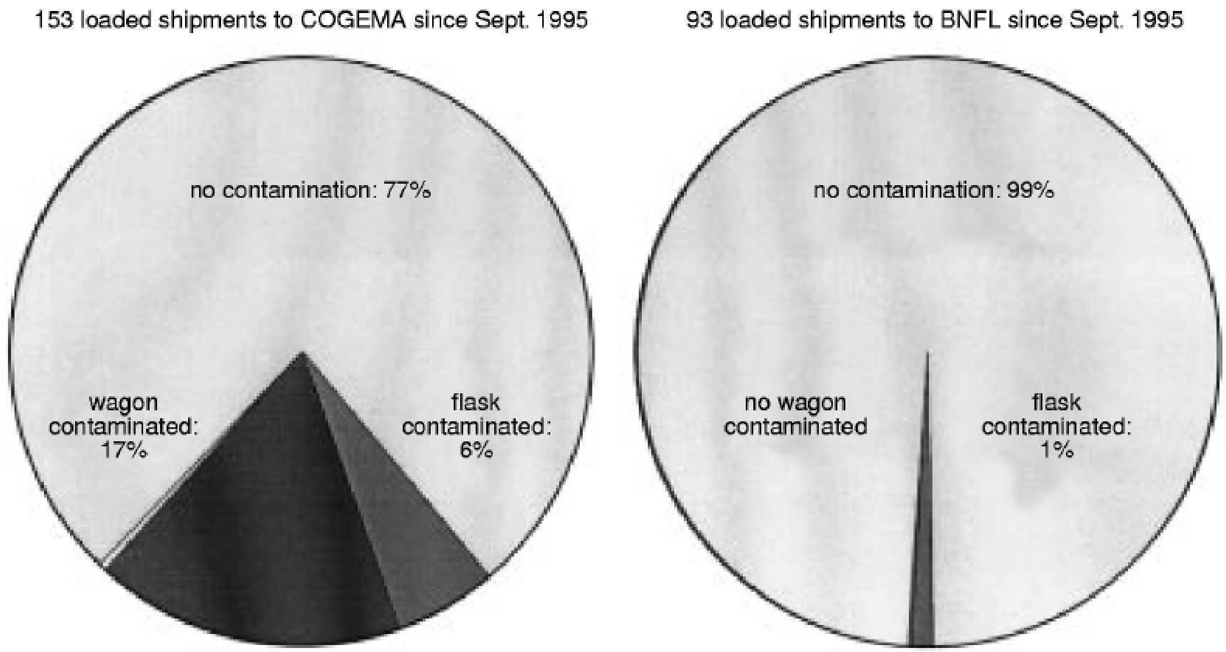

Fig. 3-2. Frequency of contamination instances on loaded SNF cask shipments to Valognes and BNFL (Common Report 1999).

Shipments were allowed to continue once tighter controls and increased monitoring were established. Instances of contamination were greatly reduced; however, incidents did continue, as seen in Table 3-4 (from Pertuis 2000). Shipments from the Bugey and Saint Alban power plants, which had the highest levels of contamination, were suspended until (1) the operator could determine the reason that contamination at higher levels was still occurring at these two plants and not the others, and (2) corrective actions could be taken. More details are included in Pertuis (2000), which concluded that improved procedures at facilities and increased monitoring by the regulator is leading to reductions in the frequency and magnitude of radioactive contamination on shipments.

Table 3-4. Frequency of contamination instances on loaded SNF cask shipments to Valognes and BNFL (Pertuis 2000).

Arrival date at Valognes	Sender (nuclear power plant)	Type of Protection	Location of contamination points	Max. value measured ($Bq.cm^{-2}$)
16/07/1998	Flamanville	Cover	Cask	15
18/09/1998	Belleville	(in air)	Cask	31
			Wagon	74
26/10/1998	Gravelines	Cover	Cask	11
27/10/1998	Penly	(in air)	Cask	26
26/11/1998	Bugey	Adhesive film	Cask	9
10/12/1998	Saint Alban	Adhesive film	Wagon (drip tray)*	716
18/12/1998	Bugey	Adhesive film	Wagon	33
31/12/1998	Saint Alban	Adhesive film	Wagon (drip tray)	592
15/02/1999	Tricastin	Peelable paint	Wagon (bodywork)	9.4
23/02/1999	Bugey	Adhesive film	Wagon (water retention collector)	1036

An additional reference presents instances of surface contamination on casks being shipped to COGEMA and BNFL from the power plant Gemeinschaftskernkraftwerk Neckar (GKN) in Germany (Bentele and

Kinzelmann 1999). The number of shipments on which contamination was detected from 1978–1998 is presented in Table 3-5, which originally appeared in the Bentele and Kinzelmann (1999).

Table 3-5. Instances of contamination on casks leaving the GKN plant in Germany (Bentele and Kinzelmann 1999).

			Excessive contamination			
			Arrival GKN		**Arrival reprocessing plant**	
Year	**Destination**	**Number of casks**	**Casks**	**Vehicles**	**Casks**	**Vehicles**
1978-98	Cogema	147	21	2		
	BNFL	9	2	0		
	WAK	18	0	1		
	Total abs.	174	23	3		
	Total rel.		13.2%	1.7%		
1984-98	Cogema	93			31	
	BNFL	9			0	
	WAK	17			2	
	Total abs.	119			33	
	Total rel.				27.7%	
1984-98	Cogema	92				19
	BNFL	9				0
	Total abs.	101				19
	Total rel.					18.8%

In response to the incidents involving excess contamination on SNF casks in Europe, research was conducted into best practices, and papers such as James and Gwyther (2000) were published. While earlier papers (e.g., Blackburn and Brown 1991) addressed contamination control practices such as using metallic skirts around the casks to avoid contact with water contaminated with fission products and crud in the spent fuel pool, James and Gwyther analyzed other factors in contamination control and made recommendations such as maintaining the integrity of a high-quality paint system on casks to prevent contamination, reducing the amount of time casks spends in the spent fuel pool, reducing the amount of time between immersion in the pool and initiation of decontamination procedures, and keeping the paint clean and dry at all times possible. It will be important to review current best practices information from international sources before the SNF and HLW shipments planned by NFST commence.

3.2.5.3 Protests surrounding shipments

The most recent incidents surrounding SNF and HLW shipments have also been the most disruptive. Shipments of HLW from the facility in La Hague, France, to Germany have been the scene of large-scale protests, beginning with a small local protest in 1979 (Bellona 2010). Larger protests delayed shipments in 1997, 2006, 2008, 2010, and 2011. A news article from 2010 describes that year's protest as the largest and longest antinuclear protest in a series, with estimates ranging from 25,000 to 50,000 participants. Due to the protests, which included both German and international activists blocking the rails on which the shipment was to be made, the transport costs increased by an estimated €25 million (nearly $30 million) (Bellona 2010). The 2011 protests were larger than those of the previous year and were more destructive; thousands of protesters and 20,000 police clashed at times over the course of the shipments, with protestors throwing stones and firecrackers and burning barricades, and police responding with batons and water cannons (Spiegel 2011). Over 200 people were injured, including approximately 160 protestors and 51 security officials. In order to delay the HLW shipment, protestors chained themselves to the rail tracks or to a 600 kg (1,323 lb) concrete block they had built on the rails, and some built and lit a barricade of car tires on fire.

More recently, in 2013, a shipment of HLW was delayed and/or re-routed in the Champagne-Ardenne region of France. A French-language new report contains details (Gonzalez 2013).

The fact that SNF and HLW transportation has been the scene of nonviolent and violent protests which have led to delays, cost increases, and injuries, serves to illustrate the importance of sound institutional planning of future NFST-related shipments. Radioactive contamination on casks can be minimized by following best practices, and radiological consequences can be prevented even in severe transportation accidents by robust cask design, but there is no purely technical solution to the protest issue.

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4. A LOOK AT A PAST TRANSPORTATION ACCIDENT

On December 8, 1971, a truck carrying one SNF assembly was involved in an accident outside of Clinton, Tennessee, while on its way to ORNL. This was the most severe SNF transportation accident in US history. The driver of the truck was killed due to the physical trauma of the accident; his death was unrelated to the radioactive cargo. There was no damage to the SNF, and there were no radiological consequences. This section summarizes a report written shortly after the accident (Chandler 1972). All historical information in this section is taken from that reference unless otherwise noted.

The Hallam cask used during the shipment was originally designed and built to transport material from the Hallam nuclear reactor in Nebraska. It was licensed by the US Atomic Energy Commission (AEC) after it was demonstrated to be in compliance with 10 CFR 71. Subsequently, DOT issued a special permit for the cask, and ORNL was registered as a permitted shipper of the cask.

The cask was similar in size to current legal weight truck casks in operation. A size comparison with the currently most widely used truck cask in the US, the NAC-LWT, is provided in Table 4-1.

Table 4-1. Comparison of Hallam cask with NAC-LWT cask.

	Hallam cask	NAC-LWT
Length	~241.5 in.	199.8 in.
Outer diameter	24 in.	44.2 in.
Cavity length	204 in.	180.9 in.
Cavity diameter	5.5 in.	13.375 in.
Weight (empty)	~23 tons	24.0 tons

4.1 The Accident

During transportation, the cask would rest in a structural steel shipping cradle assembly or *skid*. Four trunnions welded to the cask, each four inches in diameter, would be bolted to the skid. The cask was further secured to the skid by a center girdle. Insulation mats 2 inches thick completely surrounded the cask, and around this was placed a canvas tarpaulin secured by hemp rope. The skid was secured to the trailer by heavy chains. A single fuel element was being transported in the Hallam cask at the time of the accident. It was placed inside a hermetically sealed aluminum canister with a steel lining, and the canister was placed inside the cask, along with a shock absorber.

On the day of the accident, while traveling to ORNL on US 25W outside of Clinton, Tennessee, the truck hauling the cask swerved off the road in order to avoid a head-on collision with an oncoming tractor-trailer that had crossed over the center line of the highway. The driver of the cask truck lost control of the vehicle when it left the road surface, and the truck traveled approximately 300 feet before overturning in the ditch beside the road, which contained standing water. The cask and tractor-trailer together skidded approximately 90 feet through the ditch, and the cask became embedded in the soil. The cask then separated from the tractor-trailer, with the tractor-trailer continuing another 52 feet, hitting trees along the side of the road before coming to rest. A photograph of the cask at rest in the ditch is shown as Fig. 4-1. Figure 4-2 shows the cask with the overturned tractor-trailer in the background. Standing water is clearly visible in the ditch in Fig. 4-2.

Fig. 4-1. Hallam cask embedded in ditch after accident (Chandler 1972).

Fig. 4-2. Cask separated from tractor-trailer (Chandler 1972).

