Air Transport of Spent Nuclear Fuel (SNF) Assemblies

M. Jonathan Haire and Stanley D. Moses
Oak Ridge National Laboratory*
P.O. Box 2008; Oak Ridge, TN 37831-6166
Tel: (865) 574-7141; Fax: (865) 574-0382
E-mail: hairemj@ornl.gov

Vyacheslav I. Shapovalov and Alexander Morenko
All-Russian Scientific Research Institute of Experimental Physics
Sarov, Nzhni Novogorod, 607190, Russia
Tel: 7 83130 44689
E-mail: evgkush@rof.ru

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Oak Ridge National Laboratory
Oak Ridge, TN, 37381-6166, USA
hairemj@ornl.gov

Vyacheslav I. Shapovalov and Alexander Morenko
All-Russian Scientific Research Institute of Experimental Physics
Sarov, Nizhni Novogorod, 607190, Russia
evgkush@rof.ru

ABSTRACT

Sometimes the only feasible means of shipping research reactor spent nuclear fuel (SNF) among countries is via air transport because of location or political conditions. The International Atomic Energy Agency (IAEA) has established a regulatory framework to certify air transport Type C casks. However, no such cask has been designed, built, tested, and certified. In lieu of an air transport cask, SNF has been transported using a Type B cask under an exemption with special arrangements for administrative and security controls. This work indicates that it may be feasible to transport commercial SNF assemblies via air, and that the cost is only about three times that of shipping it by railway. Optimization (i.e., reduction) of this cost factor has yet to be done.

INTRODUCTION

The United States and Russia are cooperating, through the IAEA, in converting research reactors that use highly enriched uranium (HEU) fuel to the use of low enriched uranium (LEU) fuel by facilitating the return of HEU fuel to its country of origin. Most research reactors were built to operate on HEU (sometimes weapons-grade) fuel. The objective is to reduce and eventually eliminate civilian use of HEU worldwide. Twenty-seven countries have participated in the program on the U.S. side, returning a total of 6783 SNF assemblies to the United States. However, ~15,000 fuel assemblies remain stored outside the United States. About 4,000 kg of Russian-origin research reactor fuel have been placed in 16 countries. So far, only 112 kg of fresh fuel from seven of these countries have been returned to Russia [1].

Transportation from some countries is sometimes difficult because of location or the political conditions in neighboring countries. There has already been a need to ship SNF by air on several occasions (e.g., from the countries of Georgia and Iraq). In lieu of a Type C air transport cask, the SNF was transported under an exemption using Type B casks with special arrangements for administrative and security controls. The IAEA has established standards for an air transport Type C cask. However, no successful Type C casks have yet been designed, built, tested, and certified.

This paper also evaluates a scenario in which a Type C cask proposed for the air transport of ~20 Russian research reactor fuel assemblies is used to air transport one commercial pressurized-water reactor (PWR) SNF assembly. Unit SNF assembly air transport costs will be less than projected if the cask/aircraft system were optimized to transport multiple SNF assemblies per cask. A dedicated aircraft could be used to transport SNF. A backlog exists of many thousands of potential air shipments of SNF, and after the backlog is taken care of, a couple of thousand air shipments per year could be used in the United States. Thus, one might envision for an optimized system, for example, the design limits for the Type C cask being incorporated into the design of a dedicated aircraft frame, thereby possibly increasing payload weight.

Some advantages of SNF air transport are better security and aircraft routing to avoid highly populated areas.

Aircraft Payload Capacity

New technology has enabled aircraft with increasingly heavy-lift capability to be designed and deployed during the past 20 years. For example, the U.S. military aircraft, Lockheed C-5A/B Galaxy, has a payload capacity of 92,000 kg (see Fig. 1). The U.S. civilian Boeing 747-400F (Freighter) aircraft has a payload capacity of 112,000 kg [2].

Fig. 1. B747-400F aircraft (payload 112 tonnes) preparing to load a 40-ft-long pipe in Spain (photo provided by Tailwind Air Charters, Addison, Texas).

The Russian aircraft, Ilyushin Il-76, has a payload of 40,000 kg. The Antonov An-124 Russian Condor has a payload of 120,000 kg (see Fig. 2). And, the giant Antonov AN-225 "Mria" Cossack aircraft has a payload of 250,000 kg (i.e., 250 metric tonnes) [3]. The approximate weight of an SNF storage cask is ~150 tonne, so the air transport of SNF is feasible with current, conventional aircraft.

Fig. 2. Russian Antonov An-124 Aircraft (payload 120 tonnes) loading refinery heating unit through the rear door (photo provided by Tailwind Air Charters, Addison, Texas).

