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REVIEW OF NUCLEAR SAFETY PROCEDURES RELATING TO THE BERTHING, REFITTING AND REFUELLING OF ROYAL NAVY NUCLEAR POWERED SUBMARINES AT DEVONPORT ROYAL DOCKYARD

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REPORT REF N° R3038-A1

22 MAY 2000

First Issued 4 May 2000

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NUCLEAR SAFETY AT DEVONPORT ROYAL DOCKYARD

SUMMARY

This review briefly considers the nuclear activities undertaken at the Dockyard that are at risk of a severely damaging incident and radioactive release. The type of incident identified to present the greatest demands upon the emergency contingency planning is reckoned to stem from a primary circuit coolant accident (LOCA) in the reactor compartment of a Royal Navy nuclear powered submarine when in the approaches to, manoeuvring within or berthed in the Dockyard basin.

Depending on the severity of the loss of coolant and, particularly, the position of the breach in the primary circuit the event, from initiation to rupture of the submarine hull containment and release of radioactivity to atmosphere, could be completed within a few minutes. Again according to the severity of the events during and immediately following the LOCA, the fuel temperature could elevate sufficiently to liberate virtually all of the fission product inventory over a relatively short period of, perhaps, less than 1 hour or within a few hours.

In this extreme accident scenario the effectiveness of sheltering and iodine prophylactic measures are likely to be totally swamped by the magnitude of the release and the very high rates of radiation exposure to those individuals caught in the path of the radiation zone of the radioactive release plume. The only remaining option to mitigate the continuing health detriment to those under exposure would be for immediate evacuation from the (radio)active areas.

Although the Royal Navy acknowledges this severely damaging LOCA to have a probability of occurrence, the present contingency planning for Devonport, *DEVPUBSAFE*, could not effectively safeguard members of the public from the consequences of this and less severe accidents that initiate and progress to radioactive release in very short time scales.

The point here is that, other than to isolate and distance all potential accident sites from members of the public, it is not practicably possible to implement countermeasures that would completely safeguard the public in the immediate aftermath of a severely damaging LOCA. However, that said, contingency planning for such a severe event can include organisational features and identify resources to be deployed necessary to mitigate the radiological consequences in the aftermath of the accident.

In the immediate aftermath or, where applicable, during the build-up to an accidental release of radioactivity, the local authorities and public emergency services are almost wholly dependent upon the Royal Navy's assessment of the nuclear fuel within the reactor – this particularly applies to the 2 km radius pre-planned countermeasures zone where contingency measures are implemented at the say so of the Royal Navy. However, the means and criteria by which the Royal Navy assesses the condition of the reactor fuel and how it translates this into human health protection measures remains restricted information beyond the public domain.

The Devonport plan, *DEVPUBSAFE*, is reviewed in terms of the shortfalls that may arise from these two aspects, that is failure to plan for the extreme accident and lack of publicly available information relating to the assessment of the hazard once that a reactor accident is underway.

NUCLEAR SAFETY AT DEVONPORT ROYAL DOCKYARD

POTENTIAL ACCIDENT SCENARIOS

At and about the Dockyard there exists a number of potential sources of radioactive release, including:-

a) the reactor and reactor compartment enclosures of an operational nuclear powered submarine in the approaches to, manoeuvring in the Tamar including for transferring ordnance at the proposed RAFT, or at berth in the Dockyard basins and quays;

b) the reactor compartment whilst the submarine is dry docked and undergoing reactor maintenance, including refuelling;

c) an incident involving radioactive wastes stored at the Dockyard; and

d) the irradiated fuel cores from nuclear powered submarines presently stored at the Dockyard.

Each of these generalised accident scenarios could result in dispersion of significant quantities of radioactivity to the populated areas beyond the landside perimeter of the Dockyard.

Potentially, the most significant accident scenario at the Dockyard involves the malfunctioning of the nuclear reactor of an operational submarine.

RADIOACTIVE RELEASE

For a radioactive release to occur, both the *reactor primary circuit* and the *fuel cladding* system of the nuclear fuel within the reactor core must fail permitting the radioactivity spread into the submarine *reactor compartment*.