Upon review of the accident scene, it was determined that the tie-downs securing the cask to the trailer failed while the cask was buried in the soil and the trailer continued to travel. The thermal insulation and tarp covering the cask were also torn from the cask, with only the top and bottom of the cask keeping its insulation. The investigators believed that even if a fire had occurred that was more severe than the hypothetical accident conditions specified in the regulations, it would not have damaged the cask. This was due to half of the cask being buried in water and soil two feet below the road grade, and it was also due to the cask cradle still being present, providing some thermal shielding from a potential fire.

The structural and load-bearing components of the cask, including the cask flange bolts, flange peripheral welds, cask axial welds, trunnion welds, and the load-bearing welds and bolts on the structural steel support were all inspected before and during the retrieval of the cask. No damage was found to any of these components upon inspection.

The accident occurred at approximately 1:30 PM on December 8, 1971. The Anderson County Sheriff's Department arrived at the accident, stopped traffic, and upon noting the radioactive placards on the trailer, evacuated the public within 500 yards. It is unclear from the reference when the Sheriff's Department was notified of the accident. The sheriff notified the AEC Oak Ridge Office (AEC-ORO) at 1:55 PM, and the AEC-ORO emergency response team arrived at the accident site between 2:15 and 2:30 PM. They performed radiation surveys as shown in Fig. 4-3, and they determined that no radiological contamination had occurred. Because of this, traffic was allowed to proceed along the road as soon as the accident wreckage could be cleared, and although the reference report is not clear on this, it appears that the evacuation order within 500 yards of the accident was also lifted at this time. The shipping papers that were found accompanying stated that the cask was to be received at ORNL by J. M. Chandler. Chandler was contacted at 2:45 PM and asked to come to the accident scene; he brought health physicist H. P. Ward with him to the scene, along with some reference documents, including the cask safety analysis report.

Fig. 4-3. Radiation survey performed on cask at accident site (Chandler 1972).

To begin the cask recovery process, the cask was first inspected to confirm the integrity of its structural welds and bolts. This required removing some of the dirt around the cask. A 25-ton mobile crane was initially sent to the site but was found inadequate for the lift in the location, so a 50-ton mobile crane was sent. The reference notes that the recovery was delayed two hours waiting for the proper crane to arrive. While waiting for the crane, smears of the cask surface were taken, along with samples of the water in the ditch where the cask came to rest, and sent to ORNL. No activity significantly different from background was found on the cask surface, and no radioactive material was detected in the water sample. Samples were taken the following day of the trailer wreckage, and tests performed at ORNL showed no contamination of the conveyance. Furthermore, no radioactivity was found upon a survey of the accident scene the following day.

Upon arrival of the 50-ton mobile crane, the cask was first lifted out of the ditch by its cradle, and then cables were secured around the cask to complete the move. A photograph of the initial lift is shown as Fig. 4-4. The cask was placed on a trailer, as shown in Fig. 4-5, and police escorts were arranged for the remainder of the journey to ORNL. Since the original permit for the shipment allowed only daylight travel, permission was required to complete the shipment at night; this was granted by the officer in charge.

Fig. 4-4. Initial lift during cask retrieval (Chandler 1972).

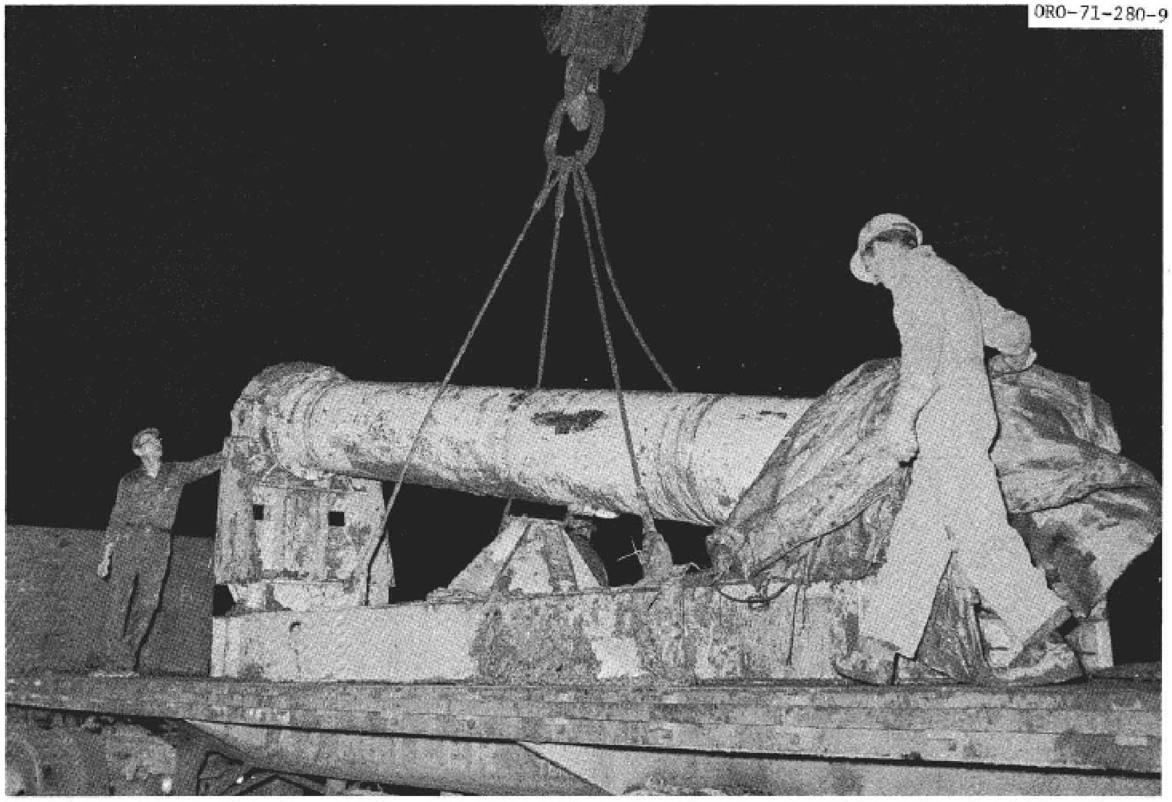

Fig. 4-5. Cask placed on trailer (Chandler 1972).

Delivery of the Hallam cask to ORNL was delayed seven hours by the accident; it was delivered at 10:45 PM on December 8 without further incident. A photograph of the cask taken at ORNL the following day is shown in Fig. 4-6.

4.2 Aftermath

On December 9, the cask was washed in order to remove mud and debris, and an inspection was performed. No further damage to the cask was identified. A radiation survey of the cask was performed in an attempt to locate any breaches in the shielding through which radiation would stream. The reference notes that this was a very thorough survey and that no breaches were found in the shielding. The cask was then lowered into a horizontal orientation for unloading, and the fuel element was removed without incident. The cask cavity was examined, and the absence of any mud or water in the cask indicated that none of the containment system O-rings had failed.

After the canister was unloaded, it was inspected. Small scratches were found on the outside of the canister but were determined to be normal incidental to handling. No other damage to the canister was found. The shock-absorbing cylinder was also inspected and found to be undamaged; it was decontaminated and packaged for reuse in future shipments.

The fuel element was unloaded from the canister without incident. It was not found to have any nicks, unusual marks, or breakage. Photographs documenting the lack of damage to the fuel element were taken (Fig. 4-7 and Fig. 4-8).

An additional inspection was performed of the cask after the fuel had been unloaded. No further damage was found beyond that noted at the accident site, and there had been no deformation of the cask or of the cradle during transport.

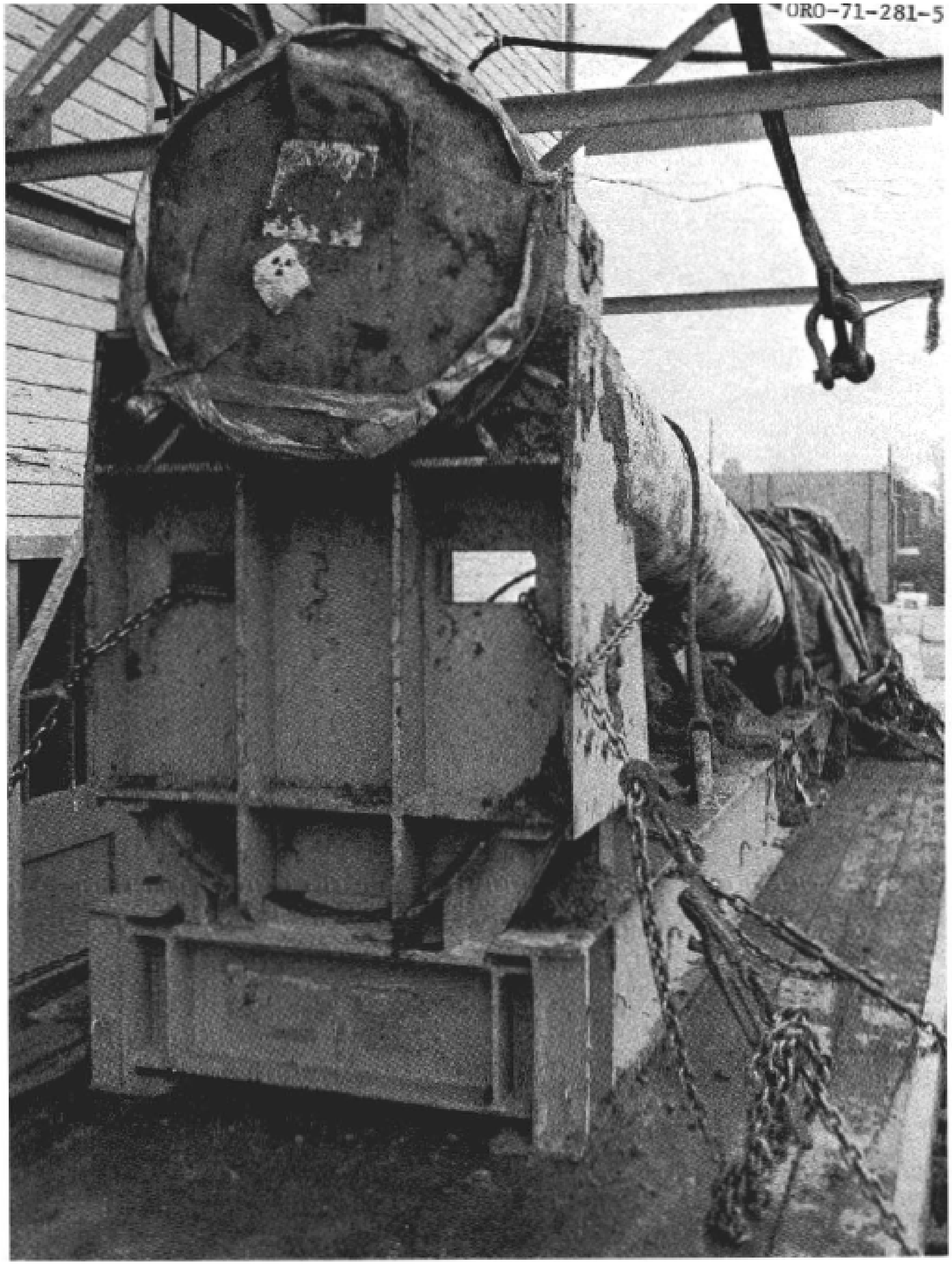

Fig. 4-6. Cask as received at ORNL (Chandler 1972).

