RISK ASSESSMENT FOR TRANSPORT OF SPENT NUCLEAR FUEL IN RUSSIA

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ABSTRACT

In Russia spent nuclear fuel from VVER-440 reactors is transported to the reprocessing plant in Mayak. This paper presents a risk assessment of the transport of VVER-440 fuel from the Novovoronezh power plant. The work consisted of a survey of hazards along the route, assessment of normal transport risks using INTERTRAN 2, compilation of accident statistics for the route, assessment of damage to the TK-6 container in accidents, and assessment of the risks due to accidents using INTERTRAN 2. The work was funded by the European Commission under Contract No. 4.1020/D/97-002.

INTRODUCTION

The organisation of the project team was as follows:

a. Ove Arup & Partners International Ltd (UK) were the project leaders, responsible for project planning, project management and technical management.
b. VNIPIET (The All Russian Design and Scientific Research Institute of Complex Power Technology, Saint Petersburg) were responsible for provision of all data inputs, liaison with interested parties in Russia, data analysis, calculation of risks using INTERTRAN 2, and co-ordination of all activities in Russia.
c. VNIIGZH (The All Russian Scientific Research Institute of Railway Hygiene, Moscow) were responsible for provision of rail accident statistics and route survey.

The route from Novovoronezh to Mayak is a distance of 2,260km by rail one way. A number of different routes are used and the route parameters derived in this study were obtained as the average of these routes. The only transport mode used is rail. Each train is dedicated for only spent fuel transport, and a typical train is composed of:

- Locomotive
- Barrier wagon(s) (up to 3 are possible)
- 8 container wagons
- Guard's wagon (which also contains other staff travelling with the train

Four containers is sufficient for the fuel from one reactor, so eight containers (one train load) is sufficient to service the two VVER-440 reactors at Novovoronezh. The average number of trains from Novovoronezh is one per year, but occasionally there are two trains per year.

The spent fuel container used for VVER-440 fuel is the TK-6, see Figure 1. It consists of an electroslag welded forged carbon steel body and a forged stainless steel lid which provides shielding and containment of the nuclear fuel. The lid is attached to the body by means of 24 high strength bolts, and containment at the joint is provided by a rubber seal. Two modes of operation are possible, depending upon the burnup of the fuel. For low burnup the container may be transported dry, with the cavity filled with nitrogen. For higher burnup fuel the container is transported with a water coolant in the cavity. The maximum all-up weight of a loaded container is 92 tonnes. For further details see [1]. The performance of the TK-6 container in real accident conditions was assessed in [2]. The results are summarised in the following table.

Target	IAEA	Concrete Highway*		Hard Soil**
Drop Height (m)	9	9	36	9
Maximum impact force (MN)	174	19	30	11
Reduction in precompression of rubber seals (mm)	0.85	0.12	-	0.1

* = 200mm of 35MPa concrete on 300mm stone on >300mm soil
** = hard soil which could not be dug with simple pick and shovel tools.

In this work the IAEA target was taken to represent hard rock, the concrete highway to represent soft rock or hard soil.

The TK-6 spent fuel container is transported on a 12 axle rail wagon, which provides a controlled environment during transport, see Figure 2. The wagon is divided into three compartments, a cargo compartment and two support compartments. The cargo compartment completely encloses the container. It has thermal insulation and is lined with stainless steel inside. The support compartments contain heating and ventilation equipment for controlling the environment within the cargo compartment.

Shipment is performed using freight trains under exclusive use. Strict control of the train's running schedule is implemented by the Ministry of Railways of Russia. The rate of adherence to the schedule is virtually 100%, and each particular case of delay is subject to official investigation. During shipment railway personnel inspect and service the rolling stock of the container wagons. The leader of the team accompanying the shipment is responsible for prevention of over-exposure of personnel. Radiologists from Sanepidnadzor (the Federal Sanitary-Epidemiotical Supervision) railway centres perform a systematic check for compliance with radiation safety standards during spent fuel shipment. There has never been an event with a threat of radiation emergency during the whole period of spent fuel transportation.

RISK ASSESSMENT FOR INCIDENT FREE TRANSPORT

Assessment of the risks during normal transport requires the preparation of significant amounts of data for input to the code INTERTRAN 2 [3], some of which are discussed here.