Costs

A typical roundtrip (5,000 km) cost for a dedicated Boeing 747-400F aircraft freighter is estimated to be ~$150,000 [4]. This includes loading, off-loading, and pallet build and break. No aircraft repositioning cost is assumed. A Type C cask for air transport for one PWR SNF weighs ~19,000 kg. This analysis was performed based on the An-124 Russian Condor aircraft payload weight of 120,000 kg. Additionally, administrative costs must be considered for items such as cask licensing, landing fees, and the import/export process. To be conservative, our initial concept assumes only one SNF assembly per cask and five casks per flight. No attempt has been made to optimize (i.e., increase) the number of SNF assemblies per cask. This analysis estimates that air shipment costs will be ~$30,000 per SNF assembly.

The enroute average shipping cost via railway for commercial nuclear reactor SNF in the United States is estimated to be $235, 480 for a shipment of 10 metric tonnes uranium (i.e., ~20 SNF assemblies) [5]. This corresponds to a cost of about $11,000 for each PWR fuel assembly.

The construction cost for a 319-mile railway from Yucca Mountain (YM) to an existing line is not included in this analysis. This construction cost, according to a study by Dilger and Halstead, would range from $880M to $1.5B [6]. The estimated current inventory of SNF assemblies in the United States is ~55,800 tons [7], which makes up ~100,000 SNF assemblies. At the above cost of ~$30,000 per SNF assembly, the current inventory of SNF could be air transported to the proposed YM site for ~$3B, or about two to three times the cost of the railroad spur alone. Again, the very conservative assumption is made that each air transport cask contains only one SNF assembly.

To summarize cost comparisons, the most economical means of shipping power reactor SNF is via railway. The average cost per shipment for air and rail is about the same. But, fewer fuel assemblies per shipment can be transported using airplanes. The cost of shipping SNF assemblies via air is roughly three times that of shipping via rail. But, in certain circumstances when shipping by rail is not possible, the cost of shipping via air is within reason. This assumes cask cost, cask loading costs, and cask unloading costs are the same.

Tests Required to Certify Air Transport Casks

Test requirements for the Type C cask are only slightly more stringent than those for Type B casks, except for the much more stringent 90 m/s impact test required for Type C casks.

The IAEA regulations for the safe transport of radioactive material and associated safety requirements provide the basis for the certification of Type C air transport casks [8]. These regulations provide the basis for testing and analysis for Type C casks. Type C packages have basically the same design requirements as that of Type A and B casks. However, there is an additional design requirement [IAEA regulation paragraph (¶) 680] for packages that are shipped by air. The principal requirements are given in Table I. Paragraph 667 states that Type C packages shall be designed to meet the requirements for all packages (¶606–619), for Type A packages [¶634–647, except as specified in ¶646(a)], and for Type B(U) packages (¶651–655, 659–664), in addition to ¶668–670, which are uniquely Type C requirements.

Table I. Design and Testing Requirements for Type C Packages [8]

Paragraph number	Description
667	*Type C packages* shall be designed to meet the requirements specified in paragraphs 606–619 and 634–647, except as specified in paragraph 646(a), and of the requirements specified in paragraphs 651–655, 659–664, and 668–670.
668	A *package* shall be capable of meeting the assessment criteria prescribed for tests in paragraphs 657(b) and 661 after burial in an environment defined by a thermal conductivity of 0.33 W/(m·K) and a temperature of 38°C in the steady state. Initial conditions for the assessment shall assume that any thermal insulation of the *package* remains intact, the *package* is at the *maximum normal operating pressure*, and the ambient temperature is 38°C.
669	A *package* shall be so designed that, if it were at the *maximum normal operating pressure* and subjected to: (a) the tests specified in paragraphs 719–724, it would restrict the loss of *radioactive contents* to not more than $10^6 A2$ per hour; and (b) the test sequences in paragraph 734, it would meet the following requirements: (i) retain sufficient shielding to ensure that the *radiation level* at 1 m from the surface of the *package* would not exceed 10 mSv/h with the maximum *radioactive contents* which the *package* is designed to contain; and (ii) restrict the accumulated loss of *radioactive contents* in a period of one week to not more than 10*A2* for krypton-85 and not more than *A2* for all other radionuclides. Where mixtures of different radionuclides are present, the provisions of paragraphs 404–406 shall apply, except that for krypton-85 an effective *A2*(i) value equal to 10*A2* may be used. For case (a) above, the assessment shall take into account the external *contamination* limits of paragraph 508.

