EVALUATION OF THE SAFETY OF VITRIFIED HIGH LEVEL WASTE SHIPMENTS FROM UK TO CONTINENTAL EUROPE BY SEA.

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SUMMARY

The return of vitrified high level waste arising from the reprocessing of spent nuclear fuel at Sellafield to continental Europe, e.g. Germany, will start around the end of the century. The shipment of the specific flasks will include transportation via the Irish Sea, the English Channel and the North Sea with ships of the Pacific Nuclear Transport Limited (PNTL) classified to the INF 3 standard. The assessment approach is to analyse the severity and the frequency of mechanical impacts, fires and explosions with the potential to affect the package.

The results show that there is a high safety margin due to the special safety features of the INF 3 ships compared to conventional ships. The remaining accident probability for a transport of vitrified high level waste from UK to the continent is very low. No realistic severe accident scenarios that could seriously affect the flasks and could lead to a radioactivity release have been identified.

BACKGROUND AND OBJECTIVES

It is the approach of the International Atomic Energy Agency (IAEA) Transport Regulations that the safety in the transport of radioactive materials should be provided principally by the design of the package. In 1993 the International Maritime Organisation (IMO) adopted a code for the safe carriage of irradiated nuclear fuel, plutonium and high level radioactive wastes in flasks on board ships (INF Code). This code requires higher safety standards in design and construction for ships carrying INF materials and is to be seen as an added safety measure, which additionally enhances the safety level in the sea transport of radioactive material. Ships carrying several flasks with vitrified high level waste from reprocessing plants are required to be class INF 3 ships by the code.

Vitrified high level waste arising from the reprocessing of spent nuclear fuel will be returned from the UK to continental Northern Europe towards the end of this decade. The modes of transport for these return shipments to destinations in continental Europe include transportation by sea with ships of the Pacific Nuclear Transport Limited (PNTL) classified to the INF 3 standard.

The intention of the study is to analyse the severity and the frequency of mechanical impacts, fires and explosions with the potential to affect the package. The assessment approach is to apply information on accident severities and frequencies derived from general maritime accident data and to adapt this to the much increased safety features of a specific INF 3 ship. The analysis should help to judge whether and if so at which level of probability accidents involving ships might subject packages to more severe accident conditions than the IAEA regulatory tests. The information is also intended to serve as an objective contribution to the public discussions that are anticipated as a run-up of such transports of vitrified high level waste.

The study was prepared under EC contract and is part of the Co-ordinated Research Programme on Accident Severities at Sea initiated by the IAEA.

SHIP SAFETY FEATURES

One important aspect of the study is to identify and explain the differences between ships carrying hazardous cargoes and those of INF 3 standard which are used for the transportation of high level vitrified waste. Publicly available descriptions of ship design are given in [SPI 88] and [MIL 96]. Figure 1 shows some of the safety features of the ship, especially the fire fighting systems. Nine specific areas of the ships design and operation have been identified as adding overall safety "value" to the transportation of this type of material:

- **Ship structure:** double hull; 400 tonnes additional steel; watertight longitudinal and transverse bulkheads; designed against collision with a vessel of 24,000 tonnes and 15 knots
- **Propulsion systems:** duplicate diesel engines, gearboxes, propellers and a bow thruster drive system at the front of the ship
- **Power plant for electrical systems:** two independent generating systems at the front and rear of the ship; additional separate emergency generator and battery system; redundancy of power cabling along both sides of the ship
- **Fire safety:** very low fire load densities within the cargo holds and the passageways; water filled bulkhead between living accommodation/engine room and the cargo holds; watertight and fire resistant bulkhead doors along the passageways; a full multi-zone and multi-sensor fire detection system signalling to bridge and engine room; Halon extinguishing systems with supply for cargo holds, engine room, fore and aft generator rooms; fire hose reels and portable extinguishing systems within accommodation areas and machinery spaces; back up redundant sprinkler systems within each of the holds, fed from both sides of the ship's fire ring main, requires manual connection; 4 main plus 1 emergency fire pump
- **Cargoes:** the cargo of the ship consists exclusively of very heavy (50 to 100 tonne range) flasks of type B standard similar to those used for spent fuel which are mounted rigidly
- **Crew:** 26 men; higher certificates of competence for navigating and engineer officers; multi-skilling; training programmes
- **Communications:** multiple alternate systems such as satellite communication, telex over radio, radio telephone; automatic voyage monitoring system which transmits position, speed and heading reports to the UK control centre every two hours

- **Radar and anti-collision systems:** two independent, type approved radar systems, anti-collision system (ARPA = Auto Radar Plotting Aid)
- **Emergency preparedness:** special home based emergency team; home based tracking system; provision for emergency personnel, procedures and equipment.