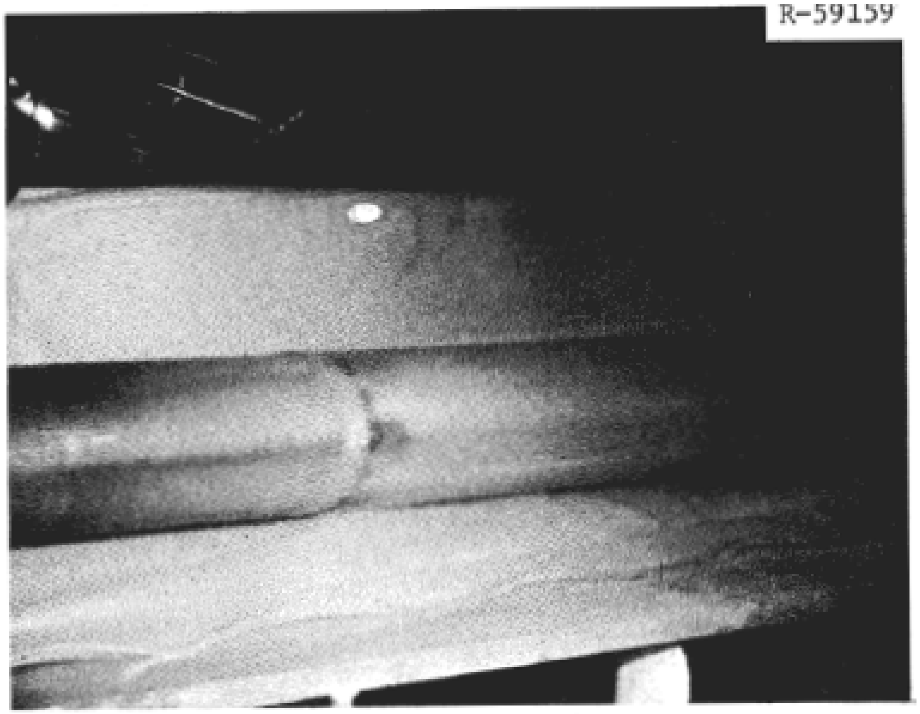

Fig. 4-7. Bottom end of fuel element (Chandler 1972).

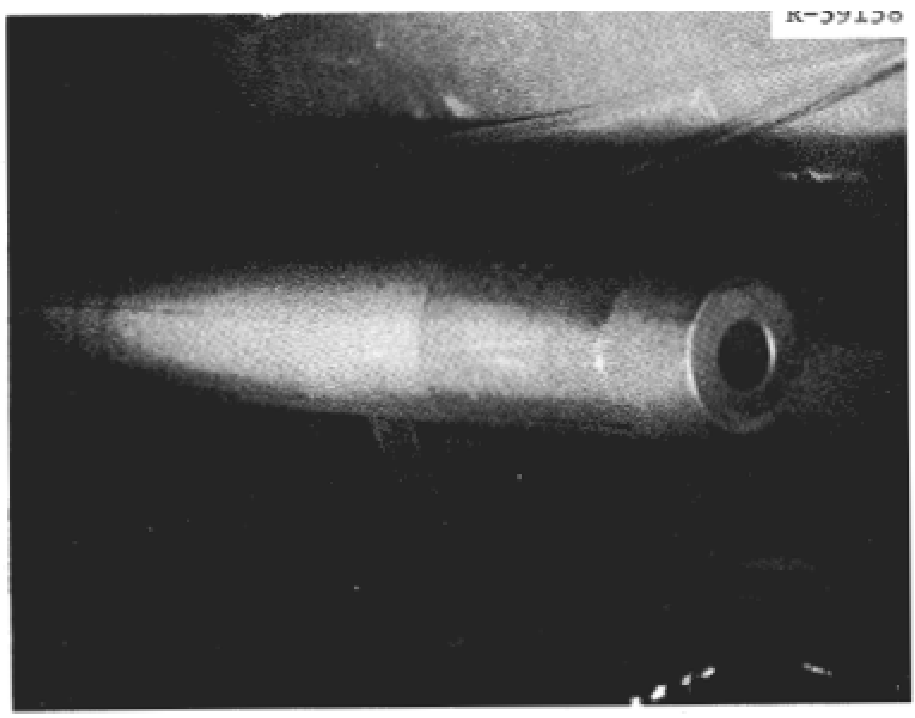

Fig. 4-8. Top end of fuel element (Chandler 1972).

A series of repairs was made to the cask to prepare it for future shipments. The entire cask was sandblasted and repainted, and since some paint had been scraped off in the accident, the whole cask was refinished. The cradle was also sandblasted and repainted. All of the bolts, nuts, and washers that would be taken off and put back on at every loading and unloading were replaced as preventative maintenance, even though none were found to have failed in the accident. Also, all four of the O-rings were replaced. The steel dowel pins and bolts that had aligned and bolted together the cask center support girdle were replaced; two of each of these items had failed in the accident. The repairs were completed January 12, 1972. A photograph of the cask being returned to service upon completion of the repairs is shown as Figure Fig. 4-9.

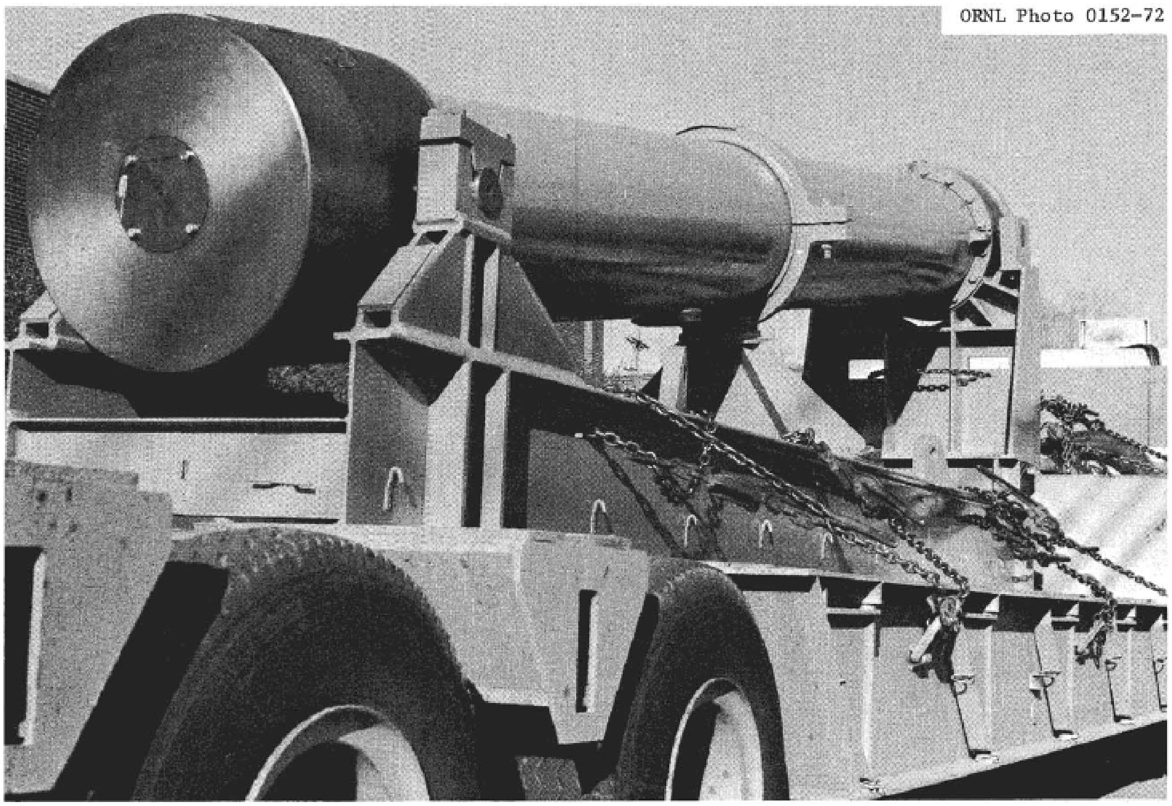

Fig. 4-9. Hallam cask returned to service after repairs (Chandler 1972).

Future shipments used a trailer with a lower center of gravity and improved tie-downs. The trailer had been under development and was planned for future shipments of the Hallam cask before the accident; the reference report noted that coincidentally, recommendations to use trailers with improved tie-downs and lower centers of gravity were made without knowing that a trailer was already planned for use with those improvements.

In analyzing factors that contributed to the accident, the high center of gravity of the cask and trailer was determined to be a contributing factor in the driver's inability to regain control of vehicle.

The report also noted that the officer who responded to accident showed good judgement in rerouting traffic and contacting radiation experts.

Finally, the author of the report envisioned a need for consists of radioactive material traveling on trains to reduce the possibility of traffic accidents involving multiple containers of radioactive material, given that he expected the quantity of SNF shipments to increase considerably with a significant expansion of nuclear power in the coming decades. The recommendation to ship SNF mostly by rail was later issued by the National Academy of Sciences in its report, *Going the Distance? The Safe Transport of Spent Nuclear Fuel and High-Level Radioactive Waste in the United States* (NAS 2006) 34 years after the Hallam cask accident report was written.

5. NRC REPORTS ON SNF TRANSPORTATION

The NRC has published four reports since 1977 specifically focused on investigating the transportation of SNF and assessing and quantifying the risks inherent in this activity. The first, entitled *Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes*, was issued December 1977 and designated NUREG-0170 (NRC 1977). It included SNF in its investigation but provided a broader analysis of all transportation of radioactive material. This study was revisited in 1987 to make more realistic assumptions about cask performance during accidents on roads and rails; the study, often referred to as the “Modal Study,” was designated NUREG/CR-4829 (Fischer et al. 1987) and titled *Shipping Container Response to Severe Highway and Railway Accident Conditions*. A report issued in 2000, *Re-examination of Spent Fuel Shipment Risk Estimates*, was designated NUREG/CR-6672 (Sprung et al. 2000), and the most recent study, NUREG-2125 *Spent Fuel Transportation Risk Assessment* (NRC 2014) was released in 2014. This section reviews all four of these documents.