Paragraph number	Description
670	A *package* shall be so designed that there will be no rupture of the *containment system* following performance of the enhanced water immersion test specified in paragraph 730.
680	For *packages* to be transported by air: (a) the *package* shall be subcritical under conditions consistent with the Type C package tests specified in paragraph 734 assuming reflection by at least 20 cm of water but no water in-leakage; and (b) in the assessment of paragraph 679 allowance shall not be made for special features of paragraph 677 unless, following the Type C package tests specified in paragraph 734 and, subsequently, the water in-leakage test of paragraph 733, leakage of water into or out of the void spaces is prevented.
730	**Enhanced water immersion test for Type B(U) and Type B(M) packages containing more than 105*A2* and Type C packages** Enhanced water immersion test: The specimen shall be immersed under a head of water of at least 200 m for a period of not less than one hour. For demonstration purposes, an external gauge pressure of at least 2 MPa shall be considered to meet these conditions.
734	**Tests for Type C packages** Specimens shall be subjected to the effects of each of the following test sequences in the order specified: (a) the tests specified in paragraphs 727(a), 727(c), 735, 736, and 737.
727	Mechanical test: The mechanical test consists of three different drop tests. Each specimen shall be subjected to the applicable drops as specified in Paragraphs 657 or 682. The order in which the specimen is subjected to the drops shall be such that, on completion of the mechanical test, the specimen shall have suffered such damage as will lead to maximum damage in the thermal test which follows: (a) For drop I, the specimen shall drop onto the target so as to suffer maximum damage, and the height of the drop measured from the lowest point of the specimen to the upper surface of the target shall be 9 m. The target shall be as defined in paragraph 717. (c) For drop III, the specimen shall be subjected to a dynamic crush test by positioning the specimen on the target so as to suffer maximum damage by the drop of a 500 kg mass from 9 m onto the specimen. The mass shall consist of a solid mild steel plate 1 m × 1 m and shall fall in a horizontal attitude. The height of the drop shall be measured from the underside of the plate to the highest point of the specimen. The target on which the specimen rests shall be as defined in paragraph 717.

Paragraph number	Description
735	Puncture/tearing test: The specimen shall be subjected to the damaging effects of a solid probe made of mild steel. The orientation of the probe to the surface of the specimen shall be such as to cause maximum damage at the conclusion of the test sequence specified in paragraph 734(a): For *packages* having a mass of 250 kg or more, the base of the probe shall be placed on a target and the specimen dropped onto the probe. The height of the drop, measured from the point of impact with the specimen to the upper surface of the probe, shall be 3 m. For this test, the probe shall have the same properties and dimensions as specified in (a) above, except that the length and mass of the probe shall be such as to incur maximum damage to the specimen. The target on which the base of the probe is placed shall be as specified in paragraph 717.
736	Enhanced thermal test: The conditions for this test shall be as specified in paragraph 728, except that the exposure to the thermal environment shall be for a period of 60 minutes.
737	Impact test: The specimen shall be subject to an impact on a target at a velocity of not less than 90 m/s, at such an orientation as to suffer maximum damage. The target shall be as defined in paragraph 717, except that the target surface may be at any orientation as long as the surface is normal to the specimen path.

