Fire Risks Posed to Fuel Transport Flasks During Short Sea Crossings

M. Hussain
Nuclear Transport Ltd.

INTRODUCTION

Nuclear Transport Limited (NTL) is an international company formed in 1972 for the transportation of irradiated fuel from European nuclear reactors to the reprocessing plants of the United Kingdom (UK) and France. The transport of fuel flasks involves crossing the English Channel and NTL have utilised the Trainferry *Nord Pas-de-Calais* for the sea journey from Dunkirk in France to Dover in the south of England. Over 100 transports have been made through the port of Dover.

Owned and operated by *Sociate Nationale Armament Transmanche (SNAT)*, an associate company of the French railway owner *Sociate Nationale des Chemins de fer Francais (SNCF),* the Trainferry makes three round trips daily.

In December 1995, however, the Trainferry ceases to operate between the ports of Dunkirk and Dover. Alternative arrangements have been made for a secure route using the purpose-built ship *M.V. European Shearwater*, owned by British Nuclear Fuels plc, for the sea crossing from Dunkirk to Barrow-in-Furness in the north of England.

This paper presents the fire studies concerning the Trainferry *Nord Pas-de-Calais.*

THE TRAINFERRY *Nord Pas-de-Calais*

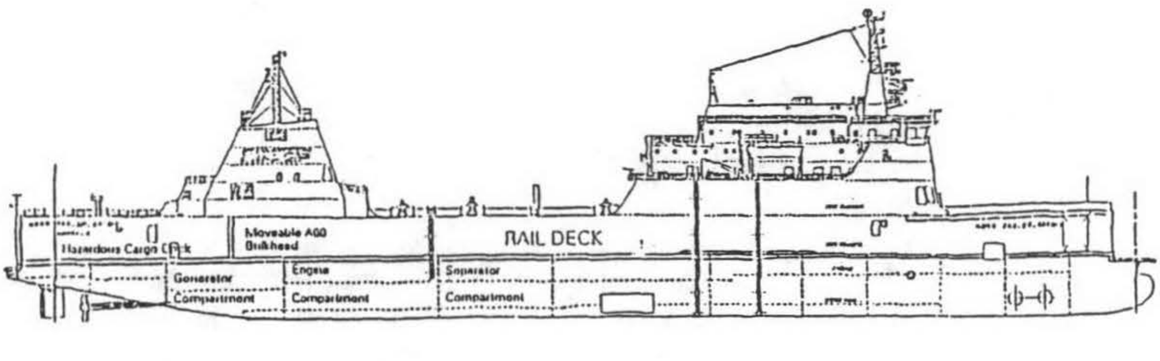
In December 1987 the Trainferry entered service, having been designed and built to the highest standards for a freight-carrying passenger ship. The vessel is primarily freight only but is certified to carry a maximum of 115 persons; that is 80 drivers of road vehicles and the rest crew. She is 13,727 gross tons with an overall length of 160 m and an in-service speed of 21.5 knots.

This vessel satisfies a more demanding standard regarding stability, compartmentalisation, damage stability, and fire safety than a conventional cargo ship. She complies with the International Maritime Organisations (IMO) Regulations for Safety of Life at Sea (SOLAS) 1974, 1974/1981 amendments and 1974/1983 amendments. In 1989 the vessel's safety was further improved by the installation of television monitors, emergency lighting, draught meters and gravity metacentric meters as recommended by the 1988/1989 amendments to the SOLAS convention.There are also a number of closed-circuit television cameras installed in the engine area which provide a good view of the machinery, via television screens, on the bridge and in the engine control room.

The Trianferry has the highest classification for a cargo vessel from the French Certification Society *Bureau Veritas* of 1 3/3F High Sea AUT-PORT. She also qualifies under the Irradiated Nuclear Fuels (INF) code as a Class 2 vessel.

Both through-decks of the Trianferry can transport roadfreight. However, the lower one is fitted with rails, with an effective length of 600 m, for the carriage of rail wagons. This lower deck can be divided, by a movable steel bulkhead, to create a space open at the stern and a closed space towards the bow of the vessel. NTL rail wagons carried the fuel flasks weighing up to 100 tonnes, classified under the International Maritime Dangerous Goods code as Class 7 goods. This means they would be segregated and would not be co-loaded with other specified dangerous goods. The fuel flasks did not travel in the aft section where highly flammable cargo would be stored. Figure 1 shows a longitudinal section of the vessel.

Figure 1. Trainferry *Nord Pas-de-Calais* Longitudinal Section



Some Member States of the IMO have expressed concerns regarding safety at sea when nuclear material is transported, particularly when using nonpurpose built ships. In view of this, NTL commissioned independent investigations into the likelihood of ship fires and the major fire scenarios that may present a threat to the fuel flasks. In 1991, the UK Atomic Energy Authority (AEA) Technology [Consultancy Services (SRD)] commenced studies for NTL into the risks posed by fire to the fuel flasks being transported.

