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REVIEW

THE SEA TRANSPORTATION OF IRRADIATED FUEL BY SKB

PART II

SEA TRANSPORTATION OF SPENT FUEL - FREQUENCY OF ACCIDENTS

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SEA TRANSPORTATION OF IRRADIATED FUEL BY SKB

PART II - SEA TRANSPORTATION OF SPENT FUEL - FREQUENCY OF ACCIDENTS

ABSTRACT

PART I of this Review determined the number of voyages to be undertaken by *M/S Sigyn* (and its successors) to move the fuel from the nuclear power plants to the central store (CLAB) and then, at some time after year 2008, from CLAB to the final disposal repository. This section of the Review identifies the most likely, seriously damaging accident to be a ramming or collision at sea followed by intense fire. Without demonstration at this stage, the very high forces arising during collision/ramming events are considered sufficient to breach the flask containment and, if followed by fierce fire, the sustained temperatures involved will result in a significant airborne release of radioactivity, with the fire plume simultaneously providing an efficient dispersal mechanism by which a very significant radioactive release could be delivered directly to a human population.

Based upon recorded incidents at sea, the probability or chance of a seriously damaging event involving M/S Sigyn, or its successors, is reckoned to be:-

ACCIDENT SCENARIO	LIKELIHOOD PER VOYAGE PER YEAR	NO EXPECTED OVER TOTAL SIGYN VOYAGES	LEAST SEVERE	MOST SEVERE
COLLISION/RAMMING	1:340	2 TO 4	NONE EG BUMP OR SCRAPE	FLASK(S) CRUSHED OPEN
FIRE PORT/APPROACHES	1:2600	0 TO <1	NONE EG CONTAINED FIRE	SEE LATER
1 IN 3 FIRES ARE SERIOUS	1:7800/YR	1:240 TO 390 LIFETIME	VERY SERIOUS FIRES	MACHINERY AND CARGO SPACES
1 IN 50 WILL BREACH FLASK	1:130000/YR	1:4000 TO 6500 LIFETIME	1 IN 50 TO BREACH FLASK	EXCEED IAEA SS6 STANDARDS

These statistics, albeit drawn from a collection of real ship fires for a variety of types and tonnage of ships, suggest that during its working lifetime of carrying irradiated fuel (ignoring voyages carrying other radioactive wastes to the SFR) *M/S Sigyn* would be expected to experience a small number of collisions and fires.

Fire-fighting ship fires suggest that about one in three fires will develop to serious fires. This yields the chance of outbreak of serious fire over the lifetime of *M/S Sigyn* of about 1 in 250 to 1 in 400. This severity of fire is at or beyond the level that the ship's crew would abandon ship, from which time the risks of grounding and/or sinking would be much elevated.

As acknowledged by an experienced irradiated fuel transporter (BNFL), 1 in 50 fires would be expected to develop to such severity as to breach the fuel flasks carried on board – this category of fire results in radioactive release and airborne dispersion of the release. The chance of such a serious fire event and the accompanying radioactive release over the service lifetime of *M/S Sigyn* is about 1 in 4,000 to 1 in 6,500.

Statistics are, of course, just statistics predicting neither the certainty nor frequency of the sampled event. The fuel flasks on board *M/S Sigyn* are at theoretical risk of 1 in 4,000 to 6,500 which compares with the NASA space shuttle Columbus, designed to be fail-safe to a chance of one in a million (1:1,000,000), but which failed on its 27th launch (1:27) and, of course, SS Titanic, the unsinkable ship designed never to sink, that foundered on its maiden voyage (1:1).

PART II - SEA TRANSPORTATION OF SPENT FUEL - FREQUENCY OF ACCIDENTS

CREDIBILITY OF ACCIDENT INVOLVING SHIPS – FIRES AND COLLISIONS

Accidents involving ships include collisions, rammings, groundings, fire and explosions, foundering and miscellaneous causes including equipment and material failure and the result of hostile action. Such accidents occur in ports and approaches, at sea over continental shelves and slopes, and at deep ocean locations.