To progress from the compartment into the atmosphere the reactor compartment, forming the *secondary containment*, must be breached to enable a plume of radioactivity gases, vapours and particulate matter to release to the immediate environment.

FIGURE 1 shows a Swiftsure class of submarine with the reactor compartment located behind the sail or conning tower. **FIGURE 2** shows the type of fuel assembly deployed in a submarine reactor and **FIGURE 3** is a schematic diagram identifying the main components of the reactor and steam raising equipment housed within the reactor compartment.

EXPOSURE PATHWAY AND RADIOACTIVE DOSE UPTAKE

So far as members of public are concerned, the primary means of delivery of the radioactivity, or *source term*, in the immediate aftermath of the accident is via the release being dispersed to the atmosphere, being carried aloft airborne as a plume, progressively cooling and thence settling down to provide an inhaled or respiratory *uptake* of the individuals so exposed.

So, the factors that need to be considered in evaluating the consequences of an accidental release of radioactivity have to account for the:-

1) size and radionuclide inventory or the *source term* available for release;

2) severity and nature of the accident;

3) surety of the containments that dictate how much of the source term is ejected to the atmosphere;

4) efficacy of dispersion of the release plume of radioactivity, its pattern of deposition as determined by the energy of the accident release, the prevailing meteorological conditions and local terrain; and

5) degree of exposure of the receptor group and, of course, the susceptibility of the group to harm from the exposure; and the

6) extent of mitigation achieved by effective intervention countermeasures.

1) RADIONUCLIDE INVENTORY – FISSION PRODUCT INVENTORY

The nucleus of a uranium-235 atom is bound together by very strong subatomic forces, so a great deal of energy is stored within an intact U^{235} atom. This energy can be released, much of it as useful heat, if the atom can be split or fissioned and rendered unstable. The heat liberated by this fission process is used to raise steam to drive the turbines that raise power for the propeller and other services of the submarine.

Essentially, when an atom is fissioned it breaks into two unstable fragments that immediately commence to radioactively decay. Because fission can occur in a large number of different ways, this results in hundreds of different fission products being generated within the body or matrix of the fuel.

The fission products remain in the irradiated fuel, sealed in by the fuel casing or cladding.

So, it follows, for every fission occurrence the radioactive inventory of the reactor fuel core increases. However, since the rate of radioactive decay for the various fission products generated differs (from a few tenths of second, to hours, days, years and tens of thousands of years), to determine the inventory at any one time in the reactor fuel life it is necessary to have knowledge of the previous operating history of the fuel core and, for this analysis, if and for how long the reactor had been shut down at the time of the radioactive release.

The Royal Navy adopts[1] what it refers to as a *Standard Core History* for which the 70MW[2] PWR1[3] reactor is assumed to have been operating continuously at 100% *maximum rated power* (MRP - *Plant State A*) for the previous 100 hours and at all previous times at 25% MRP. This Standard Core History gives a rather low inventory (**TABLE 1**), not particularly typical of a submarine that has been in operation for one year or more and where the same fuel will remain in the core for up to eight or more years between refuels.

TABLE 1 ROYAL NAVY <u>STANDARD CORE HISTORY</u> IMMEDIATELY FOLLOWING SHUT DOWN

	TBq[4]			
NUCLIDE/GROUP	TOTAL CORE	MAX RELEASE FRACTION	PROBABLE RELEASE	
Halogens - Volatile Iodine	40,000	4000	400	
All other nuclides	400,000	40,000	4,000	
	440,000	**44,000**	**4,400**	**Core/Release inventory**

On this basis, it might be more appropriate to consider a nuclear powered submarine that has been operating for one year at full power for which TABLE 2 gives the fuel inventory.

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[1] Restricted Royal Navy document December 1977.

[2] 70MW = 70 million watts of thermal power or capable of delivering about 15,000 shaft horsepower.

[3] PWR – Pressurised Water Reactor.