The purpose was to define and quantify the frequency of a fire that could threaten the fuel flasks. The scope was extended to examine fire scenarios in the machinery space and on the raildeck to predict likely temperatures that could be established.

SHIP FIRE STUDIES

Frequency of fire presented in the report by Selway et al. (1991), SRD/22459/NTL/001. Where possible statistics referring to UK flag ships and vessels in UK waters have been used.This was decided as it was felt that the operation and maintenance of the vessel would be better reflected by UK data. The main fire casualty data source used was from the UK Department of Transports annual publication Casualties to Vessels and Accidents to Men (CVAM) which was superseded in 1989 by the annual review of the Marine Accident Investigation Branch (MAIB). The size of the fire that should be reported under the UK Merchant Shipping Regulations is not well-defined but in general a fire would be of a size that caused or had the potential to cause injury. Thus very small nuisance fires can be expected to be excluded. Fires remote from the raildeck or the machinery space would be included to determine an initiating fire frequency.

An average per year of over 2,000 vessels and 32 fires for vessels over 100 gross tons from 1981 to 1990 were considered. There was evidence to suggest , however, that roll-on/roll-off vessels did have a different fire frequency than general cargo vessels. Roll-on/roll-off vessel are differentiated from other vessels in the MAIB records, and so data from 1989 to 1992 involving an average per year of 125 roll-on/roll-off vessels and nine fires was considered to determine an initiating fire frequency.

The approach used to determine a fire that would be classed as *severe* included the development of event trees for the machinery space, roaddeck, raildeck, and collision followed by fire using the initiating fire frequency. The initiating fire frequency can be further divided to specific locations for the vessel. This information was found from the MAIB records and enabled the percentage of fires by location to be determined for the engine room, the roaddeck, and the raildeck.

A fire was defined as being *severe* if the containment of the compartment in which it started was breached or the fuel flasks were threatened. Thus a *severe fire* in the closed section of the raildeck would need to develop such that it threatened the rail wagons, or a fire starting in the machinery area would need to have the potential to spread beyond this space. Following an inspection of the ship, 7 fire scenarios were identified as most likely to lead to a *severe fire*. These were as follows:

- *fire in the machinery space;*
- *fire on the roaddeck at sea;*
- *fire on the roaddeck during loading/unloading;*

- *fire on the raildeck at sea;*
- *fire on the raildeck during loading/unloading;*
- *collision resulting in a fire that does not sink the ship; and*
- *fire during refuelling.*

Event tree analysis was used to investigate the identified scenarios. This technique uses a tree branch structure to define the possible outcomes of a chain of events in probabilistic terms. They have been constructed by determining the major questions that might arise during the development of a fire and the fire fighting efforts of the crew and assigning probabilities to the outcomes.

The most probable outcome was a *severe* machinery space fire at 3.8x10^{-3}/year, whereas a *severe* fire near the flask had a probability of only 2.7x10^{-4}/year. For the continuous operation of the Trainferry the general frequency was 7.0x10^{-3}/year. With an estimated maximum number of 50 flask journeys per year (that is about 3,200 km/year), the probability of a *severe* fire with a flask on board was estimated to be 1.6x10^{-4}/year. A summary of the calculated fire frequencies for the Trianferry is provided in Table 1.

Table 1. A summary of calculated fire frequencies - Trainferry *Nord Pas-de-Calais*

Initiating fire scenario	***Fire frequency***
Severe fire in machinery space	3.8x10^{-3}/year
Severe fire on road freight deck at sea	1.7x10^{-3}/year
Severe fire on road freight deck - Loading/Unloading	4.9x10^{-4}/year
Severe fire following a collision	3.9x10^{-4}/year
Severe fire on closed-section raildeck at sea	2.7x10^{-4}/year
Severe fire on raildeck - Loading/Unloading	2.1x10^{-4}/year
Severe fire on open-section raildeck at sea	1.1x10^{-4}/year

General frequency for the Trainferry	7.0x10^{-3}/year
50 flask journeys/year (3,200 km/year)	1.6x10^{-4}/year

The results were examined for areas of sensitivity to determine those probabilities that had a particularly large impact on the results. It appeared that significant reductions in fire frequencies could be achieved by increasing the probabilities of successful extinguishment by manual means, and accessing the fire control room.

Extending the study further to a deterministic phase involved using computer modelling techniques that consider the likely consequences of a fire on the raildeck and in the machinery space. The machinery space was selected because of its unfavorable location below the raildeck, and because it had the highest probability of a fire.