The number of packages per shipment was taken to be 1, in order to prevent INTERTRAN 2 from making an automatic adjustment to the transport index which is not correct. The number of shipments per year was taken to be 16, corresponding to the case where 2 trains are transported in a year.
The total transport distance was 2,260km, of which 88.5% was taken to be in rural areas, 4.2% in suburban areas and 7.3% in urban areas. The rural population density was 21 persons/km², suburban population 3,750/km² and urban population density 8,250/km².
The train velocity in rural areas was taken to be 80km/hr, suburban areas 50km/hr and urban areas 35km/hr.
The number of persons per vehicle sharing the transport link was taken to be 34, being the average number of passengers per carriage in passenger trains moving in the opposite direction.
The building shielding factor for rural zones was 0.11, for suburban zones 0.029 and for urban zones 0.021.
The package dose rate at 1 metre was 15.4 mrem/hr, and the fraction of gamma radiation was 0.026.

The maximum exposure of the public occurs mainly to passengers in trains travelling in the opposite direction to the fuel train. INTERTRAN 2 does not take into account the effect of shielding for this case. The shielding factor (or transmission factor) was estimated as 0.435. If this factor is applied to the INTERTRAN 2 results then the following incident-free total dose results are obtained:

Public	Off link On link During stops	0.61mSv (0.061 person rem) 5.525mSv (0.5525 person rem) 1.69mSv (0.169 person rem)
Crew		0.843mSv (0.0843 person rem)
Total		8.67mSv (0.867 person rem)

The maximum individual dose is 86.5×10^{-9} Sv (8.65×10^{-6} rem). The "maximum individual dose" is automatically calculated by INTERTRAN 2 as hypothetical dose to an individual member of the public who lives beside the railroad track. The individual is modelled as living 30 metres from the rail track and the train is modelled as passing by at 24km/hr.

RISK ASSESSMENT FOR ACCIDENT CONDITIONS OF TRANSPORT

To assess the risks under accident conditions of transport it was necessary to carry out various tasks aimed at generating the necessary input for INTERTRAN 2, including compiling rail accident statistics, a probabilistic brittle fracture assessment, and a route survey to identify hazards.

RAIL ACCIDENT STATISTICS

Rail accident statistics were compiled for the regions through which the trains pass. As there have never been any accidents to spent fuel trains it was necessary to use accident statistics for conventional freight trains instead. As conventional freight trains are not subject to such strict controls as spent fuel trains this is likely to be conservative.

Accidents were compiled for the period 1994 to 1998. In order to get a statistically significant set of results statistics were compiled not only for the routes used, but for other similar routes. The total length of routes covered was 30,451km, with an annual traffic of 4.464×10^8 train-km/year. Minor events were ignored (events classified as “faulty operation” and “special cases of faulty operation”), cases considered were classified as “train emergencies” or “railway accidents”. The overall accident rate obtained was 2.46×10^{-8} accidents/km. Approximately 16% of those accidents involved a fire. The velocity distribution of the accidents was as follows:

Velocity, km/hr	Percentage of accidents, %
1-10	1.8
11-20	18.2
21-30	5.3
31-40	7.3
41-50	18.2
51-60	25.5
61-70	16.4
71-80	7.3
Total	100

PROBABILISTIC BRITTLE FRACTURE ASSESSMENT

A probabilistic brittle fracture assessment of the TK-6 container was carried out, using a methodology very similar to [4], but with parameter values based upon [5]. Stresses in the container when subjected to both impacts onto an IAEA unyielding target and real targets were calculated using the code LS-DYNA3D [6], Figure 3 shows the model used. The probability distribution of the fracture toughness of the container body material was calculated from climate data for the Chelyabinsk region, temperatures measured on the surface of the body during transport in both winter and summer time, and fracture toughness tests at a range of temperatures.

The results of the analysis indicated the following:

a. Probabilities for brittle failure were calculated for various impact events (assuming the probability of occurrence of that event is 100%) as follows:
   Lid edge attitude from 9 metres onto an IAEA target: 9.81×10^{-4}
   Axis horizontal attitude from 9 metres onto IAEA target: 2.2×10^{-3}
   Lid edge attitude from 9 metres onto concrete target: 2.9×10^{-7}
b. The probability of brittle fracture is reduced by a factor of at least 3,000 for a drop onto a concrete target as compared to a drop onto an unyielding target.
c. The model showed that most of the calculated risk comes from small (~3mm) flaws subjected to high stresses. For these cases there is likely to be a very significant enhancement of fracture toughness due to loss of constraint [7], and this effect has not been taken into account in the model. This is a topic which should be researched further.