OPERATING EXPERIENCE

The six ships of the PNTL fleet have been operated during the last 20 years without any significant accident. In this period

- an experience of about 90 ship years has been accumulated
- about 150 shipments have been performed
- about 4.5 million nautical miles (nm) travelled
- about 8000 tonnes of nuclear fuel transported
- about 4000 flasks (max. 5 tonnes fuel/flask) transported.

ACCIDENT STATISTICS

By employing statistical methods to statistical data without any event, an occurrence frequency (expected value) of an accident of $1.1 \cdot 10^{-7}$/nm can be derived from this experience. However the PNTL fleet specific database is not sufficient to estimate realistic probabilities of extreme accident scenarios.. An alternative method to provide a more realistic estimation of the accident probability of an INF 3 ship is to consider the accident statistics for conventional cargo ships. For this reason there are several attempts in the literature to apply the world wide experience of the large conventional transportation fleet to nuclear cargo transporting ships. The databases for these studies are taken from

- Lloyd's Register of Shipping keeping the world fleet and casualty statistics
- Marine Accident Investigation Branch (MAIB), recording incidents and accidents to British-registered vessels
- IMO Fire Casualty Records, based on incidents reports submitted to the IMO by all member countries
- Bureau Veritas
- U.S. Coast Guard commercial vessel casualty database.

These databases differ concerning the number of ships, type of ships included in the data base, definition of accidents, number of recorded incidents, time period. The interpretation of these databases within the different studies therefore gives a wide range of probabilistic information. A summary of the most important data originating from the statistics of the conventional cargo carrying ships is given in Table 1.

Table 1: Probabilistic Data from Conventional Ships' Statistics

Type of event	Frequency Probability	Source	Remarks
Ship fire and explosion, all reported incidents	$2.6 \cdot 10^{-3}$ /year per ship	[KAY 95], based on Lloyd's world-wide data 1984-93	32422 ships (oil tankers excl.); 859 incidents in 10 years
Ship fire and explosion, serious fires affecting cargo hold	$2.9 \cdot 10^{-4}$ /year per ship	[KAY 95], based on Lloyd's world-wide data 1984-93	32422 ships (oil tankers excl.); 93 incidents in 10 years
Ship fire and explosion, all reported incidents on Ro-Ro ferries	$6.7 \cdot 10^{-2}$ /year per ship	[KAY 93], based on MAIB reports for UK Ro-Ro ferries, 1989-92	124 ships; 33 incidents in 4 years
Ship fire and explosion, with total loss	$4.2 \cdot 10^{-4}$ /year per ship	[DEL 96], based on Lloyd's world-wide data 1994	42689 ships (cargo): 18 incidents
Ship fire and explosion, with total loss / repair	$2.1 \cdot 10^{-3}$ /year per ship; $3.5 \cdot 10^{-8}$ / nm 68% mach. room	[DEL 96], based on Bureau Veritas data 1978-88	599 fires in 287675 ship-years, (cargo, container, Ro-Ro/passenger). 108156 km average annual distance
Ship fire and explosion, all reported incidents	$1.5 \cdot 10^{-7}$ / nm; $5.4 \cdot 10^{-5}$ / port call	[SPR 96], based on Lloyd's world-wide data 1979-93	2547 fire events, 975 of which occurred in ports
Ship fire and explosion, all reported incidents	$1.7 \cdot 10^{-2}$ / year per ship	[MAI 95], based on registered UK merchant vessels 1990-94	105 fires in 6300 ship-years
Collision, all reported incidents	$7.6 \cdot 10^{-8}$ / nm ($1.5 \cdot 10^{-7}$ / nm North Sea, Channel, Irish Sea) $4.1 \cdot 10^{-5}$ / port call	[SPR 96], based on Lloyd's world-wide data 1979-93	1947 collision events, 702 of which occurred in ports
Collisions and contacts, all reported incidents	$4.3 \cdot 10^{-2}$ / year per ship	[MAI 95], based on registered UK merchant vessels 1990-94	273 collision events in 6300 ship-years
Collision, with total loss	$2.8 \cdot 10^{-4}$ /year per ship; $4.7 \cdot 10^{-9}$ / nm	[DEL 96], based on Lloyd's world-wide data 1994	42689 ships (cargo); 11 collisions (12 ships lost); 110000 km average annual distance
Collision with subsequent fire, all reported incidents	$4.2 \cdot 10^{-9}$ / nm for North Sea	[SPR 96], based on Lloyd's world-wide data 1979-93	1947 collision events, 50 of which led to fire
Collision with subsequent fire, total loss	$3.5 \cdot 10^{-10}$ / nm	[DEL 96], based on Lloyd's world-wide data 1985-94	9 incidents in 10 years; 42689 ships, 110000 km average annual distance
Foundering	$1.4 \cdot 10^{-3}$ /year per ship; $2.4 \cdot 10^{-8}$ / nm	[RAF 97], based on Lloyd's world-wide data 1994	59 incidents; 42689 ships, 110000 km average annual distance
Foundering and flooding	$3.8 \cdot 10^{-3}$ / year per ship	[MAI 95], based on registered UK merchant vessels 1990-94	24 events in 6300 ship-years