Consequence of fire presented in the report by Selway et al. (1992), NPS/FGH/J363/P1. This study used fire modelling techniques to investigated the growth of fires initiating on the raildeck and in the machinery space of the Trainferry. The results establish the likely temperatures to which the fuel flask could be subjected. To predict the growth of fires it was necessary to:

- *establish typical cargo inventories;*
- *develop some typical cargo fire scenarios;*
- *develop some machinery space fire scenarios;*
- *use computational means to model fire scenarios;and*
- *conduct sensitivity analysis.*

The results of the detailed consequence analysis were obtained with the assistance of the computer program called FAST, part of the HAZARD I package developed by the National Institute of Standards and Technology of the US Department of Commerce. FAST consisted of a two-layer zone model for the analysis of smoke movement, gas concentration, and heat transfer. Two-layer zone models explicitly treat the stratification observed in smoke flows by dividing volumes into two layers of variable depth. The output from the run includes upper layer and lower layer gas temperatures, the depth of the hot layer, and the temperatures of all noninsulated surrounding surfaces.

Three fire scenarios were considered for the raildeck and four in the machinery space involving burning fuel, all with varying levels of ventilation. In case of fire in the machinery space, dampers shut the ventilation and fire resisting doors seal the area. For the worst scenario on the raildeck, two flat bed wagons containing sawn timber were positioned close to each other and to the fuel flask.

Raildeck Models - The properties of cargo most relevant to the development of fire are the rate of fire growth and the rate of combustion of the materials being transported. Fire growth coefficient are experimently derived, and a value of 0.1 kW/s^2 was used for the property of the sawn timber with 15 MJ/kg for the heat of combustion. The fire load is the total potential energy that could be released in a fire. The amount of timber in the wagons was far in excess of that which could be burnt in a few hours.

In the model the 6 m high deck was divided into three sections. A centrally located 35 m x 18 m section with two adjoining sections either side of each 52.5 m x 14 m. The opening area between the compartments was restricted. A leakage area of 1.1 m^2 was assumed for the raildeck.The mild steel ceiling/floor and walls are 15 mm and 11.5 mm thick, respectively. Two arrangements of freight vehicles were modelled for the raildeck. Eight vehicles surrounded the fuel flask on the railwagon and the two with the swan timber were positioned either side by side or end to end around the fuel flask. The potential size of the fire burning at peak rate was 20 MW.

Machinery Space Models - The machinery space includes the generator, engine, and separator compartments on two levels each of 3 m in height.There are 11 ventilation dampers providing about 2.5 m^2 of total vent area in the separator room of 18 m x 10 m x 6 m. The engine room is 21 m x 19 m with four ventilation dampers providing a total of about 1 m^2 vent area. Combining the machinery space dimensions gave a room size of 63 m x 19 m x 6 m. Four vents were modelled to the outside.

The main engines use fuel oil, and electric power is generated by diesel oil. The volumes are 319 m^3 and 137 m^3 respectively. Although kept in separate tanks they were modelled as one system.The fire burning rate for the fuel of 0.035 $kg/m^2/s$ was used with a calorific value of 10,140 kcal/kg. A pyrolysis rate of 1 kg/s gave a pool fire of 28.6 m^2 for a free burning fire. If such a fire was continuously fed it would burn for about 5 days at the optimum ventilation rate. That is a vent area of about 19 m^2 which is much greater then that available should all vents and fire doors remain open. A large release of fuel of say 100 m^3 would cover the separator room to 0.5 m depth providing a pool size of about 180 m^2 .

Ignition has been assumed to occur at a pool size of 28.6 m^2. An oxygen depletion value of 5% was used to restrict the fire with time and the ventilation was considered direct to the outside. Four ventilation areas were modelled by adjusting the horizontal width but keeping the vertical height to provide the actual ventilation damper area in the machinery space. The potential size of the fire burning at peak rate was 40 MW.

Results - A maximum air temperature of about 450°C was predicted for the raildeck scenarios, with a rapid decline after 0.5 hours. The upper gas layer depth was typically 5 m (height of compartment being 6 m).The amount of ventilation available restricted fire growth.

For the machinery space, the worst scenario was taken to be a fire in the whole engine, separator, and generator compartments, with the ventilation dampers, the end fire door, and all internal doors failing to close successfully. The results show that the machinery area ceiling, that is the raildeck underside, reached a temperature of approximately 400°C after 2.5 hours. A maximum air temperature of about 630°C was predicted for the machinery space. Again the amount of ventilation available restricted fire growth.

A sensitivity analysis of the machinery space scenario extended the fire duration to many hours and found that the ceiling temperature reached a maximum of 440°C after 8 hours.