Idealised and 'Unsinkable' Ship

One relatively recent design for the 'unsinkable'[a] ship is the conceptual, radioactive waste emplacement ship *Glosten*.[1,b] The intended role of the *Glosten* was to transport ‘sticks’ or torpedoes of irradiated fuel which were to be remotely emplaced within the sea bed.

The design of the *Glosten* concept ship[c] would enable it withstand collisions, rammings, groundings, fire and extreme adverse weather conditions, although it was acknowledged that *Glosten* could not be expected to be proofed against all extremely damaging events. For this reason, the safety case compiled for the *Glosten* in its radioactive fuel-carrying role took into account a range of statistical probabilities associated with the common maritime risks collisions, rammings, sinkings and fires.

Rammings and Collisions

Significant ramming and collision events were qualified as being those of sufficient severity that could, potentially, imperil the ship – this is not to imply that each event would actually result in serious damage, simply that the incident included the *potential* to escalate to a seriously damaging event.

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a For many years, perhaps since the very onset of the formal design of ships, naval architects and marine engineers have endeavoured to produce the 'unsinkable' ship design. Brunel first introduced the design concept of cellular construction, including a watertight double bottom cavity, in the 1850s for the then revolutionary *SS Great Eastern* steamship. Other ships, including the *SS Titanic*, have claimed to be unsinkable but to date no ship design has been demonstrated totally resistance to accidental sinking, either as a result of battering by the natural elements or, perhaps less often, by the intervention of human error either at design or operation stages.

b *Glosten* was part of a US programme then considering the emplacement of radioactive spent fuel and HLW capsules in the sea bed – the 29,600 tonne displacement *Glosten* was to collect the waste, transport it to a deep water site and then emplace the waste in boreholes – like the similar Nuclear Energy Agency proposal of the late 1980s, the *Glosten* project was subsequently abandoned.

c Protection from sinking was to be provided by infills of urethane foam along the side wing tanks and on the bottom, with the foam also serving to provide collision and ramming protection - the foam and combined hull and bulkheads (of massive 74mm and 38mm thickness respectively) provide, so it is claimed, a collision energy absorption capacity of $3.16.10^6$kN-m that is sufficient to prevent penetration into the cargo hold by any vessel ramming at a speed of less than 24 knots, regardless of the mass or bow construction. The cargo holds carrying the radioactive waste would have been lined with 230mm of ceramic fibre insulation sufficient to isolate the cargo from a 72-hour fire of 928°C temperature.

Ramming and collision frequencies assumed for the *Glosten* were as follows:-

TABLE 7 SHIP COLLISION/RAMMING/GROUNDING PROBABILITIES
EACH OUTWARD BOUND TRANSIT OF *GLOSTEN*

	PROBABILITY		
GENERAL LOCATION	COLLISION	RAMMING	GROUNDING
PORT AND APPROACHES	$1.90\ 10^{-4}$	$4.87\ 10^{-4}$	$7.79\ 10^{-4}$
CONTINENTAL SHELF	$1.82\ 10^{-6}$	-	-
CONTINENTAL SLOPE	$3.63\ 10^{-6}$	-	-
DEEP OCEAN	$4.13\ 10^{-5}$	-	-
TOTALS	**$2.37\ 10^{-4}$**	**$7.24\ 10^{-4}$**	**$15.03\ 10^{-4}$**

For this advanced ship design, the highest risk of collision and rammings occurs in harbours and the approaches – these *Glosten* probabilities are based on an assumed rate of one collision per 100,000 encounters.

TABLE 7 provides the overall risk of collision (serious but not necessarily sinking) for each loaded journey of about once in every 4,200 years ($2.37.10^{-4}$), of incidents involving collision or ramming of about once every 1,400 years ($7.24.10^{-4}$), and for all incidents about once every 650 years ($15.03.10^{-4}$).

To apply this analysis to *M/S Sigyn* operations, modifications have to be made in account that each sea voyage includes at least two legs of port approach/departure and berthing and, effectively, there is no deep ocean element – this gives a collision risk of $\sim 4.10^{-4}$, with ramming 14.10^{-4} and all risk with grounding 30.10^{-4}, which resolves to a risk of a seagoing incident (not necessarily culminating in severe damage or sinking) once every 340 years per voyage. Or, put another way, referring to TABLE 4 (PART I), to complete the total fuel transfers *M/S Sigyn* will have to undertake either 825 or 1,328 voyages (for the 25 and 40 year scenarios), then it (or its successors) would be expected to be involved in 2 to 3 or 4 to 5 potentially seriously damaging incidents during the course of its entire service life.