Attention must be paid to the fact that the derived probabilistic data in Table 1 originate from relatively severe accidents, since only accidents leading to deaths, injuries and/or considerable commercial losses are enlisted in the casualty records. Initiating events or precursors which result in less serious consequences (e.g. in case of successful fire fighting in an early stage) will have higher frequencies than given in Table 1.

ACCIDENT RISK ANALYSIS

Regarding the above accident data based on statistics relating to conventional cargo ships, it is evident that these statistics cannot be directly applied to an INF 3 ship. There are different approaches to deal with the accident risk associated with an INF 3 ship, bearing in mind that the undesirable event is not the fire or collision accident itself but the potential resulting loads on the cargo exceeding the design criteria of the flasks. For a reference voyage from the BNFL berth at Barrow-in-Furness to a north European port with an assumed voyage length of 1000 nautical miles the probabilities and severities of the accidents which could involve the cargo have been estimated. The following types of accidents were investigated:

- **Internal Fire**

A fire analysis taking into account the particular safety features of the INF 3 ship has been performed to quantify the probability of ship internal fires which could affect the cargo. The procedure of the fire risk analysis for the PNTL ship is adopted from the fire safety analysis for nuclear power plants. From the potential fire scenarios on board a PNTL ship, the locations with the highest frequencies for initiating fires were identified following expert evaluation and take into account their severity with respect to cargo. Based on the fire loads present, considerations of event frequencies and the possibilities of fire spread to the cargo holds, main engine room fires dominate the fire risk to the cargo.

The results of the detailed analysis are summarised in the form of an event tree in Figure 2. As mentioned previously, the available accident statistics of the insurance companies include only so-called damage fires, i.e. fires which have developed from an initiating fire to a severity with relevance to the insurers. The event tree therefore starts at the top with such a damage fire inside the main engine room, for which, as a conservative estimate, an occurrence frequency of $2 \cdot 10^{-7}$/nm has been derived from the accident statistics for cargo ships in general as summarised in Table 1 [SPR 96] [MAI 95] [DEL 96]. This reveals an occurrence frequency for a fully developed main engine room fire of $2 \cdot 10^{-4}$/voyage.

This assumption of a fully developed fire - excluded an initial fire without damage - is reflected in the first level of the event tree where only a 20% probability for successful manual fire fighting is assumed. The consecutive level of the event tree refers to the success or failure of the halon system to extinguish the fire in the engine room at this stage. If unsuccessful, the next line of defence with respect to the cargo is a water filled steel bulkhead which separates the main engine room from the cargo area. Concerning all conceivable combustible fire loads in the main engine room this barrier is sufficient to prevent a fire spread to one of the passageways on both sides of the ship running along the bulkheads of the cargo holds. Only in the case that one of the fire doors leading from the main engine room to a passageway is inadvertently open - contrary to specified procedures and including surveillance from the navigation bridge - there is a possibility for fire propagating to the passageway. For this conditional probability a conservative value of 10^{-1} was chosen from literature on fire safety analysis [FAK 97].