At this writing, the NRC is examining actual transportation accidents during which severe fires were present to estimate the effects of these accidents on a hypothetical cask containing SNF. These reports, NUREG/CR-7206, 7207, and 7209, have not yet been released in final form and are not addressed in this current report.

5.1 NUREG-0170

The purpose of *Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes* was to reevaluate regulations of shipping radioactive materials in air. Although the primary focus was to consider air shipments, alternative modes also needed to be compared. One alternative considered was to ship radioactive material by special trains. However, aspects of rail shipments such as routing and vehicle safety features were beyond the work scope. Furthermore, the report focused on all radioactive materials rather than specifically SNF and/or HLW. In addition, the report did not consider the alternative of shipping reduced quantities of radioactive material to reduce risks since it was assumed that the benefits of shipping the material outweighed any risks.

Although the report was issued after reprocessing of SNF was banned in the US, the study was done prior to the ban being issued, so the report states that its projections estimating future shipments of materials including plutonium would need to be revisited.

The introduction section of NUREG-0170 ends by noting that the validity of the risk assessment was strongly contested within the NRC. The assumptions made for this report where data was not available were very conservative, and many of the contributors to the report did not consider the assumptions realistic. The introduction notes that improved data should be collected and the analysis revisited in the future, but since the report concludes that risks of transporting radioactive material are very low compared to transportation in general, the overly conservation assumptions made are, in general, not detrimental to the report’s conclusions.

The report begins by reviewing air transportation, a mode not used for SNF. More than half of the doses received during air transportation would be received by transportation workers, while the remainder would be received by approximately 10 percent of the US population. This dose is almost entirely due to radiation from compliant packages. More than half of the dose is due to shipments of medical isotopes. None of the dose would lead to short-term fatalities.

Accident consequences would be limited for most shipments due to the short half-lives of material most frequently carried, the low radiotoxicity of those materials, and limited dispersibility of those materials. The report conveys that a worst-case accident scenario in radioactive material transportation would be an accident involving a shipment of plutonium or ^{210}Po, leading to a release of material in an area of high population density. The effects of this could include as many as 60 people receiving an acute radiation dose causing some health effects, and potentially the death of the person receiving the highest exposure.

However, in order for this to happen, the package would undergo gross failure as opposed to a closure seal leak or a similar issue, and the material would have to be released in a respirable form. Furthermore, to reach a worst-case scenario, the report authors assumed that meteorological conditions would keep this material airborne in high quantities for a long time and that they would take no mitigating actions such as evacuation of the area. The report assumed that an accident involving SNF would not lead to consequences as significant as in this worst-case scenario.

SNF transportation was considered specifically in some sections of this report. While nuclear fuel cycle shipments and radioactive waste shipments combined constituted just under 25% of all radioactive material shipments, only a small fraction of this would be likely to be SNF. The unavoidable negative effects of SNF transportation were considered to be routine radiation exposures to the public and the potential for accidents. Both the accident potential and exposure to the public are very small, but they are impossible to eliminate entirely.

The principal environmental impact of SNF shipments considered in the study was direct radiological exposure to people during transport. Due to the large mass of SNF shipments, the only modes considered for this material were truck, rail, barge, and ship. Exposure to the public during barge and ship transportation was assumed to be negligible due to their distance from the public. Therefore, road and rail transportation were analyzed in greater detail. However, the conservative assumption was made that buildings, terrain, and vehicles would not provide any shielding to members of the public along transportation routes for SNF shipments.

For all truck shipments of radioactive material not limited to SNF, the typical maximum annual dose to a truck driver was estimated at 870 mrem, the total collective population dose for people along the transportation route would be 348 person-rem, and 172 person-rem would be the expected dose to the public sharing the roads with the shipment. A driver who followed a truck shipment for its entire duration could be expected to receive 1.9 mrem. The maximum expected dose to a resident along the most-used route for SNF would be 0.009 mrem per year. The report does not provide context for these figures; 100 mrem is the regulatory dose limit for members of the public in any given year.

Shipments of radioactive material by rail would be expected to yield lower doses to workers and members of the public. The maximum annual dose to a train crew member was estimated to be 1.2 mrem, the collective population dose to people sharing the rails was estimated at 0.012 person-rem, and the off-link dose to the population near the rail route would be 23 person-rem per year. Doses to people when trains hauling SNF pass through stations were considered negligible compared to these quantities.

It was estimated that a typical shipment of radioactive material would result in a dose of 0.2 person-rem to handlers. However, this dose may be lower for SNF shipments. Due to the large sizes of SNF casks and the need for heavy equipment to handle them, handlers will stand farther away and therefore receive a lower dose than they would receive when working with other radioactive material shipments.

The report defines the *annual radiological risk* as the product of the accident probability and its consequence. *Probability of an accident* was defined as the accident rate per vehicle kilometer (a national average by mode, not defined at the route or local level) multiplied by the distance of a shipment, multiplied by the total number of shipments using a particular mode. The consequences of an accident were estimated using probabilities of the severity of an accident. Furthermore, accidents were expected to have more severe consequences in rural areas when compared to urban areas since travel speed is usually higher outside of urban areas. Since there was a dearth of data on release fractions and probabilities of release in accidents, estimates were made which the report describes as extremely conservative.

The probability of one or more early fatalities due to an accident in the transportation of all radioactive material (of which SNF transportation is a small fraction) was estimated at 3.5×10^{-4}, with 0.068 latent cancer fatalities expected from shipments of all radioactive material in 1975. The report anticipated larger quantities of radioactive material to be transported in 1985, expecting 1.09 latent cancer fatalities from exposure to population from all shipments in 1985. Approximately 50 times more fatalities were expected to result from nonradiological accidents transporting all radioactive materials (such as traffic accidents) than from any radiological consequences of accidents, but less than one fatality was expected per five years from all transportation of radioactive material.

It should be noted that since the release of NUREG-0170 in 1977, the International Commission on Radiological Protection (ICRP) stated in its 2007 recommendations (ICRP 2007) that such predictions as latent cancer fatalities should not be projected based on “trivial exposures to large populations,” although it does not define the term “trivial” as used in that recommendation.

The overall risk to an individual was estimated at 1 in 200,000,000,000 per year due to transportation of radioactive materials, and the report concluded that because of the many benefits of the use of radioactive materials requiring their transportation, this was an acceptable risk.

5.2 NUREG/CR-4829

In the 1980s, the NUREG described in the previous section was revisited, and an effort was launched to improve the estimates of the actual responses of SNF casks to transportation accidents. Since the previous study on radioactive materials transportation, improved computational tools had become available which would allow for more realistic, less conservative estimates to be made. The new study was released as NUREG/CR-4829, *Shipping Container Response to Severe Highway and Railway Accident Conditions*, in 1987.

Because all casks must meet the requirements described in 10 CFR 71 to become certified for transportation of radioactive materials, it was assumed that any accident less severe than the hypothetical accident conditions described in the regulation would result in no release of radioactive material. The goal of this report, referred to as “the Modal Study,” was to estimate the effects of accidents more severe than the regulatory hypothetical accident conditions.

To estimate the response of the cask to accident conditions, models used in the report took into account (1) cask impact velocity in accidents where a cask struck an object, (2) hardness and weight of the object struck, and (3) cask orientation. In accidents involving fires worse than the 30-minute engulfing fire at 1475°F specified in the regulation, the fire duration, flame temperature, and distance of the fire from the cask were also taken into account.

The approach taken in this study was to develop a probability tree of transportation accidents. Given an accident, probabilities were determined for collisions with vehicles or objects and other accident characteristics such as whether the vehicle overturns or if there is a fire. The type of soil or other material impacted was also included in these probability trees since impacting a bridge abutment would cause more severe consequences to a cask than impacting soft soil. Accident probabilities for road transport were derived using data from California accident records, and it was assumed that the California information was representative of transportation accidents nationwide in terms of their probabilities and effects. Accident data from the FRA were used to determine rail accident probabilities. When data were not available for parameters such as cask orientation or distance of the cask from the center of a fire, the report authors made assumptions for these parameters. These assumptions included the probability that a cask comes to rest close enough to a fire to raise the internal temperature by enough to damage particular cask internal components.

While many models of casks have been certified for the transport of SNF, two representative designs were used for the analysis in the Modal Study. One cask model was developed for truck transportation, and one cask model was developed for rail transportation. Each model had a steel shell, closure seals and bolts, lead gamma shielding, and a neutron shield assumed to be lost in an accident. The truck cask had a capacity of 1 PWR assembly, and the rail cask was assumed to carry 21 PWR assemblies. Soft impact limiters were modeled to increase subsequent damage from accidents (for example, to increase damage to the modeled lead gamma shield). Criticality was not explicitly addressed; instead, the report concluded that criticality would only be a concern when an accident leads to the loss of the fuel assembly's integrity and the cask lands in a moderating material.

Upon an initial screening, 99.4% of all potential accidents fell into a category where no radiological significance would exist in such an accident. This was due to accident conditions being significantly less severe than the hypothetical accident conditions outlined in the regulations. Nineteen other potential cask responses were determined for more severe accidents, however, analytical computational tools were used to determine the mechanical and thermal loads on a cask in a hypothetical accident. Based on these consequence categories and the probability data on transportation accidents, it was estimated that fewer than 0.001% of truck accidents and less than 0.012% of rail accidents would be severe enough to cause release of radiation or radioactive material in excess of regulatory limits. Compared with the conclusions of NUREG-0170, this means that on the order of ten times fewer potential accidents would be of radiological concern. Furthermore, the direct radiation risk per accident was estimated at approximately 3 times lower than NUREG-0170 risks for rail accidents and 25 times lower than that estimated for truck accidents.

The conclusions section of the Modal Study describes several severe transportation accidents that had occurred recent to the study. In one accident a train carrying flammable chemicals derailed and burned for five days before emergency personnel could mitigate the accident. This is the only accident for which the authors expected any radiological consequences resulting from the accident.

5.3 NUREG/CR-6672

In 1996, the NRC launched an effort to reexamine the conclusions of NUREG-0170. The resulting report, *Reexamination of Spent Fuel Shipment Risk Estimates*, was published in 2000 as NUREG/CR-6672. As for the previous risk assessment revisiting SNF transportation, this study was implemented in anticipation of future large-scale SNF shipments and was enabled by the availability of improved data and analysis methodologies.

To reexamine the conclusions regarding incident-free transportation, a set of transportation routes was developed going from existing at-reactor SNF storage locations to potential storage or disposal facilities for both rail and road shipments. A total of 741 different truck routes and 741 different rail routes were analyzed to determine the length, fraction of the route that is through urban and rural areas, and population density along potential routes for SNF transport. A smaller subset of hypothetical routes was developed based on these parameters to ensure that routes for which incident-free risk assessment calculations were performed represented actual future SNF routes. Collective population doses were estimated based on these hypothetical representative routes. Unlike the analysis performed for NUREG-0170, NUREG/CR-6672 takes radiation shielding due to buildings when a cask is transported through a populated area into account. Shielding factors are based on the attenuation of gamma radiation in typical construction materials. It is assumed that all radiation from a cask in shipment is gamma radiation (as opposed to neutrons) and that the external dose rate is the maximum allowed by regulation. Thus, the incident-free population dose is expected to still be somewhat conservative, although it is significantly more realistic than the dose estimated by NUREG-0170.