This crude application of the statistics derived from the *Glosten* study, gives no regard of the routing of *M/S Sigyn* which operates in the busy sea lanes of the Baltic, The Sound and Kattegat. This routing factor alone would be likely to increase the rate of potentially seriously damaging incidents.

In summary: So, obviously, collisions involving *M/S Sigyn* with some other vessel or structure are possible and, on the balance of probabilities, likely to occur a few times during the SKB fuel transfer programme. Thus, a ramming/collision incident is a *Credible* accident for the SKB irradiated fuel transfers by ship:-[d]

LIST 1A CREDIBLE ACCIDENTS FOR M/S SIGYN

ACCIDENT SCENARIO	LIKELIHOOD PER VOYAGE PER YEAR	NO EXPECTED OVER TOTAL SIGYN VOYAGES	LEAST SEVERE	MOST SEVERE
A) COLLISION/RAMMING	1:340	2 TO 4	SERIOUSLY DAMAGING	FLASK(S) CRUSHED OPEN

Frequency of Ship Fires

Statistical records for damage to and total losses of ships due to fire and explosion do not show any trend of reducing incidence with advancing fire containment/fighting technology. To the contrary, a generally increasing incidence of severely damaging fires and explosions on board ships is found, with fire and/or explosion contributing to about 30 to 40% of the total losses from all causes during the period 1974 to 1984.[2] In certain years losses from this cause alone reached 47% (1983), 46% (1982) and 45% (1977, 1980). During the previous decade (1960-70) fires and explosions contributed on average to 23% of the total losses.

World losses resulting from (serious) fires and explosions, expressed as a percentile of all serious incidents, on board ships are as follows:-[3]

TABLE 8 CHARACTERISTICS OF FIRE/EXPLOSION LOSSES

	1974	75	76	77	78	79	80	81	82	83	84
WORLD TONNAGE 10^6	304	334	364	385	397	404	411	412	415	413	409
TOTAL LOSSES											
N° TOTAL LOSSES	54	48	57	65	71	63	56	69	72	66	56
% FIRE/EXPL LOSSES	0.10	0.06	0.10	0.14	0.10	0.17	0.20	0.16	0.16	0.15	0.10
% TOTAL TONNAGE	0.34	0.31	0.32	0.31	0.35	0.56	0.43	0.39	0.35	0.33	0.32
% FIRE LOSS	29.5	19.5	29.5	45.1	28.9	31.2	45.0	41.8	46.0	47.2	30.7

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[d] Although Part 3 of this report will not consider mechanical failure of the flask by impact alone, the forces arising from rammings and collisions can be very significant indeed. The loss of a flask at sea with a flask being lost over the side and then plummeting freely to the bottom, can also give rise to very significant impact forces - in account of the buoyancy forces and drag resistance, the flask reaches a terminal velocity, thereafter descending at a constant speed which, for the prevalent depths of water, always exceeds the IAEA 9m free fall in air drop test – for a sinking flask, the terminal velocity is given by $V=\sqrt{(\rho_f/\rho_w-1)*l*g/(2(2C_f l+C_d d/4))}$, where Cf would be ~0.0025 and Cd between 0.3 to 0.1 for differing Reynolds No. Even so, SKB dismisses this (SKB *En Delrapport fran Projektet "Beskrivning av Risk"*, R-97-22) on the premise that the sea bottom will be sandy and absorb much of the impact force.