[4] TBq = 10^{12} Becquerel where $3.7.10^{10}$Bq = 1 Curie so 440,000 TBq is about 10 million Ci = 10MCi

Table 2 Royal Navy One Year Continuous Operation immediately following Shut Down

Nuclide/Group	TBq	
Halogens - Volatile Iodine	**746,000**	
Krypton/Xenon	1,114,000	
Tellurium	800,000	
Caesium	3,000	
Strontium	3,000	
Ruthenium	13,000	
	~2,000,000	**Total other nuclides**
	2,746,000	**Core inventory**

This assumption for a *one-year* core, which corresponds to the safety case assumed by the United State Navy for its inventory assessments, might be realistically extended to a core history of 600 days which yields, for an equivalent 70MW reactor run continuously at 100% MRP, the inventory given in Table 3.

Table 3 70MW Core at 600 Days Full Power immediately following Shut Down

Nuclide/Group	TBq	
Halogens - Volatile Iodine	**458,000**	
Noble Gases – Krypton/Xenon	217,000	
Alkali Metals - Caesium	83,000	
Chalogens – Antimony/Tellurium	138,000	
Strontium/Barium	364,000	
Metals – Moly/Ruth/Rhodium	276,000	
Lanthanides – Yttrium, etc	1,264,000	
	2,340,000	**All other Nuclides**
	~2,800,000	**Core Inventory**

In fact, some of the radioactive decay rates, or *half-lives*,[5] are very short. Of the 180 or so different fission products generated, about 100 have half-lives less than one hour, 30 or so have half-lives between one hour and one day, leaving the remaining 40 or so radionuclides with significant half-lives, some of which are

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[5] The radioactive half-life is the time period over which the (radio)activity halves so, starting at an activity of, say, 1000 disintegrations per second (dps - the clicks of a Geiger counter), at the passing of one half-life the strength is one-half or 500 dps, at two halves-lives one-quarter or 250 dps, at three half-lives one-eighth or 125 dps, and so on – if the half-life was 1 year, the remaining radioactivity at three years would of one-eighth of the original activity

very persistent indeed. This initial rapid decay of the reactor core radioactivity results in the total activity level of the reactor reducing significantly within thirty minutes of shut-down and reduced overall to about two-thirds by three days following shutdown.

This rapid decay is important if the time frame of the accident scenario and release occurs over a reasonably extended period, particularly so for the halogens as shown by TABLE 4.

TABLE 4 70MW CORE AT 600 DAYS FULL POWER IMMEDIATELY AND 3 DAYS FOLLOWING SHUT DOWN

NUCLIDE/GROUP	HALF LIVE	TBq Immediate	TBq 3 Days	
Halogens – Iodine-131	8.05d	68,000	52,500	
Iodine-132	0.1d	105,000	55,300	
Iodine-133	21h	151,000	14,000	
Iodine-135	6.7h	134,000	-	
Total Halogens		**458,000**	**122,000**	**~x4 reduction**
Alkali Metals - Caesium		82,700	82,700	
Chalogens – Antimony/Tellurium[7]		137,800	79,000	
Strontiums/Barium		364,000	39,500	
Metals – Moly/Ruth/Rhodium		276,000	199,200	
Lanthanides – Yttrium, etc		1,264,000	1,100,000	
		2,340,000	**1,500,400**	**All other Nuclides**
		~2,800,000	**1,622,000**	**Core Inventory**

This three day interval from full power to a lower level of reactor power, called *Plant State B*, at the time of the accident to be considered here might be a reasonable expectation for, say, a nuclear powered submarine returning from patrol, surfacing at the approaches and derating to *Plant State B*[3] for the two or three days of disarming in the Tamar at RAFT and, subsequently, reverting to *Plant State A for* manoeuvring into and about the Dockyard basin.

In summary: The fuel core of a naval propulsion reactor represents a very significant radioactive source term. This is because although the total fuel is small, the extent of fuel irradiation or 'burn-up' is high, particularly towards the end of the fuel cycle life at which time the fuel might have been in the reactor for eight or more years.

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[7] Tellurium-132 with a half-life of 77 hours, decays to Iodine-132 at a rate of ~1,300TBq/MW or about 90,000TBq at 24 hours following shutdown

2) NATURE AND SEVERITY OF THE ACCIDENT – SOURCE TERM RELEASE

As outlined previously, for a fission product radioactive release from an operational nuclear powered submarine to occur three containment barriers have to fail.