Truck and rail accident rates were taken from published statistics to derive accident probabilities. Truck and train data became available from a wider variety of sources since the publication of the Modal Study, including studies sponsored by DOT and DOE. Thus, accident probabilities have been updated since the Modal Study, and reported accident rates for both truck and train transportation have decreased with the addition of this new data.

Four generic models for casks were used in this report. Two truck casks, one with lead shielding and one with depleted uranium (DU) shielding, were modeled. The generic rail cask models had lead shielding and a monolithic steel cask in which gamma shielding is supplied by the great thickness of steel. The report notes that the cask models are designed for performance of 3-D computational structural analysis, and although they are representative of SNF shipping casks, they are not designed to accurately portray any particular cask model or any cask developed by a specific vendor. The rail casks were assumed to carry up to 24 PWR or 52 BWR assemblies; the lead-shielded steel truck cask could contain 1 PWR or 2 BWR assemblies, and the DU-shielded steel truck cask could contain 3 PWR or 7 BWR assemblies. Thus, the SNF source term was greater in this analysis than that performed in the Modal Study, which assumed a smaller capacity for all casks.

Structural analysis of the generic casks was performed using 3-D finite element computational tools with the goal of determining whether impacts to the cask would be sufficient to cause the necessary deformation around the bolts and O-ring seals of casks to release any material within the cask. Strain in the closure bolts which could be conservatively assumed to fail was estimated to be reached in side impacts involving the rail casks over 60 mph, corner impacts over 90 mph, and end impacts over 120 mph onto an unyielding surface. In corner impacts over 60 mph for the rail casks (and for side impacts of 120 mph for the monolithic steel rail cask), a leak path could also be opened at the O-ring seal. In high-speed end-on impacts, some radiation shielding may also be lost due to lead slumping, because lead is a soft metal and may change position in high-speed impacts. Gamma radiation would be able to stream through the part of the cask from which the lead shielding has moved. The report includes this possibility for the 120 mph end-on impact of both the truck and rail casks using lead shielding; this effect is not observed in the DU-shielded truck cask or the monolithic steel rail cask.

The report further notes that the impact velocities used in the calculations are for impacts with rigid objects in which the energy of the impact is absorbed by the cask. For comparison, for a cask to impact soil and absorb the same amount of energy as a 120 mph collision with a rigid surface, it must strike the soil at 309 mph. Similarly, for impacts of actual casks on concrete and water, the impact velocity must be significantly higher than that for a rigid surface. In cases where bolt or O-ring deformations were hypothesized by the computational analysis, casks would have to strike soil, concrete, or water at more than 150 mph.

Due to the thickness of the casks, punctures were considered highly unlikely in any accident; data from the rail industry indicated that tank cars with a shell thickness of greater than one inch rarely suffer punctures in accidents. All of the generic cask models in this report have steel shells thicker than one inch. However, for conservatism, the report assumed that truck casks would puncture in 0.1% of accidents and that rail casks would puncture in 1% of rail coupling impacts and 0.1% of all other accidents.

Thermal analysis was performed on all four cask models. Casks were treated as one-dimensional cylinders, with the SNF being treated as an internal heat source. Fires were modeled outside the cask: one at 800ºC (the regulatory specification), and one at 1,000ºC. This analysis therefore assumed that the fires uniformly engulfed the casks. The time required to reach certain temperatures inside the cask was estimated from the analysis. At 350ºC, the elastomeric closure seals of casks would be expected to degrade and potentially cause leakage, and at 750ºC, the SNF rods would begin to rupture, releasing radioactive material otherwise contained by the cladding. In a 1,000ºC fire, the seal failure temperature would be expected to be reached at approximately one hour for all four casks. The truck casks would reach rod rupture temperature after approximately two hours, while the lead-shielded rail cask would reach that temperature after three hours, and the monolithic steel rail cask would be expected to insulate the rods from rupture temperature until more than six hours into the fire. It would take more than twice as much time to reach this rod failure temperature in a fire at the 800ºC temperature specified in the regulations. Conservatisms introduced to the thermal models include the use of SNF which has been cooled for only three years (thus generating more internal heat and being at a higher internal temperature initially), and the assumption that the neutron shield disappears at the beginning of the fire, where neutron shields are typically hydrogenous materials which would provide some thermal shielding for minutes.

Using event trees such as those used in the Modal Study but with updated accident data, probabilities of particular transportation accidents were estimated. Accidents were further classified by impact velocity from which strain of cask components and SNF rods could be determined, along with the temperature and duration of any fire present. Based on the earlier structural and thermal analysis, only a severe collision and/or a long duration fire would have the potential to release radioactive material.

It is concluded that incident-free population doses due to truck transportation will be higher than those for train transportation by a factor of 180–585. This is due to the much smaller capacity of truck casks when compared to rail casks, which necessitates a much greater quantity of truck shipments necessary to move the same quantity of SNF. While the consequences of a train accident would be expected to be greater than the consequences from a truck accident due to the larger quantity of radioactive material in a rail cask, the overall truck accident dose risks exceed train accident dose risks as well by as much as a factor of 26. The text of the report lists a factor of 260, but this figure is likely written due to a decimal place error.

Compared to the results of NUREG-0170, NUREG/CR-6672 estimates the population dose per incident-free shipment as lower in every case using the newer data and analysis methods. Furthermore, the accident risk estimated in NUREG/CR-6672 was lower than the incident free dose risk by an order of 10^4.

A table was included listing the dose risks if the entire inventory of SNF as of 1994 were to be shipped. Incident-free population doses were estimated at 61 person-rem from rail transportation, and 1,040–3,290 person-rem from truck transportation. Accident population dose risks ranged from 0.0054 person-rem to 0.046 person-rem, with dose risks being lower from rail transportation than truck. These doses are lower than those estimated by NUREG-0170, which concluded that the risks were low in comparison to the benefits to society of the continued usage of radioactive materials.

5.4 NUREG-2125

The most recent risk assessment report released by the NRC, *Spent Fuel Transportation Risk Assessment*, was designated NUREG-2125 and issued in 2014. It echoes previous reports in that the risks of transporting SNF are small, but it puts these dose risks into perspective by comparisons with natural background radiation. The collective dose risks estimated in the NUREG reports described in previous sections do not change considerably in the new calculations performed for NUREG-2125. What has changed is the statement that these population doses are four to five orders of magnitude lower than the natural background radiation dose received by the same population during the same time period.

The comparison of population dose during incident-free transport to natural background radiation dose also adds perspective to the accident dose risk. NUREG/CR-6672 estimated accident dose risk to be smaller than incident-free dose by approximately four orders of magnitude. Based on the comparisons made in NUREG-2125, this suggests that the radiological accident dose risk from SNF transportation estimated in NUREG/CR-6672 is eight to nine orders of magnitude smaller than the dose received by the public from all naturally occurring sources.

Although the incident-free dose risk estimates did not change substantially in NUREG-2125 from earlier analyses, the accident calculations were updated using improved computational models, especially for modeling fire scenarios. Detailed three-dimensional computational analysis was performed for three actual models of a truck cask and two rail casks. A significant change from earlier analysis was that in the event of a fire involving a truck cask and a loaded tanker truck, there would be no release of radioactive material since a fire fueled by a full tanker truck, even if it completely engulfed the cask, would burn for one hour, which is not enough time to cause damage to the cask containment seals or to reduce the effectiveness of the lead gamma radiation shield. Thus, this report found no credible truck accident in which radioactive material would be released; the only radiological consequence of an accident with a truck cask containing SNF would be the additional exposure to the emergency personnel during the time the accident scene is cleared. This additional exposure would not approach the limits specified in regulations for allowable occupational dose.

Furthermore, the report could not foresee a credible accident in which SNF contained in a welded canister inside the cask could release any radioactive material. This is significant because it is considered likely that much SNF will be shipped from reactor sites to interim storage or a repository in welded canisters inside casks. For an accident in which the SNF in the cask is not stored in a welded canister, the estimated risks of radiological effects to members of the public remain small and indeed are smaller than the risks estimated earlier using less realistic computational models and tools. NUREG-2125 estimates the radiological risk of rail shipments as 2.5×10^{-13} person-Sv per shipment from accidents in which the effectiveness of the lead radiation shielding of the cask is compromised in a severe fire, and the collective dose risk due to a release of radioactive material from the cask is estimated as 3.5×10^{-14} person-Sv. It is estimated that the individual with the greatest exposure in the most severe accident envisioned in this report would receive a dose of 1.6 Sv, which would not be an acute fatal dose.

5.5 OBSERVATIONS

In every reinvestigation of SNF transportation risk assessment undertaken by the NRC, the radiological risks of SNF transportation have been estimated to be low in comparison to the risks inherent in truck and rail transportation. Furthermore, the collective dose received by the general public from SNF and HLW shipments is smaller than the naturally occurring background dose received by the same population in the same period of time by four orders of magnitude.

As computational analysis methods have improved, estimated risks of SNF transportation have decreased. In the earliest risk assessment reports, it was assumed that casks would rupture in accidents and release all of their contents since the mechanisms for cask failure could not be modeled. As methods improved, it became possible to model strains on cask components and SNF rods, as well as the effects of high temperatures on containment seals and cask shielding. As more detailed and realistic simulations were performed, the estimated probabilities of component failure decreased. The risks themselves have not changed over time: only the estimates of the risks based on available analysis methodologies and tools have changed. As methods and assumptions have improved and uncertainties have been reduced, it has become possible to develop more reliable estimates of the actual risks involved in SNF transportation.

Since the NRC's first investigation of SNF transportation risk, regulations on casks have always been found adequate to protect the health and safety of the public in the event of a transportation accident. The hypothetical accident conditions described in the regulations are in fact much more severe than the majority of potential transportation accidents.

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6. CONCLUSIONS

The transportation of SNF has a safe history spanning over fifty years. In the US alone, over one million miles of SNF shipments have been safely conducted. Worldwide, the number of SNF shipments that have been made is not significantly less than 20,000, but due to incomplete records, may be much greater. Similarly, at least 35,000 tons of SNF have been shipped worldwide over the last 50 years or more, but the total quantity shipped may be greater. In developing a large-scale SNF transportation system, DOE must remain cognizant of the wealth of experience worldwide in shipping SNF safely.