LOCATION OF ALL FIRE/EXPLOSION INCIDENTS (TOTAL AND PARTIAL DAMAGE)

% AT SEA	41	32	38	41	40	41	41	41	49	47	49
% PORT IN REPAIR	4	5	3	4	5	7	7	6	5	7	9
% PORT AT BERTH	54	59	59	55	55	52	52	53	46	46	42
N^O TOTAL EVENTS	402	366	349	360	347	343	314	354	329	286	260

FIRES/EXPLOSIONS ARISING FROM COLLISION AT SEA

% COLLISIONS	4.2	4.5	0.8	4.7	-	10.8	4.6	-	0.6	-	-

LOCATION OF OUTBREAKS OF FIRE/EXPLOSION (KNOWN AND REPORTED IN SUFFICIENT DETAIL)

% ACCOMMODATION	20.6	16.1	11.8	9.0	12.9	10.3	10.5	11.5	20.9	13.1	12.8
% CARGO SPACE	29.3	34.4	37.1	32.2	30.1	26.9	27.2	37.8	25.8	24.1	26.7
% ELECTRICAL	5.6	2.9	0.8	0.8	2.9	4.5	5.7	3.4	3.1	2.6	5.6
% MACHINERY	33.8	37.7	43.2	49.0	45.6	48.8	49.6	41.2	45.8	58.7	50.8
% STOKEHOLDS	6.3	6.2	0.3	5.1	5.4	4.5	2.2	3.4	3.6	1.6	0.5
% OTHER	4.4	2.6	0.3	3.9	2.9	4.9	4.8	2.7	0.9	0.0	3.6

VESSEL SIZE TONNES (DISPLACED) N^O OF TOTAL LOSSES

500- 1000	14	8	10	5	14	4	7	8	6	8	11
1000- 2000	9	12	9	10	19	13	10	16	11	11	11
2000- 4000	13	10	12	15	11	20	12	9	15	9	10
4000- 6000	4	5	6	8	7	-	3	5	8	6	3
6000- 7000	2	2	3	3	2	1	4	1	1	3	2
7000- 8000	3	3	2	3	3	5	1	2	4	2	1
8000-10000	1	3	4	5	6	7	4	8	10	12	4
10000- 15000	5	4	7	11	2	3	5	11	9	10	8
15000- 30000	2	1	2	1	5	5	4	4	3	-	4
30000- 50000	-	-	2	2	2	2	1	3	3	4	1
50000- 75000	1	-	-	2	-	1	1	2	1	-	1
75000- 100000	-	-	-	-	-	1	1	-	1	-	-
>100000	-	-	-	-	-	1	1	-	1	-	-

Notes: Excludes losses due to military action and known acts of terrorism, malicious acts sabotage, etc.

Further analysis of the statistics[4] of TABLE 8 provides an insight into seriously damaging outcome of fires on board ships, the size and locations of ships most vulnerable.

First, although all losses due to fire and explosion represent a small proportion of the total World shipping (between 0.1 and 0.2%), fire and explosions on board ships contribute to, on average, 36% of the total losses from all causes. Secondly, vessels of the size of *M/S Sigyn* between 2,000 to 6,000 tonnes displacement register the highest number of losses. Thirdly, accommodation, cargo and machinery spaces feature strongly in the location of the outbreak of fire and or explosion. Fourthly, incidents involving fire and explosion on board ships occur about as frequently (if not at a slightly greater frequency) for berthed vessels than for vessels underway at sea.

In fact, fires and explosions nearby ports (when the vessel is in the approaches) significantly increase according United States shipping data,[5] with 97.5% of the fire and explosion accidents occurring in harbours and approaches, with the remainder of incidents occurring as a function of the time spent over each offshore depth.[e]

TABLE 9 % TOTAL LOSSES ARISING FROM FIRES AND EXPLOSIONS

YEAR	LOSS(%)	YEAR	LOSS(%)
1960	12	1974	30
1961	35	1975	20
1962	12	1976	30
1963	17	1977	45
1964	23	1978	29
1965	21	1979	31
1966	30	1980	45
1967	25	1981	42
1968	23	1982	46
1969	35	1983	47
1970	25	1984	31
AVERAGE	**23**	AVERAGE	**36**

Referring once again the risk analysis undertaken for the *Glosten* concept ship:

TABLE 10 *GLOSTEN* SHIP FIRE AND EXPLOSION PROBABILITIES
EACH LOADED TRANSIT

GENERAL LOCATION	PROBABILITY FIRE AND EXPLOSION
PORT AND APPROACHES	$1.90\ 10^{-4}$
CONTINENTAL SHELF	$2.70\ 10^{-8}$
CONTINENTAL SLOPE	$5.40\ 10^{-8}$
DEEP OCEAN	$4.79\ 10^{-6}$
TOTALS	**$1.95\ 10^{-4}$**