The air temperature would reach a maximum of 670°C. A lack of air ingress restricts a potential conflagration. A summary of calculated temperatures is provided in Table 2.

Table 2. A Summary of Maximum Temperatures Calculated for Fire Scenario Models -Trainferry *Nord Pas-de-Calais*

Fire scenario	***Maximum temperature***
Raildeck	Air temperature of 450°C in 40 minutes
Separator room with no air ingress	Ceiling temperature of 43°C in 3 minutes
Separator room with limited ventilation	Ceiling temperature of 95°C in 10 minutes
Whole machinery space modelled as one area (i.e. engine/separator/generator compartments) with ventilation dampers opened but end fire door *closed.*	Ceiling temperature of 157°C in 20 minutes
Whole machinery space modelled as one area (i.e., engine/separator/generator compartments) with ventilation dampers and end fire door *open*ed.	Ceiling temperature of 400°C in 2.5 hours. Extending fire to 8 hours gave ceiling temperature of 440°C, with a diminishing further rise of 4°C every 10 minutes.

COMPARISON OF TEMPERATURES AGAINST THE IAEA THERMAL TEST

The International Atomic Energy Agency (IAEA) Thermal Test briefly consists of the exposure of a specimen to a specially constructed, fully engulfing hydrocarbon fuel/air fire with an average flame temperature of at least 800°C for a period of 30 minutes or shall be any other test which provides the equivalent total heat input to the package. All theoretical calculations should use a uniform average temperature of 800°C for the radiation source and for convective heat transfer.

In an accident situation, however, the following arguments, as discussed by Pope et al. (1980) ASME publication, would apply:

- *package would probably not be optimally located within the fire source;*
- *package would probably not be supported at an optimum distance above an ideal fuel pool;*
- *actual fire source could be less severe than the well-controlled, uniformly-fed pool fire test;*
- *intervening structures could shield the package from the fire and act as heat sinks;*
- *total thermal radiation heat input to a package nearby, but not in, would be less*

than an engulfing thermal source;

- *convective heat input from a fire source not co-located with the package would be minimal; and*
- *fires usually consume and move on with a growth and a decay period;*

The maximum air temperature predicted for the Trainferry raildeck space of about 450°C would not expose the flasks to a temperature environment exceeding the IAEA Thermal Test. Extending the fire duration for the whole machinery space to 8 hours gave an air temperature of about 670°C and the machinery space ceiling temperature increased to about 440°C. All fires being severely restricted by the lack of air ingress. The machinery space ceiling forms part of the raildeck and has SOLAS A60 rating. It is constructed of materials tested to withstand a 60 minute simulated fire in a furnace heated to 900°C on a pre-set temperature curve. There are also networks of pipes running along the ceiling giving it added fire protection. A ceiling temperature of about 440°C would not threaten the integrity of the raildeck above the machinery space.

INPUT OF SHIP FIRE STUDIES TO THE IAEA/IMO

A summary of the Trainferry fire studies was submitted to the second technical committee meeting of the Joint IAEA/IMO/[UNEP] Working Group "on the safe carriage of irradiated nuclear fuel by sea," (UNEP-United Nations Environment Programme). This was held in Vienna, Austria, during April 1993. The Working Group was established to resolve safety issues of mutual interest concerning the carriage of irradiated nuclear fuel in purpose-built and nonpurpose built ships. It concluded that while the work on the Trainferry had a number of limitations, it did contribute to the Group's work in assessing marine safety.

One of the main conclusions of the Working Group was that all the information available to it demonstrated very low levels of radiological risk and environmental consequences from marine transport of radioactive material. Recommendations were also made to keep the matter under review. A code of practice for the carriage of irradiated nuclear fuel, plutonium, and hig-level radioactive wastes in flasks on board ships has since been adopted by the eighteenth meeting of the IMO Assembly.

In the ninth meeting of the IAEA's Standing Advisory Group on the Safe Transport of Radioactive Material it was recommended that a new Co-ordinated Research Programme (CRP) be established to study the fire environment on board ships. It was expected that the work would support the IAEA's review process on the safe carriage of irradiated nuclear fuel by sea. NTL has made available its ship fire studies for input to the IAEA's currently running CRP on "accident severity at sea during transport of radioactive material."

CONCLUSIONS

In the unlikely event of a major fire on the Trainferry *Nord Pas-de-Calais,* the temperatures predicted would not expose the fuel flask to fire conditions more severe than those specified in the IAEA Regulatory Thermal Test. The ship fire studies demonstrate, by using a detailed analytical approach with well-established probabilistic and consequence techniques, that the carriage of irradiated nuclear fuel transport flasks across the English Channel, using the Trainferry *Nord Pas-de-Calais* is acceptably safe.

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