There have been few transportation incidents involving SNF over its history. SNF and HLW transportation incidents can be divided into three general categories. The first and most common category involves radioactive contamination on the surface of SNF casks and/or the vehicles on which they are transported. Instances of contamination have occurred in many countries where SNF and HLW have been transported, and proper operating procedures and cask maintenance have led to a reduction in the frequency of contamination incidents and the levels of contamination. The second category involves transportation accidents. While it may be impossible to completely prevent transportation accidents, the transport safety regulations specify that SNF and HLW casks be designed to contain their radioactive contents even in severe accidents. This has led to an exemplary record over which no injury has ever been caused by the radiological nature of SNF or HLW in a transportation accident. The third category, which has had the most severe effects in terms of schedule, cost, and public safety, is a result of public demonstrations and protests that have led to the disruption of shipments. Although no radiological effects have resulted from delays and protests of HLW shipments, there have been injuries due to clashes between protestors and police forces.

The most severe accident in transporting SNF known to the authors was examined in this report as a case study. There were no radiological consequences in the fatal truck accident in which the trailer carrying the SNF cask overturned and was embedded in a mud- and water-filled ditch on the roadside. The lack of radiological consequences in this accident was due to the high regulatory standards and robust design and construction of the SNF cask, and it serves to illustrate the safe performance of SNF packages in accident conditions. This is essential since it is impossible to avoid all transportation accidents.

The NRC is focused on understanding transportation accidents and their potential consequences on SNF. Four times in the past 40 years, the NRC has issued reports assessing the risks inherent in SNF transportation. As data have become more available and analytical methods have improved, the NRC has been able to make more realistic assumptions with each study. The use of realistic as opposed to conservative models and assumptions has led to an improved understanding of the risks of transporting SNF; the estimated risks and consequences have decreased as models have improved.

While it is impossible to eliminate all risks from the transportation of SNF, continued study has shown the risks of SNF transportation to be low, and the record of SNF transportation worldwide is a successful, safe record, with tens of thousands of safe shipments over more than fifty years.

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7. REFERENCES

Alter, U., F. W. Collin and Ch. Fasten, "Transport of Radioactive Material in the Federal Republic of Germany (FRG) since 03. October 1990 – a Survey," PATRAM '92, *Proceedings of the 10th International Symposium on Packaging and Transportation of Radioactive Materials*, Yokohama City, Japan, Science and Technology Agency, Ministry of Transport, Japan, Vol. 1 (1992): 113–120.

Alter, U., "Summary of Nuclear Material Transport in the Federal Republic of Germany (1990–1994)," PATRAM '95, P*roceedings of the 11th International Symposium on Packaging and Transportation of Radioactive Materials*, Las Vegas, NV, USA, University of Nevada Las Vegas, Vol. 2 (1995): 584–591.

Alter, U., A. Heimbel, and W. Kachel, "Summary of Rail Shipments in the Federal Republic of Germany (1972-1997) – 25 Years of Experience," PATRAM '98, *Proceedings of the 12th International Symposium on Packaging and Transportation of Radioactive Materials*, Paris, France, Vol. 3 (1998): 951–960.

Alter, U., "Shipments of vitrified high-level radioactive waste from France to Germany as routine shipments with special train service," PATRAM 2004, *Proceedings of the 14th International Symposium on Packaging and Transportation of Radioactive Materials*, Berlin, Germany, Paper No. 234 (2004).

Aoki, S., S. Fukuda, K. Watanabe, and Y. Mori, "Present Status of Nuclear Fuel Material Transportation in Japan," PATRAM '95, *Proceedings of the 11th International Symposium on Packaging and Transportation of Radioactive Materials*, Las Vegas, NV, USA, University of Nevada Las Vegas, Vol. 2, (1995): 559–563.

Bellona, "Thousands attend unprecedented anti-nuclear protests in Germany: Local action achieves global impact," Bellona Foundation, November 18, 2010. Accessed June 10, 2015 from http://bellona.org/news/nuclear-issues/radioactive-waste-and-spent-nuclear-fuel/2010-11-thousands-attend-unprecedented-anti-nuclear-protests-in-germany-local-action-achieves-global-impact.

Bentele, W., and T. Kinzelmann, "Experience with the loading and transport of fuel assembly transport casks, including CASTOR casks, and the radiation exposure of personnel," *Journal of Radiological Protection*, **19**, (1999): pp. 353-359.

Bernard, H., "Transportation of Spent Fuel from Light Water Reactors," PATRAM '92, *Proceedings of the 10th International Symposium on Packaging and Transportation of Radioactive Materials*, Yokohama City, Japan, Science and Technology Agency, Ministry of Transport, Japan, Vol. 1 (1992): 105–112.

Blackburn, S., and A. Brown, "Experience in the European Transport of Spent Nuclear Fuel," *International Journal of Radioactive Materials Transport*, **2**, (1991): 15–121.

Bolshinsky, I., K. Allen, L. Biro, and A. Buchelnikov, "Air Shipment of Spent Nuclear Fuel from Romania to Russia," PATRAM 2010, *Proceedings of the 16th International Symposium on Packaging and Transportation of Radioactive Materials*, London, United Kingdom, paper no. 296, Institute of Nuclear Materials Management, Chicago, IL, USA (2010a).

Bolshinsky, I., K. Allen, L. Biro, and A. Buchelnikov, "Air Shipment of Spent Nuclear Fuel from Romania to Russia," *Proceedings of the 16th International Symposium on Packaging and Transportation of Radioactive Materials* PATRAM 2010, London, United Kingdom, presentation no. 296, Institute of Nuclear Materials Management, Chicago, IL, USA (2010b).

Brachet, Y, "Spent Fuel Cask Contamination: The Transnucleaire Experience," *International Journal of Radioactive Materials Transport*, **11**, (2000): 179–181.

Budu, M. E., S. N. Komarov, S. V. Komarov, K. J. Allen, S. D. Moses, and E. N. Lazarev, "Seven SNF Air Shipments in Type B Packages – Summary and Lessons Learned," PATRAM 2013, *Proceedings of the 17th International Symposium on Packaging and Transportation of Radioactive Materials*, San Francisco, CA, USA, Institute of Nuclear Materials Management, Chicago, IL, USA (2013).

Cashwell, J. W., K. S. Neauhauser, "Analyses of the Transportation of Spent Research Reactor Fuel in the United States," PATRAM 1989, *Proceedings of the 9th International Symposium on Packaging and Transportation of Radioactive Materials*, Washington, DC, USA, Oak Ridge National Laboratory, CONF-890631-Vol. 2, (1989): 1066–1073.

Chandler, J. M., "The Peach Bottom Spent Fuel Element Shipping Cask Accident December 8, 1971," Oak Ridge National Laboratory, ORNL-TM-3844, July 1972.

Common Report of the Competent Authorities of France, Germany, Switzerland, and the United Kingdom, Surface Contamination of Nuclear Spent Fuel Shipments, *International Journal of Radioactive Materials Transport*, **10**, (1999): 73–84.

Di Gasbarro, F., J. Paschal, R. Donati, and G. Lombardi, "Italian-French Experience in the Transportation of INF for Reprocessing," PATRAM 2010, *Proceedings of the 16th International Symposium on Packaging and Transportation of Radioactive Materials,* London, United Kingdom, Institute of Nuclear Materials Management, Chicago, IL, USA (2010).

Dommann, F., "Transport of Nuclear Wastes and Spent Fuel in Switzerland," PATRAM '86, *Proceedings of the International Symposium on Packaging and Transportation of Radioactive Materials*, Davos, Switzerland, International Atomic Energy Agency, STI/PUB/718, Vol. 1 (1987): 7–11.

Dybeck, P., and B. Gustafsson, "A Decade of Successful Domestic Sea Transports or Radioactive Waste in Sweden 1982–1992, PATRAM '92, *Proceedings of the 10th International Symposium on Packaging and Transportation of Radioactive Materials*, Yokohama City, Japan, Science and Technology Agency, Ministry of Transport, Japan, Vol. 1 (1992): 211–218.

EPRI, "Factors Affecting Surface Decontamination of Spent-Fuel Casks," EPRI-NP-3906, February (1985).

Fasten, Ch., F. W. Collin, M. Cosack, and U. Müller, "Transport of Nuclear Material in Germany Since the Enforcement of the First Atomic Law in 1959: Experiences, Assessment and Tendencies," PATRAM '95, *Proceedings of the 11th International Symposium on Packaging and Transportation of Radioactive Materials*, Las Vegas, NV, USA, University of Nevada Las Vegas, Vol. 2 (1995): 568–575.

Fischer, L. E., C. K. Chou, M. A. Gerhard, C. Y. Kimura, R. W. Martin, R. W. Mensing, M. E. Mount, M. C. Witte, "Shipping Container Response to Severe Highway and Railway Accident Conditions," NUREG/CR-4829, US Nuclear Regulatory Commission, Washington, DC (1987).

Garrett, A. G., S. L. Garrett, and R. G. Ostler, "Public Information Circular For Shipments of Irradiated Reactor Fuel," NRC, NUREG-0725, Rev. 15, May (2010).

Gila, M., P. Risoluti, and D. Raisonnier, "Transport of Research Reactor Spent Fuel: Italian Experience," PATRAM '98, *Proceedings of the 12th International Symposium on Packaging and Transportation of Radioactive Materials*, Paris, France, Vol. 4 (1998): 1869–1873.

Gonzalez, L, "Le convoy de déchets radioactifs ne passe plus dans la Marne," francetv, January 15, (2013). Accessed August 2, 2016 at http://france3-regions.francetvinfo.fr/champagne-ardenne/marne/chalons-en-champagne/le-convoi-de-dechets-radioactifs-ne-passe-plus-dans-la-marne-181363.html

Gouin, P., E. Mignot, and L. Phan Hoang, "EDF, a Utility and Its Own Needs in the Field of Transport of Nuclear Materials," PATRAM 1989, *Proceedings of the 9th International Symposium on Packaging and Transportation of Radioactive Materials*, Washington, DC, USA, Oak Ridge National Laboratory, CONF-890631-Vol. 3, (1989): 1343–1351.

Gowing, R., "Experience in Wet Transport of Irradiated LWR Fuels," PATRAM 1989, *Proceedings of the 9th International Symposium on Packaging and Transportation of Radioactive Materials*, Washington, DC, USA, Oak Ridge National Laboratory, CONF-890631-Vol. 2 (1989): 1143–1150.

Guerra, K, "Pineapples spill after train crashes into semi," IndyStar, May 6 (2014). Accessed August 2, 2016 at http://www.indystar.com/story/news/2014/05/06/truck-collides-train-dumping-pineapples-indiana-road/8762649/

Gustafsson B., and A. Ekendahl, "Operation of the Swedish Sea Transportation System for Spent Fuel," *Proceedings of the International Symposium on Packaging and Transportation of Radioactive Materials*, Davos, Switzerland, International Atomic Energy Agency, STI/PUB/718, Vol. 1 (1987): 533–539.