[e] For its operation of a fleet of 5 irradiated fuel ships, BNFL assess the frequency of a seriously damaging fire on board a radioactive fuel transfer ship to be 3.10^{-5} per annum (about once in every 33,000 years for each ship year of operation) with the maximum collective radiation dose (if such an accident occurred nearby a large city) to be 300man-Sv (Salmon A, *The Transportation of Radioactive Waste*, Conference on Radioactive Waste Management, Tucson, March 1987). If such statistics are accepted, an accident is expected in BNFL's fleet of five ships operating over a twenty year period at a chance of 0.003 per annum. On the other hand, a study by the UKAEA predict (*Summary of the Risk Assessment Made of the Transport of Plutonium Nitrate*, Chicken J C, UKAEA, SRD R 187, 1980) the incidence of seriously damaging fire (sufficient to fail the flask) at once every million years for plutonium nitrate shipments from Scrabster. Since the incident of fire is greatest when in port or during the approaches (97.5%) (*The Effect of IAEA Regulations on the Design of Shielded Containers*, Dixon F ATOM Nº, 1984) the relative lengths of journey are not significant, so for the seven annual shipments of plutonium nitrate the UKAEA predictions include a staggering probability of once every 7,000,000 years for each complete voyage. On this basis, the UKAEA safety analysis assumes that in the heavy cargo ro-ro ship used for this carriage only 1 in 1,400 fires will develop to severely damaging proportions.

This aspect of the *Glosten* accident analysis applies to a complete single voyage so the risk is about once every 5,100 years per voyage. Again, the *Glosten* analysis includes all fires of a 'reportable' severity, the majority of which may not be severely damaging to the flasks.[f]

Applying the *Glosten* port approaches data to *M/S Sigyn requires* a doubling of the risk since M/S Sigyn is loaded during two harbour/port transits:

LIST 1B CREDIBLE ACCIDENTS FOR M/S SIGYN

ACCIDENT SCENARIO	LIKELIHOOD PER VOYAGE PER YEAR	NO EXPECTED OVER TOTAL SIGYN VOYAGES	LEAST SEVERE	MOST SEVERE
A) COLLISION/RAMMING	1:340	2 TO 4	NONE EG BUMP OR SCRAPE	FLASK(S) CRUSHED OPEN
B) FIRE PORT/APPROACHES	**1:2600**	**0 TO <1**	**NONE EG CONTAINED FIRE**	**SEE LATER**

Predicting the probability of a fire occurring on any one ship is rather more difficult. This is not only because maritime accident data is related to gross tonnage but, particularly, because of the range of different types of ships and the diversity of roles which these ships undertake. Such generalised and overall statistical data for commercial vessels is of limited relevance when considering specific ships that have quite specific functions.

This is not to imply that the *M/S Sigyn* is exempt from these statistics but, simply, that it is not at all clear where such a ship definitely fits into the broad range of available data - this difficulty is heightened because SKB has not published its detailed accident analysis for *M/S Sigyn* and the irradiated fuel transfer process.

As a guide, Lloyds Register (1985) gives a probability for the total construction loss by fire for commercial vessels to be 0.00407 per year per vessel (a chance of once in every 245 years for each year of operation[g]). Other sources (European Parliament - A2-329/87) state that 75% of maritime accidents arise as a direct result of human error and that for ro-ro ferries *"accidents pose particularly grave risks, and may endanger human life"*.

[f] The BNFL prediction referred to earlier (once in 33,000 years for each ship year of operation) relates to serious fires which result in radioactive material release so that, crudely, each of the loaded leg of say four voyages per year is accompanied a risk of fire once every 132,000 years (or 1:264,000 years for each complete voyage). The comparison between BNFL and *Glosten* suggests (if both are roughly correct) that on a specialised, well fire-protected ship one in fifty fire will develop to a severely damaging fire. Applying this fire frequency to *M/S Sigyn*, then the expectation is that there will occur a fire on board at a rate equivalent to once every 320 and once every 180 years and, if and when a fire does occur there is a 1:50 chance of it developing to a seriously damaging event.