ROUTE SURVEY

The routes used for spent fuel transport were surveyed, using an appropriate combination of study of maps and other documents, and on-site survey. Items measured included number and length of embankments, cuttings, tunnels, level crossings, stations, overbridges, underbridges, bridges over water, oil and gas pipelines on route, etc. The route survey did not identify any hard rock outcrops. However, it was conservatively assumed that 1% of the route consisted of hard rock outcrops (hard rock was considered to be equivalent to the IAEA unyielding target). The maximum potential drop height was found to be 27 metres.

This data in combination with the accident statistics allowed the probability of occurrence of postulated events to be calculated.

ACCIDENT PROBABILITIES

The probabilities of various postulated events was calculated from the data collected. The following table summarises the results.

Event	Probability (/year)
Derailment of a container wagon	1.268×10^{-4}
Impact of a container wagon with a bridge	5.71×10^{-8}
Container wagon fall from an embankment	2.13×10^{-6}
Container wagon fall from an underbridge	5.08×10^{-9}
Container wagon fall from a bridge over water	2.79×10^{-6} (culvert) 1.67×10^{-8} (bridge<25 metres wide) 6.86×10^{-9} (bridge 25-100m wide) 6.09×10^{-8} (bridge >100m wide)
Container wagon impacting a rock target at a cutting	1.78×10^{-8}
Collision of a train with a derailed container wagon	3.03×10^{-9}

A study of the probability of events of sufficient severity to give rise to the risk of criticality was carried out. Even taking very conservative assumptions where appropriate data was not available it was shown that such an event was "practically incredible" (i.e., $P<<10^{-9}$ /year).

A risk assessment for fire accidents was carried out using INTERTRAN 2. Separate accident rates for rural, suburban and urban regions were derived. Data on duration of fires was obtained by analysing records of fire accidents. Five different categories of accident severity were defined based upon the maximum fuel rod temperature as follows:

Category 1: An accident in which the maximum fuel rod temperature is less than 380°C, considered to be the temperature at which there will be no degradation of fuel cladding properties over 24 hours
Category 2: An accident in which the maximum fuel rod temperature is between 380 and 650°C. At 650°C the probability of fuel cladding rupture is very low, approximately one rod per TK-6
Category 3: An accident in which the maximum fuel rod temperature is between 650 and 815°C. At temperatures between 650 and 815°C about 50% of the fuel rod claddings can be breached
Category 4: An accident in which the maximum fuel rod temperature is between 815 and 900°C. For this category it is assumed that all fuel rod claddings are breached.
Category 5: Accident category 5 was defined as all accidents more severe than category 4.

It was estimated that the fraction of accidents in each category was as follows:

Category	Fraction of Accidents
1	0.8618
2	0.0909
3	0.032
4	0.0148
5	0.0005

The INTERTRAN 2 results showed that the expected population risk was 0.484mSv. Of this risk, 68% comes from ^{137} Cs, mainly as a result of groundshine. The maximum individual dose to a member of the public was 8.65×10^{-2} μSv.

There are no risk-based criteria applicable to transport of radioactive materials. However, it was shown that these results would satisfy risk-based criteria applicable to reactors in the UK [8].

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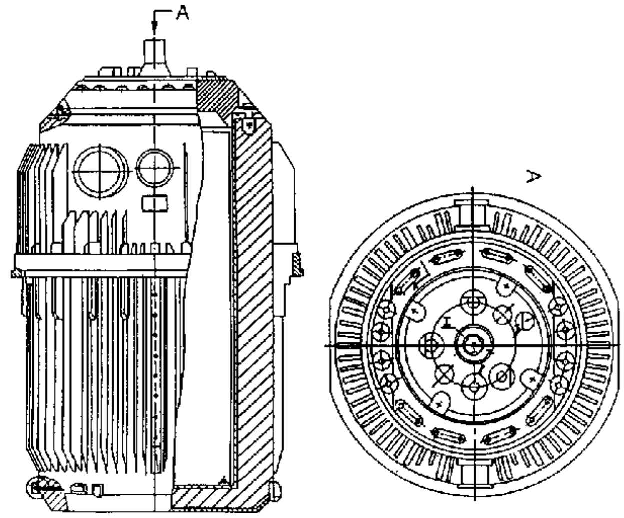