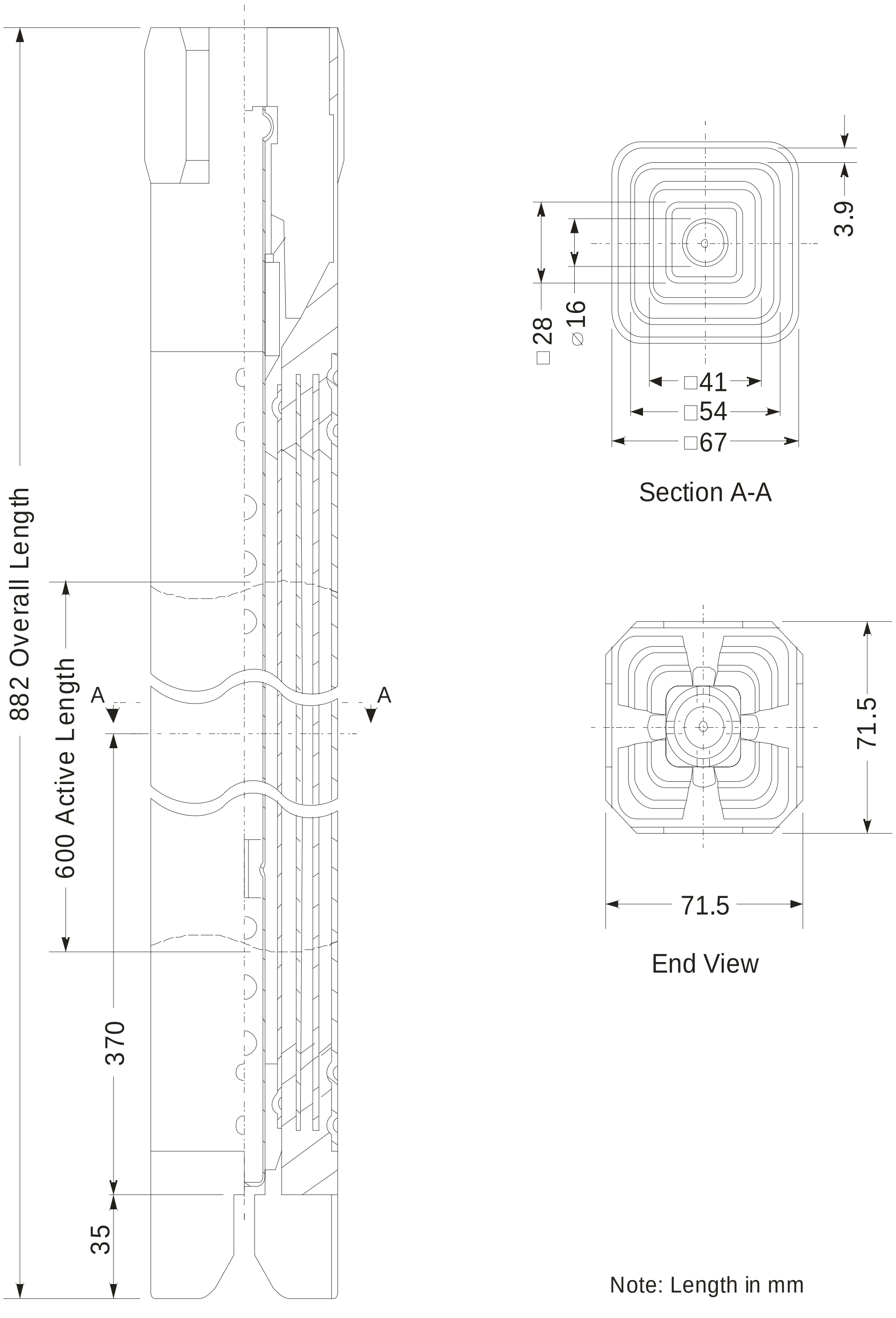
Test requirements for Type C casks are similar to Types A and B casks, except the test sequence is slightly altered, the severity is greater, and there are additional requirements. As seen in Table I, ¶730 details an enhanced water immersion test for Type C, as well as for Type B(U) or Type B(M) packages with $>10^5$A2. The test sequence outlined is for a 9-m drop, 9-m dynamic crush, the puncture/tearing test, and a fire test of 1 h (instead of 30 min.). Type C packages also must pass an impact test (¶737).

A Cask Concept for the Air Transportation of SNF from Research and Power Reactors

Figure 3 is a schematic of a typical Russian research reactor fuel assembly. Reference 9 describes an air transport Type C cask design for this Russian VPVR research reactor fuel. It is believed that an existing SKODA cask, designed and built by SKODA JS, will meet Type C standards simply by adding a special type of impact-limiting barrier.

Frequently, casks are designed for a specific nuclear reactor fuel type [e.g., research reactor, boiling water reactor (BWR), or PWR]. Table II compares various fuel assembly parameters. It is proposed that a universal cask be designed to air transport any type reactor SNF assembly. Such a preconceptual universal cask is shown schematically in Fig. 4 [9].

This proposed universal cask design is oriented toward the transport of one SNF assembly from a Russian VVER-1000 power reactor or 20 SNF assemblies from a research reactor. The envisioned universal cask includes a shielding cask with a removable impact limiter. The shielding cask is a pressurized cylinder that includes a body and two lids made from stainless steel type 12Kh18N10T.



Note: Length in mm

Fig. 3. Russian research reactor four-tube IRT-2M fuel assembly.