[g] For each and every successive year of operation.

LIST 1C CREDIBLE ACCIDENTS FOR M/S SIGYN

ACCIDENT SCENARIO	LIKELIHOOD PER VOYAGE PER YEAR	NO EXPECTED OVER TOTAL SIGYN VOYAGES	LEAST SEVERE	MOST SEVERE
A) COLLISION/RAMMING	1:340	2 TO 4	NONE EG BUMP OR SCRAPE	FLASK(S) CRUSHED OPEN
B) FIRE PORT/APPROACHES	1: 2600	0 TO <1	NONE EG CONTAINED FIRE	SEE LATER
C) FIRE SHIPS GENERALLY	1:245	N/A	-	TOTAL LOSS

There are, however, a number of shortcomings with the statistics relating fires on ships which arise, principally, because the nature of the cause of the fire or explosion is not included in any great detail within the short reports from which the statistics are compiled, nor are all fire incidents included within the statistics.[6] Comparing the Local Authority Fire Brigades (LAFBs) records for fire incidents in ships at UK ports illustrates such omissions:

TABLE 11 SHIP FIRES ATTENDED BY LAFBS

YEAR	TOTAL	FATAL	N^O F'MEN	JETS DEPLOYED				SERIOUS FIRES	
				1-2	3-4	5-7	>8	N^O	%
1974	575	5	214	148	7	9	0	164	28
1980	468	4	146	119	15	6	0	140	30
1981	460	5	162	123	8	1	2	133	29
1982	496	0	197	129	7	0	2	138	28
1983	462	2	167	143	5	2	1	151	33

Notes: 1 Fires attended whilst ship in port, includes repairs, etc
2 All other fires where the number of jets is not specified were put out using hose reels, the number of LAFB (not ship) main jets gives a crude indication of the extent and severity of the fire.

This somewhat limited data suggest that of all fires on board ships in berth about one-third (28% to 33%) develop to serious fires. This is not necessarily at odds with the implied fire development rate suggested by comparison of the *BNFL-Glosten* predictions that only one in fifty ship fires develop to seriously damaging fire sufficient to breach the flask containment, since it has to be acknowledged that to breach a dry-filled flask by fire alone, the fire severity would have to be extreme.[h,7]

[h] For example, the LAFB judgement of a serious fire is likely to relate to the intensity of firefighting required and fatalities, rather than the extreme of flame temperature and duration.

LIST 1D CREDIBLE ACCIDENTS FOR M/S SIGYN

ACCIDENT SCENARIO	LIKELIHOOD PER VOYAGE PER YEAR	NO EXPECTED OVER TOTAL SIGYN VOYAGES	LEAST SEVERE	MOST SEVERE
A) COLLISION/RAMMING	1:340	2 TO 5	NONE EG BUMP OR SCRAPE	FLASK(S) CRUSHED OPEN
B) FIRE PORT/APPROACHES	1:2600	0 TO <1	NONE EG CONTAINED FIRE	SEE LATER
C) FIRE SHIPS GENERALLY	1:245/YR	N/A	INCLUDES ENGINE & CARGO FIRES	TOTAL LOSS BUT ALL SHIP TYPES
D) LAFB 30% SERIOUS	1:7800/YR	1:240 TO 390 LIFETIME	VERY SERIOUS FIRES	BASED ON B) PORT APPROACHES
E) BNFL/GLOSTEN	1:130000/YR	1:4000 TO 6500 LIFETIM	1 IN 50 TO BREACH FLASK	BASED ON B) PORT APPROACHES

So, adopting the fire risk data applied commonly by an irradiated fuel transporter (BNFL) and for the concept *Glosten* fuel ship design, for transporting irradiated fuel alone *M/S Sigyn* runs a risk of a severe fire sufficient to damage a flask at a chance of between 1 in 4,000 to 1 in 6,500 over its operational lifetime.