Figure 1 The TK-6 Spent Fuel Container

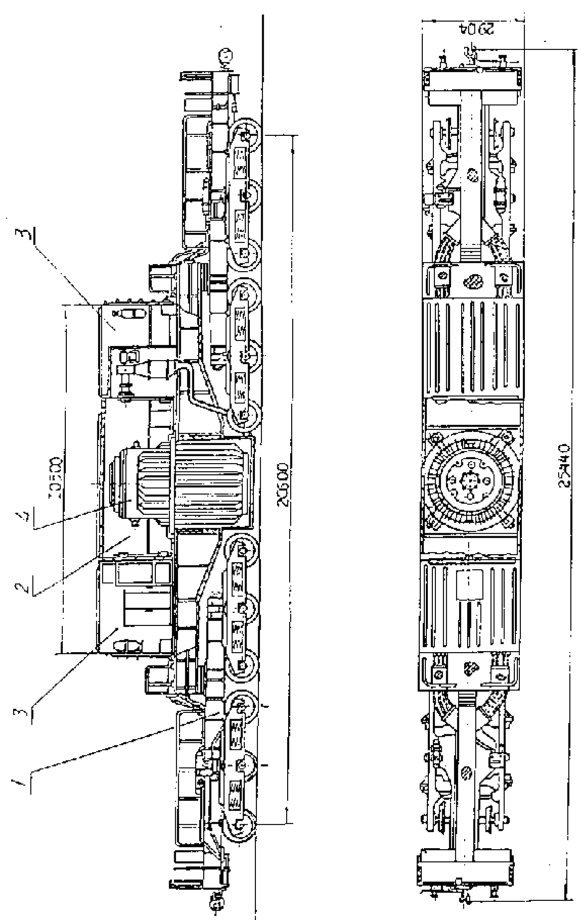

Figure 2 TK-6 Spent Rail Wagon

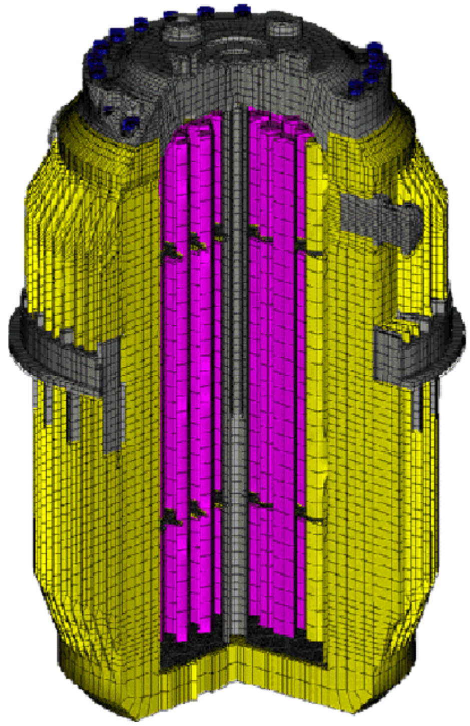

Figure 3 Finite Element Model of the TK-6 Spent Fuel Container

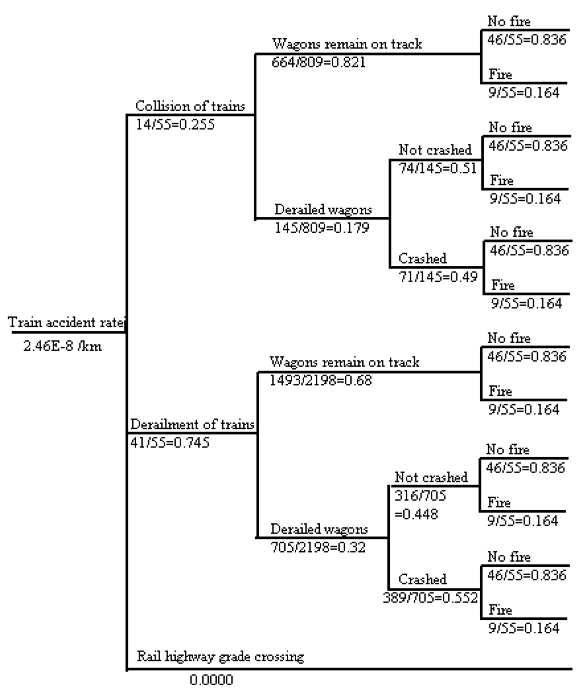

Figure 4 Fault Tree for Accidents