Table II. Typical LWR nuclear fuel assembly characteristics

Characteristic	BWR [7]	PWR [7]	VVER-1000	IRT-2M
Overall assembly length, m	4.470	4.059	4.66	0.88
Shape	Square	Square	Hexagonal	Square
Cross section, cm	13.9 × 13.9	21.4 × 21.4	22 across flats	6.7
Fuel rod length, m	4.064	3.851	3.84	0.88
Active fuel height, m	3.759	3.658	3.53	0.6
Fuel rod outer diameter, cm	1.252	0.950	0.91	0.91
Fuel rod array	8 × 8	17 × 17	hex	Square
Fuel rods (tubes) per assembly	63	264	312	3 or 4
Assembly total weight, kg	319.9	657.9		3.3
Uranium/assembly, kg	183.3	461.4	430	
UO_2/assembly, kg	208.0	523.4		

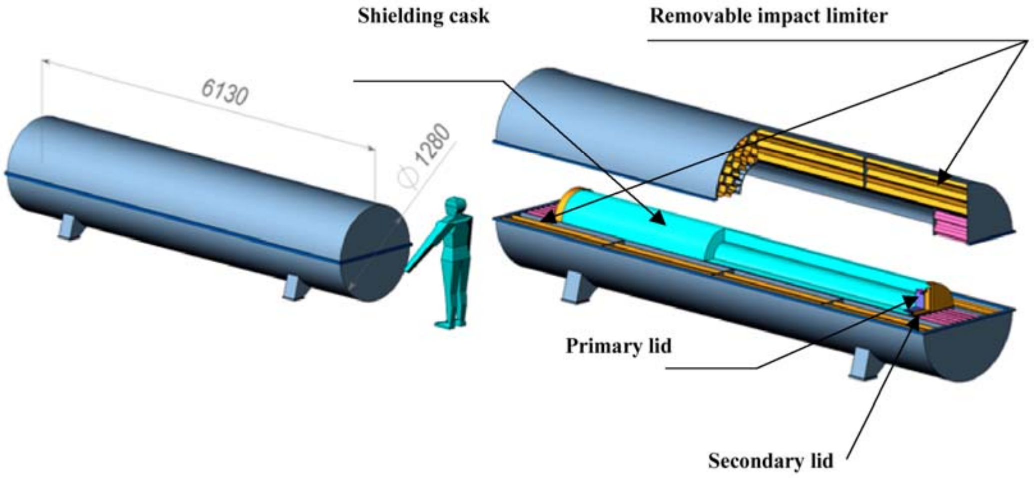


Fig. 4. Design-assembly scheme for a universal Type C cask.

Lids are mounted on the upper part of the body in a step counter bore. Each lid is sealed by two pads. The first lid—a thick disc that receives loading from the SNF assembly basket under emergency falls—is mounted onto the body by a wedge lock [9]. Such a stress-relieved joint between the lid and the cask body provides the necessary strength under shock impact of an aircraft accident. The second lid—a thin round diaphragm—is fastened to the cask body by bolts. This lid is not a load-bearing element and acts as the main seal.

The required strength of the shielding cask is provided by a removable honeycomb metal structure impact limiter for conditions representing an airplane crash. The impact limiter provides load reduction onto load-bearing and pressurized elements in conditions of an aircraft accident (i.e., at a shock impact at a speed no less than 90 m/s). The cask is designed to a load level at which the load-bearing elements of the cask work in an elastic region (i.e., a bent object returns to its original shape when a load is removed).

The shielding cask includes baskets made of atabor material (stainless steel with ~5% boron content). The baskets provide nuclear safety of the loaded cask during normal and emergency conditions. The proposed multipurpose cask has the characteristics shown in Table III.

Table III. Characteristics of a Type C cask for air transport of several types of SNF

Mass of the loaded shielding cask, kg	~ 10,000
Mass of the removable impact limiter, kg	~ 9,000
Total Type C package mass, kg	~ 19,000
Inner chamber diameter, mm	~ 300
Inner chamber length, mm	4,700
Cask length (with dynamic shock absorber), mm	~ 6,200
Outer cask diameter (with dynamic shock absorber), mm	~ 1,300

Preliminary safety calculations of the proposed “universal” cask design were carried out for [9]

- strength and hermeticity of cask design,
- thermal conditions,
- nuclear safety, and
- radiation safety.

The calculations show that the proposed universal cask design will meet safety regulations for Type C packages [9].

The main advantage of the proposed design is that it meets Russian TS-R-1 certification requirements and can be used for air transportation of spent and fresh mixed oxide (MOX) fuel and SNF from both research and power reactors. The use of such a universal cask will reduce the system cost of cask fabrication.

Conclusions

Commercial air transport of spent nuclear power reactor fuel appears feasible. A regulatory framework to define the criteria of an air transport Type C cask design is provided by the IAEA. Heavy-lift cargo aircraft are available to transport SNF, and the size and weight of such casks are well within the bounds of such aircraft’s capability. Even without optimization, an air transport cask that is of a geometry, size, and weight to be transported in currently available aircraft can be designed, built, and used at a reasonable cost. Air shipment cost would be only about three times that of rail transport in the United States.

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