Temperature, Ferocity and Duration of Ship Fires

The ferocity and duration of shipboard fires are acknowledged to result in extremely high temperatures and for very long periods. Examples of fire damage to ships illustrate the fire intensity that can take hold and persist - for example, the fire on board the MV Betelgeuse (bridge and accommodation fire on a tanker) continued for several hours *"if not days"* and resulted in all of the port glasses melting.[8] In fact, the 1984 SOLAS amendments of the International Maritime Organisation (IMO) regulations stop short considerably below the containment of fires within the ship, with the bulkhead divisions requiring only to be proofed to 843°C, whereas fires can reach temperatures well in excess of this temperature, and aluminium alloy structures (now increasingly in use in ship superstructures) are only proofed to 200°C above ambient.

Actual fire temperatures on board ships are not readily available, although adopted fire temperatures of 982°C for both external (arising from a pool of hydrocarbon on the water surface surrounding a ship) and internal (machinery space) fires on board ships have been attained and exceeded.[9] To the contrary, recent experimental studies[10][11] suggest lower fire temperatures arise within holds of ships.[i]

[i] One obvious limitation to the SANDIA work was the choice of cargo for ignition – Ref 10 and 11 assume a heat transfer rate of 30kW/m^2 from a timber source, whereas it is acknowledged that hydro-carbon fires (such as the IAEA SS6 Thermal Test) will invoke heat transfer rates at and in excess of 70kW/m^2.

LIST 1E CREDIBLE ACCIDENTS FOR M/S SIGYN

ACCIDENT SCENARIO	LIKELIHOOD PER VOYAGE PER YEAR	NO EXPECTED OVER TOTAL SIGYN VOYAGES	LEAST SEVERE	MOST SEVERE
A) COLLISION/RAMMING	1:340	2 TO 5	NONE EG BUMP OR SCRAPE	FLASK(S) CRUSHED OPEN
B) FIRE PORT/APPROACHES	1:2600	0 TO <1	NONE EG CONTAINED FIRE	SEE LATER
C) FIRE SHIPS GENERALLY	1:245/YR	N/A	INCLUDES ENGINE & CARGO FIRES	TOTAL LOSS BUT ALL SHIP TYPES
D) LAFB 30% SERIOUS	1:7800/YR	1:240 TO 390 LIFETIME	VERY SERIOUS FIRES	BASED ON B) PORT APPROACHES
E) BNFL/GLOSTEN	1:130000/YR	1:4000 TO 6500 LIFETIM	1 IN 50 TO BREACH FLASK	BASED ON B) PORT APPROACHES
F) FIRE TEMPERATURE			**DEBATE ON MAXIMUM TEMP OF SHIP FIRES > IAEA THERMAL TEST**	

Again as a guide and because of the diversity of shipping activities, the IMO records show the mean duration of serious fires at sea to be about 23 hours and fires when berthed about 20 hours - these statistics, collated for fire incidents over two decades, include a standard deviation of 68 and 44 hours respectively.

LIST 1F CREDIBLE ACCIDENTS FOR M/S SIGYN

ACCIDENT SCENARIO	LIKELIHOOD PER VOYAGE PER YEAR	NO EXPECTED OVER TOTAL SIGYN VOYAGES	LEAST SEVERE	MOST SEVERE
A) COLLISION/RAMMING	1:340	2 TO 5	NONE EG BUMP OR SCRAPE	FLASK(S) CRUSHED OPEN
B) FIRE PORT/APPROACHES	1:2600	0 TO <1	NONE EG CONTAINED FIRE	SEE LATER
C) FIRE SHIPS GENERALLY	1:245/YR	N/A	INCLUDES ENGINE & CARGO FIRES	TOTAL LOSS BUT ALL SHIP TYPES
D) LAFB 30% SERIOUS	1:7800/YR	1:240 TO 390 LIFETIME	VERY SERIOUS FIRES	BASED ON B) PORT APPROACHES
E) BNFL/GLOSTEN	1:130000/YR	1:4000 TO 6500 LIFETIM	1 IN 50 TO BREACH FLASK	BASED ON B) PORT APPROACHES
F) FIRE TEMPERATURE			DEBATE ON MAXIMUM TEMP OF SHIP FIRES > IAEA THERMAL TEST	
G) FIRES OF LONG DURATION			**ALL EXTEND BEYOND IAEA 30 MINS TO 20 HOURS OR MORE**	

In summary: Statistics of past fires are difficult to decipher and apply to specialised ships, such as the BNFL *Pacific* class and the *M/S Sigyn* radwaste ships.