All further decision levels and the associated conditional failure probabilities are evident from Figure 2. Finally, four event sequences of the tree can result in a fire propagation to the interior of a cargo hold and have the end point "potential cargo damage" with associated conditional probabilities lower than $1.5 \cdot 10^{-5}$ for each event sequence, equivalent to of $3.0 \cdot 10^{-9}$/ voyage taking into account the initial probability of $2 \cdot 10^{-4}$/voyage for a fully developed main engine room fire. This results in a summed probability of all the four branches of the event tree with the potential to affect the cargo of $5.3 \cdot 10^{-9}$ per voyage. The fire risk analysis assesses the probabilities and severities of possible fires in a cargo hold. In any case the available fire loads are small enough that the thermal threat to a large flask is negligible.

- **Collision**

In case of collision between two ships, the damage to the struck ship and its cargo is mainly influenced by:

- the speed, displacement and dimensions of the striking ship
- the shape and material properties of the striking bow
- the collision angle
- the point of impact, web frame spacing of the struck ship
- the thickness of deck, bottom and side shell plating.

The double hull of a PNTL ship is designed to withstand at least an impact energy equivalent to a 24 000 tonnes ship striking at a speed of 15 knots. It is conservatively assumed that the penetration of the cargo hold is possible if a striking ship exceeds this kinetic energy and a mechanical loading of the flask might occur. The probability of this event was evaluated to be $1.6 \cdot 10^{-7}$ per trip. The initiating collision frequency ($1.7 \cdot 10^{-4}$ per trip) can be derived from the Table 1 statistics [SPR 96]. Reducing factors for the INF 3 type ships are given by the probabilities that the INF 3 ship is the ship struck (0.5), the anti-collision safety features fail (0.1), the kinetic energy is higher than the design values (0.12), the collision angle is near 90° (0.44), striking a flask (0.35).

This low collision probability does not result in damage to the flasks sufficient to cause release of radioactivity. Finite element calculations of Sandia [POR 96] for a single hulled freighter, covering several collision cases with variation in mass and velocity of the striking ship, led to the conclusion that the impact load from collision will be lower than from a regulatory 9 metre free fall. Sandia calculations also show that crush forces to the package by the bow of the striking ship are limited, because a permanently pushed flask would penetrate the opposite hull. The maximum calculated crush forces during penetration are similar to the dynamic impact force seen in the regulatory impact test [AMM 97].

Higher crush forces could result if there is a collision in a port with the struck ship docked against a quay wall. As the velocities of ships inside ports are strictly limited this event is extremely improbable.

- **Fire Induced by Collision**

The evaluation of Lloyd's accident data covering the years 1979 through 1993 shows that only 2.5 % of the collision events led to a fire (50 fires in 1947 collision events, see Table 1). The most probable of these external events is a collision with a tanker (INF 3 ship strikes tanker) whereby flammable liquids could leak into the striking ship or - much more probable - to the water surface. Penetration of the spilled liquid into the PNTL ship's cargo holds can be excluded as the hatch covers remain closed. If there is also an ignition this scenario could lead to a fire enveloping the INF 3 ship for a longer period. The probability of a fire of this type with a duration that could lead to a thermal threat to the flasks is estimated to be in the range of $2 \cdot 10^{-10}$ per trip. Additional reduction of the 2.5 % collision plus fire probability is given by the chance of setting back the striking ship (failure 0.1), the probability that the struck ship is a tanker (0.2), the probability of long fire duration, i.e. failure of cooling and extinguishing actions (0.05). A comparable probability for this scenario can be derived on the basis of a 10 years survey concerning collision and severe fires with tankers [DEL 96].

Moreover, a fire of the INF 3 ship's fuel content following a collision where the INF 3 ship is struck could result by damage of the INF 3 ship's fuel tank and subsequent ignition of the diesel. Both events are quite improbable, because the fuel tanks are at the bottom of the ship and the diesel flash point is > 60 °C. If this scenario is supposed a fire duration threatening the cargo can be excluded, because the content of the damaged fuel tank is limited and the burning layer on the water surface would spread and rapidly burn off.