Gustafsson, B., P. Dybeck and S. Pettersson, "Development, Implementation, and Experiences of the Swedish Spent Fuel and Waste Sea Transportation System," PATRAM 1989, *Proceedings of the 9th International Symposium on Packaging and Transportation of Radioactive Materials*, Washington, DC, USA, Oak Ridge National Laboratory, CONF-890631-Vol. 2 (1989): 1115–1122.

Hafner, R. S., "Development of US Regulations for the Transportation of Radioactive Materials—A Look Back Over the Past 40 Years," UCRL-PRES-230034, Livermore, California, September 9–18 (2014).

Harvey, M. P., "Radiological Consequences Resulting from Accidents and Incidents Involving the Transport of Radioactive Materials in the UK – 2008 Review," HPA-RPD-056, July (2009).

Harvey, M. P., "Radiological Consequences Resulting from Accidents and Incidents Involving the Transport of Radioactive Materials in the UK – 2009 Review," HPA-CRCE-003, August (2010).

Harvey, M. P., and J. S. Hughes, "Radiological Consequences Resulting from Accidents and Incidents Involving the Transport of Radioactive Materials in the UK – 2007 Review," HPA-RPD-048, January (2009).

Harvey, M. P., and A. L. Jones, "Radiological Consequences Resulting from Accidents and Incidents Involving the Transport of Radioactive Materials in the UK – 2010 Review," HPA-CRCE-024, August (2011).

Harvey, M. P., and A. L. Jones, "Radiological Consequences Resulting from Accidents and Incidents Involving the Transport of Radioactive Materials in the UK – 2011 Review," HPA-CRCE-037, August (2012).

Hesketh, N., S. J. Watson, A. L. Jones, and J. S. Hughes, "Radiological Consequences Resulting from Accidents and Incidents Involving the Transport of Radioactive Materials in the UK – 2005 Review," HPA-RPD-021, April (2007).

Hughes, J. S., and M. P. Harvey, "Radiological Consequences Resulting from Accidents and Incidents Involving the Transport of Radioactive Materials in the UK – 2006 Review," HPA-RPD-034, December (2007).

Hughes, J. S., D. Roberts, and S. J. Watson, "Review of Events Involving the Transport of Radioactive Materials in the UK, from 1958 to 2004, and their Radiological Consequences," HPA-RPD-014, July (2006).

ICRP, "The 2007 Recommendations of the International Commission on Radiological Protection," ICRP Publication 103, *Annals of the ICRP*, 37 (2007).

IAEA, *Appraisal for the United Kingdom of the Safety of the Transport of Radioactive Material*, International Atomic Energy Agency, STI/PUB/1143, Vienna (2002).

IAEA, "Regulations for the Safe Transport of Radioactive Material, 2012 Edition," Specific Safety Requirements No. SSR-6 (2012).

IAEA, "Radiological aspects of non-fixed contamination of packages and conveyances: Final report of a coordinated research project 2001-2002," IAEA-TECDOC-1449, June (2005).

IRSN, "Transport of radioactive materials: Radioactive materials transports present particular hazards as they concern public highway," (2007, reprinted 2010*)*.

IRSN, "Safety of the Transport of Radioactive Materials for Civilian Use in France: Lessons Learned by IRSN from Analysis of Significant Events Reported in 2012 and 2013," IRSN, Fontenay-aux-Roses, France (2014).

James, R. H., and J. R. Gwyther, "Surface Contamination on Fuel Flasks: Best Practice Advise on Minimising and Measuring Non-Fixed Radioactive Contamination," *International Journal of Radioactive Materials Transport*, **11**, (2000): 171–177.

Jones, A. L., and M. P. Harvey. 2014. *Radiological Consequences Resulting from Accidents and Incidents Involving the Transport of Radioactive Materials in the UK – 2012 Review*, PHE-CRCE-014, August.

Kaneko, K., "30 Years of Experience in Safe Transportation of Nuclear Materials," *Proceedings of the 14th International Symposium on Packaging and Transportation of Radioactive Materials*, PATRAM 2004, Berlin, Germany, Paper No. 114 (2004).

Kondratyev, A. N., V. N. Yershov, Yu. V. Kozlov, Yu. A. Kosarev, Yu. V. Ilyin, and M. S. Pavlov, "Experience and Prospects of WWER-1000 Reactor Spent Fuel Transport," PATRAM 1989, *Proceedings of the 9th International Symposium on Packaging and Transportation of Radioactive Materials*, Washington, DC, USA, Oak Ridge National Laboratory, CONF-890631-Vol. 3 (1989).

Koskivirta, O., and P.-E. Hägg, "Transport of Spent Fuel from Loviisa Nuclear Power Plant to the USSR," PATRAM '86, *Proceedings of the International Symposium on Packaging and Transportation of Radioactive Materials*, Davos, Switzerland, International Atomic Energy Agency, STI/PUB/718, Vol. 1, (1987): 489–491.

Kudrik, I, "Spent fuel storage barge on fire," Bellona Foundation, December 17 (1999). Accessed August 2, 2016 at http://bellona.org/news/nuclear-issues/accidents-and-incidents/1999-12-spent-fuel-storage-barge-on-fire

Lee, H. Y., K. H. Yang, S. H. Chung, S. J. Yoon, and I. H. Lee, "The Experience of Spent Fuel Transportation in Korea," PATRAM '98, *Proceedings of the 12th International Symposium on Packaging and Transportation of Radioactive Materials*, Paris, France, Vol. 3, (1998): 1217–1223.

Lancelot, J., and B. Martinotti, "10 years of transport of vitrified High Level Waste (HLW) from COGEMA La Hague," *Proceedings of the 14th International Symposium on Packaging and Transportation of Radioactive Materials,* PATRAM 2004, Berlin, Germany, Paper No. 252 (2004).

Lenail, B, and H. W. Curtis, "Transport of Irradiated Fuel to the La Hague Reprocessing Plant," PATRAM 1983, *Proceedings of the International Symposium on Packaging and Transportation of Radioactive Materials*, New Orleans, LA, USA, Oak Ridge National Laboratory, CONF-830528-Vol. 1, Vol. II (1983): 1490–1494.

Lenail, B., and H. W. Curtis, "Nuclear Fuel Transport: The Special Case of Spent Fuel Transport," PATRAM '86, *Proceedings of the International Symposium on Packaging and Transportation of Radioactive Materials*, Davos, Switzerland, International Atomic Energy Agency, STI/PUB/718, Vol. 1, (1987): 493–500.

Mangusi, J., B. Hannett, and T. Staake, "MTR Irradiated Fuel Transports," PATRAM 1983, *Proceedings of the International Symposium on Packaging and Transportation of Radioactive Materials,* New Orleans, LA, USA, Oak Ridge National Laboratory, CONF-830528-Vol. 1, Vol. II (1983): 1513–1518.

Mangusi, J., G. Tjersland, R. L. Licata, and B. Hannett, "Recent Experience with the TN-8L and TN-9 Spent fuel Shipping Casks in the USA," PATRAM '86, *Proceedings of the International Symposium on Packaging and Transportation of Radioactive Materials*, Davos, Switzerland, International Atomic Energy Agency, STI/PUB/718, Vol. 1 (1987): 169–179.

Mc Cluggage, W. C., "The AEC Accident Record and Recent Changes in AEC Manual Chapter 0529," *Proceedings of the Third International Symposium on Packaging and Transportation of Radioactive Materials*, pp. 108-129, Richland, WA, August 16-20.

McClure, J. D., R. E. Luna, R. M. Jefferson, and P. C. Reardon, "Summary of Radioactive Material (RAM) Transport in the USA," PATRAM '86, *Proceedings of the International Symposium on Packaging and Transportation of Radioactive Materials*, Davos, Switzerland, International Atomic Energy Agency, STI/PUB/718, Vol. 1 (1987): 511–512.

McClure, J. D., H. R. Yoshimura, J. F. Fagan, and T. Thomas, "Radioactive Material (RAM) Transportation Accident And Incident Experience In The U.S.A. (1971-1997)," SAND-97-2909C (1997).

Meinert, N. M., and Li Xiaoqing, "The First Commercial Spent Fuel Shipment in China," *Proceedings of the 14th International Symposium on Packaging and Transportation of Radioactive Materials*, PATRAM 2004, Berlin, Germany, Paper No. 231 (2004).

Mori, M, "Spent Fuel Transport Experiences in Japan," PATRAM '2001, *Proceedings of the International Symposium on Packaging and Transportation of Radioactive Materials*, Chicago, IL, USA, Institute of Nuclear Materials Management, Chicago, IL, USA (2001).

Mummery, G. G., "20 Years Experience of Large-Scale Movement of Irradiated Fuel by the CEGB," PATRAM 1983, *Proceedings of the International Symposium on Packaging and Transportation of Radioactive Materials*, New Orleans, LA, USA, Oak Ridge National Laboratory, CONF-830528-Vol. 1, Vol. II (1983).

Mummery, G. B., and R. F. Pannett, "Ten Thousand Movements of Irradiated Fuel from CEGB Power Stations—Review of Recent Experience," PATRAM 1989, *Proceedings of the 9th International Symposium on Packaging and Transportation of Radioactive Materials*, Washington, DC, USA, Oak Ridge National Laboratory, CONF-890631-Vol. 2 (1989): 1109–1114.

Nagakura, T., S. Fukuda, Y. Tsuritani, and H. Kawai, "Present Status of Nuclear Fuel Material Transportation in Japan," PATRAM '98, *Proceedings of the 12th International Symposium on Packaging and Transportation of Radioactive Materials*, Paris, France, Vol. 3 (1998): 1281–1284.

Nagano, I., T. Harada and M. Hanate, "Experiences on Domestic Transportation of Spent Fuel in Japan," PATRAM '92, *Proceedings of the 10th International Symposium on Packaging and Transportation of Radioactive Materials*, Yokohama City, Japan, Science and Technology Agency, Ministry of Transport, Japan, Vol. 1 (1992): 97–104.

Nambu, K., and K. Nakama, "Domestic Transport for Nuclear Fuel Cycle in Japan," PATRAM '98, *Proceedings of the 12th International Symposium on Packaging and Transportation of Radioactive Materials*, Paris, France, Vol. 4 (1998): 1453–1460.

NAS, *Going the Distance? The Safe Transport of Spent Nuclear Fuel and High-Level Radioactive Waste in the United States*, National Academies Press, Washington, DC (2006).

NNSA, "NNSA Partnership Successfully Removes All Remaining HEU from Uzbekistan," National Nuclear Security Administration, Washington, DC, USA (September 29, 2015).

NRC, "Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes," NUREG-0170, US Nuclear Regulatory Commission, Washington, DC (1977).