A dominant characteristic of ship fires is that unless the initial outbreak is suppressed quickly, then the fire will continue to progress in severity.[12] In other words, immediate fire suppression activities virtually exhausts the firefighting facilities carried on board ships and, eventually, crews have to abandon ship leaving the fire completely uncontrolled. As expected, if a fire on board a ship takes hold then the fire will rage for hours (if not days), so serious ship fires are prolonged events sweeping throughout the ship compartments.[j]

[j] Engine room and machinery space fires appear most likely of all fires to lead to total loss of the ship.[j] The basic problem is that the engine room is one, single undivided compartment and although there may be sub-division for purifiers, works rooms and stores, the enclosures serving these areas are seldom wholly fire-resistant. Engine room fires at sea are usually fought by flooding the space with carbon dioxide, but the use of carbon dioxide can result in an additional hazard, that of static sparking and explosion where flammable atmospheres are present (see Butterwrth D J *Electrostatic Ignition Hazards associated with Preventative Release of Fire Control Agents, Studies on Carbon Dioxide*, CLM/RR/D2/47, October 1979). A serious shortcoming of carbon dioxide flooding is that the compartment has to be

All that can be stated with certainty is that fires do occur on board ships, that all types of ship are at risk of fire, and that some of these fires are prolonged, high temperature and severely damaging, to the extent that these fires result in the total loss cargoes and ships.

Risks Overall

Within the range of statistics for incidents involving ships, the greater proportion involved are what are best described as 'bumps and scrapes' which are often assumed not to escalate to major incidents. On the other hand, serious losses at sea (either by fire or collision alone, or by combination of both) are not that infrequent and there seems to be little to differentiate between the risk posed to the most modern, well defended sea-going and sea bedded structures[k] and poorly maintained floating hulks.[13]

So, in summary, there are a number of *Credible* accident scenarios that could beset *M/S Sigyn* – these include rammings and collisions, fire and explosion on board when at sea or at berth.

However, whatever the accident scenario, the circumstances imposed upon the flask and its contents must be sufficient to breach the containment of the flask;[l] present conditions to the fuel that will induce radioactive release, either by pulverising the fuel and/or by bringing forth highly volatile radioactive products (gases, aerosols, fine particulates); and this must be an energetic mechanism in the general and wider vicinity of the accident site that will convey the radioactive release to a human population (or to some point in a path which will eventually result in exposure of a population).

Obvious mechanisms for breaching the flask containment are the very high forces arising in ship collisions and rammings; intense fire might also serve to breach the flask and, once breached, such will enhance the release fractions of fission products, particular the gas Krypton and the volatile metal caesium from the fuel; and a fierce fire burning for several hours, or more, on board a crippled ship drifting at sea or foundered on shore could provide sufficient plume lofting to a height where wind borne dispersion carries the radioactive plume to a landside community.

evacuated of all personnel before the flooding commences. The *M/S Sigyn* utilises a halon[j] flood system in the main engine room and water sprinklers in the flask cargo holds.

k Losses such as the ro-ro ferry *Herald of Free Enterprise* at Zeebrugge, the offshore rig *Piper Alpha* in the North Sea and, most recently, the Estonian Baltic Ferry.

l The sufficiency of the fuel flask to withstand accident forces and conditions is set out by the *IAEA Safety Series 6, Regulations for the Safety Transport of Radioactive Materials,* edition as adopted by the particle State (Sweden adopts the 1990 Edition) – these regulations specify that the fuel flasks (Type B) should be capable of withstanding a number of tests, including a free drop onto an unyielding target from 9m, engulfment in a hydrocarbon fire at 800°C for 30 minutes, a spike impact and immersion in water. The TN17/2 flask complies with these requirements although the encapsulated fuel flask prototype (see Knopp, Ref 8) has yet to be tested.

Accidents are by their very nature accidental. Thus, it is beyond the wit of mankind to describe all possible combinations and severities of accidents, how frequent such will occur and, indeed, if any particular accident will ever occur. That said, accidents do happen.

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