- **Foundering**

Sinking of a ship of the PNTL fleet is highly improbable because of the stiff double hull construction with watertight subdivisions. The ships are capable of remaining afloat with all cargo holds flooded. Therefore, foundering statistics of conventional ships cannot be applied. For the relevant transports to the European continent the maximum depth is 238 metres, the vast majority of the area covered by these transports is less than 100 metres. In the event of a vessel being lost within the area covered by this study it is BNFL's policy to recover the cargo. Contingency plans are in place to cover this highly improbable situation. For the reference trip of the study it can therefore be excluded that foundering of the ship could lead to a release of radioactivity.

CONCLUSIONS

The probabilities of most severe accidents with the potential of mechanical and thermal impacts to the type B flasks in the range of the IAEA regulatory tests have been evaluated to be in the order of 10^{-7} to 10^{-10} during a 1000 nm sea voyage. The uncertainty of the probabilities is estimated to be one to two orders of magnitude. The results show that there is a high safety margin due to the special safety features of the INF 3 ships compared to conventional ships. There are no realistic severe accident scenarios that could seriously affect the flasks and could lead to a radioactivity release.

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Figure 1 Safety Features of a PNTL INF 3 Vessel

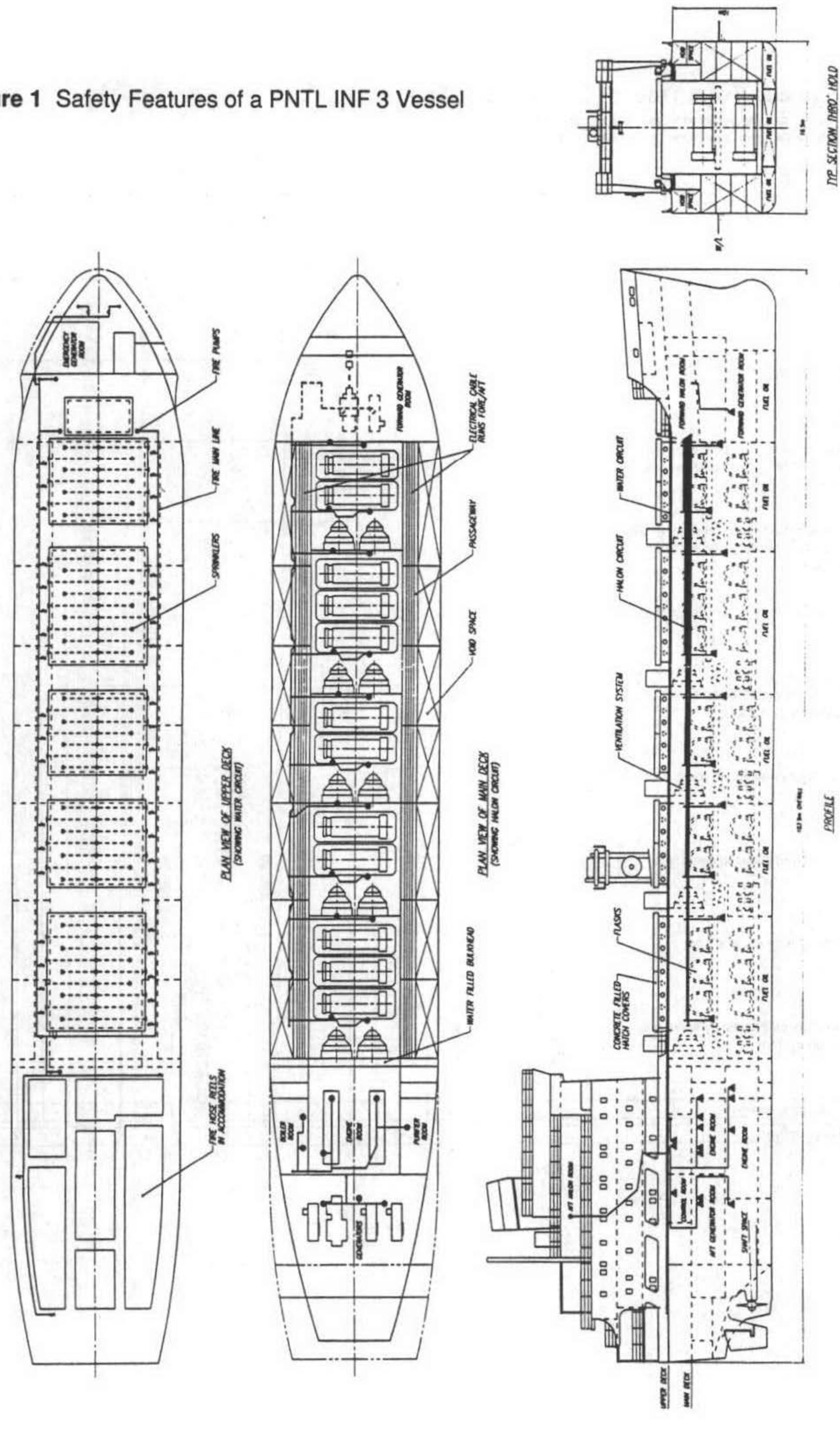
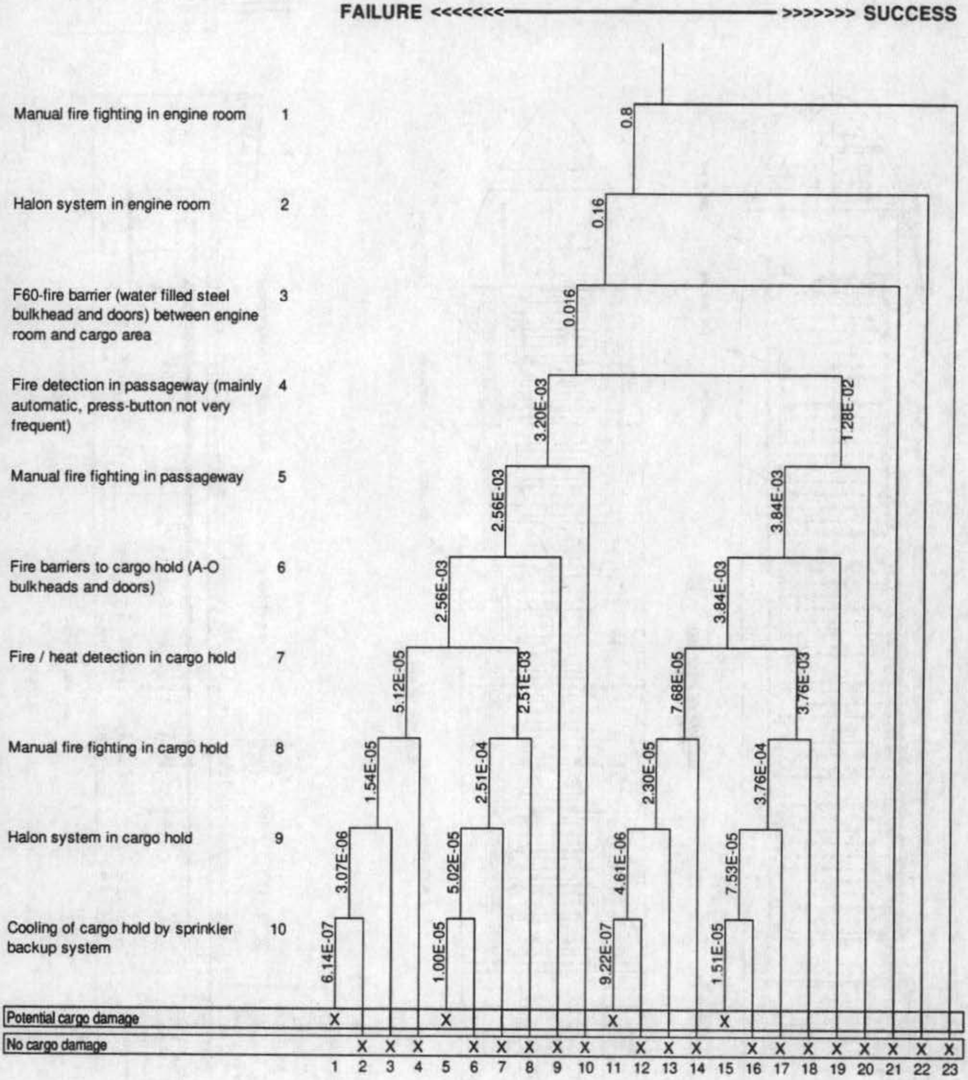


Figure 2: Event Tree for Engine Room Fire

Causing damage, reported to insurance companies
Cumulative conditional branch probabilities indicated



SESSION 12.3

LSA/SCO Materials