NRC, "Public Information Circular for Shipments of Irradiated Reactor Fuel," NUREG-0725, Rev. 13, U. S. Nuclear Regulatory Commission, Washington, DC (1998).

NRC, "Public Information Circular for Shipments of Irradiated Reactor Fuel," NUREG-0725, Rev. 15, U. S. Nuclear Regulatory Commission, Washington, DC (2010).

NRC, "Spent Fuel Transportation Risk Assessment," NUREG-2125, US Nuclear Regulatory Commission, Washington, DC (2014).

Nuclear Street, "Investigation Ordered in Derailment of Areva Train Used for Nuclear Material," July 22 (2013). Accessed August 2, 2016 at https://nuclearstreet.com/nuclear_power_industry_news/b/nuclear_power_news/archive/2013/07/22/investigation-ordered-in-derailment-of-areva-train-used-for-nuclear-material-072201#.V6Dv-aLG9GR

Ohtaka, K., T. Kobayashi, and F. Matsuura, "Experience of Spent Fuel Transportation at Tokai and Tokai-2 Power Stations," *Proceedings of the International Symposium on Packaging and Transportation of Radioactive Materials*, Chicago, IL, USA, Institute of Nuclear Materials Management, Chicago, IL, USA (2001).

Onodera, A., A. Nishikawa, H. Ino, and S. Ozaki, "Operational Experiences with the HZ-75T Spent Fuel Shipping Cask," PATRAM 1983, *Proceedings of the International Symposium on Packaging and Transportation of Radioactive Materials*, New Orleans, LA, USA, Oak Ridge National Laboratory, CONF-830528-Vol. 1, Vol. II (1983): 1513–1518.

Orsini, A., and M. Paganelli, "Spent Fuel Shipment—An Example of Compliance Assurance in Italy," PATRAM 1989, *Proceedings of the 9th International Symposium on Packaging and Transportation of Radioactive Materials*, Washington, DC, USA, Oak Ridge National Laboratory, CONF-890631-Vol. 2 (1989): 1136–1142.

Pannett, R. F. and J. H. Barnfield, "Thirty Years of Safe Irradiated Fuel Transport Maintaining the Record," PATRAM '92, *Proceedings of the 10th International Symposium on Packaging and Transportation of Radioactive Materials*, Yokohama City, Japan, Science and Technology Agency, Ministry of Transport, Japan, Vol. 1 (1992): 328–335.

Pertuis, V., "Surface Contamination of Spent Fuel Convoys: Resumption of Transport in France," *International Journal of Radioactive Materials Transport*, **11**, (2000): 183–188.

PNTL, "Fact Sheet: Sea Shipments of High Level Radioactive Waste from Europe to Japan," Pacific Nuclear Transport Limited, March (2010).

Podlaha, J., and F. Svitak, "SKODA VPVR/M Transport Packaging System and its use for Transport of Spent Fuel from Research Reactors," *Proceedings of the 17th International Symposium on Packaging and Transportation of Radioactive Materials*, PATRAM 2013, San Francisco, CA, USA, Institute of Nuclear Materials Management, Chicago, IL, USA (2013).

Pope, R. B., and J. D. McClure, "Estimated Annual Worldwide Shipments of Radioactive Material," PATRAM '86, *Proceedings of the International Symposium on Packaging and Transportation of Radioactive Materials*, Davos, Switzerland, International Atomic Energy Agency, STI/PUB/718, Vol. 1 (1987): 459–468.

Pope, R. B., M. W. Wankerl, C. R. Hamberger, and S. P. Schmid, "Historical Overview of Domestic Spent Nuclear Fuel Shipments in the United States," PATRAM '92, *Proceedings of the 10th International Symposium on Packaging and Transportation of Radioactive Materials*, Yokohama City, Japan, Science and Technology Agency, Ministry of Transport, Japan, Vol. 1 (1992): 121–128.

Pope, R., X. Bernard-Bruls, and M. T. M. Brittinger, "A World-wide Assessment of the Transport of Irradiated Nuclear Fuel and High Level Waste," *Proceedings of the International Symposium on Packaging and Transportation of Radioactive Materials*, Chicago, IL, USA, Institute of Nuclear Materials Management, Chicago, IL, USA (2001).

Posiva, *Transportation-Posiva*, Posiva Oy, Olkiluoto, Eurajoki Finland (2016). http://www.posiva.fi/en/final_disposal/transportation#.V0ieLZErKUk

Price, M. S. T., "Editorial: Large Transport Flask Contamination – An Update," *International Journal of Radioactive Materials Transport*, **11**, (2000): 275–277.

Rancillac, F., and G. Sert, "Declarations of Transport Accidents and Incidents in France and Contribution to the IAEA Database EVTRAM," *International Journal of Radioactive Materials Transport*, **10**, (1999): 21–26.

Reno, H. W., R.C. Schmitt, and W. C. Lattin, "Transporting Spent and Damaged Fuel in the United States: Recent Experience and Lessons Learned Related to the Evolving Transportation Policy of the U.S. Department of Energy," PATRAM 1989, *Proceedings of the 9th International Symposium on Packaging and Transportation of Radioactive Materials*, Washington, DC, USA, Oak Ridge National Laboratory, CONF-890631-Vol. 1 (1989): 648–653.

Roland, V., and J. Afonso, "Routine Transport with a Dual-purpose Cask: The TN 52L," *Proceedings of the International Symposium on Packaging and Transportation of Radioactive Materials*, Institute of Nuclear Materials Management, Chicago, IL, USA (2001).

Saegusa, T., "Transport and Storage of Radioactive Materials in Japan," *Proceedings of the 16th International Symposium on Packaging and Transportation of Radioactive Materials*, PATRAM 2010, London, United Kingdom, Institute of Nuclear Materials Management, Chicago, IL, USA (2010).

Schmidt, T., "NCS Experience in the Shipment of Spent Nuclear Fuel to US-DOE," *Proceedings of the International Symposium on Packaging and Transportation of Radioactive Materials*, Chicago, IL, USA, Institute of Nuclear Materials Management, Chicago, IL, USA (2001).

Shappert, L. B., D. W. Turner, C. V. Parks, and G. A. Aramayo, "Recent Experience in Planning, Packaging and Preparing Noncommerical Spent Fuel for Shipment in the United States," PATRAM '98, *Proceedings of the 12th International Symposium on Packaging and Transportation of Radioactive Materials*, Paris, France, Vol. 3 (1998): 1438–1445.

Sherman, G, C. A. Lopez, and A. T. Neumann, "Experience in the Transport of Spent Nuclear Fuel Assemblies," PATRAM 1983, *Proceedings of the International Symposium on Packaging and Transportation of Radioactive Materials*, New Orleans, LA, USA, Oak Ridge National Laboratory, CONF-830528-Vol. 1, Vol. II (1983): 1501–1504.

Sicard, D., "European Operating Experience on TN 24 Dual Purpose Spent Fuel Storage Casks," *Proceedings of the International Symposium on Packaging and Transportation of Radioactive Materials*, Chicago, IL, USA, Institute of Nuclear Materials Management, Chicago, IL, USA (2001).

SNL. 2005. Radioactive Materials Incident Report database. Sandia National Laboratories, (2005).

Speigel Online, "Radioactive Cargo Delayed: Thousands of Protesters Obstruct Nuclear Waste Transport," November 28 (2011). Accessed June 10, 2015 at http://www.spiegel.de/international/germany/radioactive-cargo-delayed-thousands-of-protesters-obstruct-nuclear-waste-transport-a-800319.html

Sprung, J. L., D. J. Ammerman, N. L. Breivik, R. J. Dukart, F. L. Kanipe, J. A. Koski, G. S. Mills, K. S. Neuhauser, H. D. Radloff, R. F. Weiner, and H. R. Yoshimura, "Reexamination of Spent Fuel Shipment Risk Estimates," NUREG/CR-6672, US Nuclear Regulatory Commission, Washington, DC (2000).

Stahmer, U. 2009. *Transport of Used Nuclear Fuel – A Summary of Canadian and International Experience*, NWMO TR-2009-12, Nuclear Waste Management Organization, April (2009).

Tamura, K., K. Matsuzawa, T. Kusunoki, and N. Kouda, "Experience on Return Shipments of Research Reactor Spent Nuclear Fuels in JAEA-Tokai," *Proceedings of the 15th International Symposium on Packaging and Transportation of Radioactive Materials*, PATRAM 2004, Miami, FL, USA, Paper No. 202 (2007).

Tozser, S., "Last Highly Enriched Uranium Leaves Czech Republic," International Atomic Energy Agency, Vienna, Austria (5 April 2013). https://www.iaea.org/newscenter/news/lasthighlyenricheduraniumleavesczechrepublic

Tozser, S., "Hungary Completes High Enriched Uranium Research Reactor Fuel Removal," International Atomic Energy Agency, Vienna, Austria (5 November 2013). https://www.iaea.org/newscenter/news/hungarycompleteshighenricheduraniumresearchreactorfuelremoval

Tyacke, M., and T. Anderson, "Lessons Learned from the West Valley Spent Nuclear Fuel Shipment within the United States," *Proceedings of the 14th International Symposium on Packaging and Transportation of Radioactive Materials*, PATRAM 2004, Berlin, Germany, Paper No. 212 (2004).

Verdier, A., J. Lancelot, A. Gisbert, and O. Bartagnon, "12 Flask Transport of Vitrified High Level Waste (HLW)," *Proceedings of the 14th International Symposium on Packaging and Transportation of Radioactive Materials*, PATRAM 2004, Berlin, Germany, Paper No. 196 (2004).

Voiland, E. E., and J. Van Hoomissen, "Recent US Spent Fuel Rail Shipping Campaign," PATRAM '86, *Proceedings of the International Symposium on Packaging and Transportation of Radioactive Materials*, Davos, Switzerland, International Atomic Energy Agency, STI/PUB/718, Vol. 1 (1987): 525.

Walters, H., "Curved: A truck hauling an empty nuclear waste cask gets hung up on the tricky 36," North Coast Journal, September 11 (2008). Accessed August 2, 2016 at http://www.northcoastjournal.com/humboldt/curved/Content?oid=2127962

WBFO, "Empty Nuclear Waste Container Not Damaged in Train Derailment," (2005).Accessed August 2, 2016 at http://news.wbfo.org/post/empty-nuclear-waste-container-not-damaged-train-derailment#stream/0

WNN (World Nuclear News), *Hungarian research reactor fuel returned to Russia*, WNN (2008). http://www.worldnuclearnews.org/ENFHungarian_research_reactor_fuel_returned_to_Russia2310085.html

WRAL, "Train Carrying Spent Nuclear Fuel Derails at Wake Plant," October 26 (2007). Accessed August 2, 2016 at http://www.wral.com/news/state/story/1972428/