First, a sufficiently severe event has to occur in the reactor pressure and/or primary circuit to fail the individual fuel element cladding, and then the overall secondary containment provided by the submarine reactor compartment must fail in order to release the radioactive fission products to atmosphere.

The accident scenario that qualifies for this is whereby the reactor primary circuit fails and there is a very rapid or near instantaneous loss of coolant water which flashes off to steam in the reactor compartment. If the rupture of the primary circuit is sufficiently large and the rate of loss of coolant is beyond the emergency core cooling water make-up capacity (which is limited on a submarine), the reactor fuel will overheat, the core will melt down and the cladding system will fail, resulting in a fission product release into the reactor primary circuit and, thence, into the reactor compartment. Even if, in the event of a severely damaging LOCA, the reactor shuts itself down immediately, there remains sufficient heat deriving from initial high rates of radioactive decay of the fuel to melt the fuel.[8]

Maximum Design Accident – MDA

This order of loss of coolant accident scenario, or LOCA, is adopted by the Royal Navy as its *Maximum Design Accident* (*MDA*) for which a guillotine breach of the primary circuit is assumed to occur in the primary pipework feeding to and from the reactor – the actual layout of a PWR1 reactor compartment of the now decommissioned *Valiant/Churchill* class, but which generally applies to the current operation *Swiftsure* and *Trafalgar* classes of SSNs, is shown by **FIGURES 4** and **5**.

The adoption of the LOCA MDA requires that the designers of the submarine ensure that there are sufficient safeguards in place to ensure that the occurrence of the MDA neither occurs at an unacceptable frequency nor does it, so far as is reasonably practicable, result in intolerable consequences. The MDA applies to all operational states of the reactor system.[9]

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[8] Radioactive decay of the fuel alone, in the absence of fissioning, immediately following reactor shut down accounts for about 8 to 10% of the maximum rated power, that is about 7MW. Since the mass of the highly enriched uranium fuel within the reactor is relatively small, approximately 220kg, the self-heating temperature to melt down temperature in the absence of water cooling is very rapid.

[9] The reactor plant on board a Royal Navy submarine is capable of operating at three different settings:-

For this MDA the reactor system and submarine hull design is considered to be sufficiently robust to maintain secondary containment, although it is acknowledged that the hull and/or bulkheads could be penetrated by, say, flying pieces of plant equipment thus providing a radioactive release route.

The estimated frequency of occurrence is reckoned 10^{-6} per reactor year of operational service (ie one in a million or once in a million years for every year that the reactor is in service).[10] For example, for a single submarine of, say, 30 years service life the odds of MDA increases to (1,000,000/30=) once in 33,333 years. Or, put another way, for a flotilla of submarines of 20 submarines the collective odds of MDA occurrence reduce to (1,000,000/(30*20)=) once in 1,666 years.[11]

LOCA MDA and Other LOCA Accident Scenarios

The aftermath of a LOCA includes a number of pressure pulses or transients that apply to and test the submarine hull and bulkhead structures – **FIGURE 6** shows the reactor compartment section and its enclosing bulkheads.

The first pressure transient occurs when the spilling coolant flashes off to steam[12] filling the normally sealed reactor compartment. The compartment enclosure, hull, bulkheads and boat services penetrations that pass through the

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a) *Plant State A:* The reactor setting for normal sea going is referred to as *Plant State A* under which the reactor is capable of operating at maximum power. At State *A* with the reactor primary circuit pressure is in excess of 170 bar at temperature of about 320°C.

b) *Plant State B:* The plant state normally adopted for docking is *State B* where the primary circuit pressure and temperatures are reduced to below 35 bar and 120°C respectively.

c) *Out of Commission:* When the boat is under refit or extensive maintenance, the primary circuit pressure is reduced to just above atmosphere (1 bar) and the temperature maintained at about 70°C. This plant state is necessary to remove the radioactive decay heat from the reactor core and is usually managed by a shoreside low-pressure decay heat removal system that matches and manages the diminishing heat output of the reactor core.

Whilst in the Dockyard submarine reactor plant may be operated at *Plant State A* during *Power Range* testing and *Fast Cruise* training.

[10] Whereas the RN states (DEVPUBSAFE) the estimated risk of accident to be between once in 10,000 to 1,000,000 years, it adopts a slightly different approach in defining the acceptable risk or frequency of accident inasmuch that for a dockyard such as Devonport the frequency of accidents is defined in terms of exceeding the Emergency Reference Level (ERL) at once every 50,000 years of continuous reactor operation so, crudely, for a 20 boat flotilla over a 30 year period, the assumed risk of accident is (50000/(30*20)=) 1 in 80 or thereabouts over the thirty year period.

[11] Of course, this probability applies to all of the whereabouts of the submarine and not just the operating in or near the Dockyard – that said, such probabilistic analysis is not particularly convincing when the Titanic sank on its maiden voyage (once in one) and space shuttle Columbus failed on its fourteenth launch even though it was designed to a failure criterion of 10^{-6} ie one in fourteen and not one in a million.

[12] The water coolant expelling from the primary circuit immediately flashes off to steam since the reactor circuit is highly pressurised in excess of 180 bar.

compartment, are all subject to an impulse shockwave which over time falls to a steady overpressure, decaying as the steam cools.

The second pressure transient follows within a few minutes (again depending on the size of the LOCA) when the by then melting fuel core flash boils any remaining coolant in the reactor pressure vessel *'pot'*. This produces a superheated steam at very high pressure that pulses a second shockwave and overpressurisation of the secondary containment.

Both the magnitude and impulsive nature of this second pressurisation event sets the design requirements for the secondary containment.

Subsequent pressure transients may arise from reactivity excursions in the molten core as it collapses into a critical mass and such, in itself, may produce a burst of fission generating fission products for release and, quite separately, from the explosive reaction between zirconium clad of the fuel and the alloyed zirconium 'meat' of the fuel.[13]

FIGURE 8 shows the pressure transient sequencing most probably adopted for the Royal Navy's LOCA MDA based upon sudden failure of the primary circuit pipework. However, there are some very significant variations of this scenario that are that are not included within the Royal Navy's adopted MDA, these are:-

a) Reactor Pressure Vessel Rupture

The severity of events that follow a loss of coolant incident are very much dictated by the rate at which coolant is lost, so it is somewhat surprising that the primary pipework breach MDA is adopted to represent the most severe scenario. A more severe LOCA scenario, particularly in terms of challenging the surety of the secondary containment, is where the reactor pressure vessel (RPV) itself catastrophically fails. This accident is reckoned by the Royal Navy to be at risk of occurrence at 10.10^{-6} per reactor year (10 times less likely than the primary pipework failure).[14]

Two contributory factors, acting either singly or jointly suggest that a RPV failure based LOCA is more challenging to the surety of the secondary

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[13] The zirconium-steam reaction is where the zirconium oxidise liberating hydrogen at temperatures in excess of ~1,000°C.

[14] This raises some doubt about the validity of the Royal Navy's safety case because there is not a sufficient margin (here just a factor of 10) between what is nominated as a *'credible'* event (the LOCA MDA with a pipework break) for which the design caters and an *'incredible'* event which is not embraced within the design nor its protection mechanisms.

containment, these are:-

The rapidity and severity of an RPV failure based LOCA are determined by the size and location of the breach in the shell of the RPV - if the breach is down low in the vessel then the fuel core becomes immediately starved of coolant and, if the breach is large, the *emergency core coolant system* (ECCS) is to no avail.

Under these conditions, first, the sequence of the pressure pulses of **FIGURE 8** is collapsed in time because, as shown by **FIGURE 7**, the loss of water in the reactor pot is immediate, whereas in the pipework LOCA coolant water level remains high in the pot providing a more leisurely (a minute or so) boil down time thus delaying the commencement of steam interactions.[15] Immediate boiling can bring forward the criticality and zirconium-steam interactions and, indeed, loss of the spatial restraint and separation of the fuel modules offered by the core basket or *'thimble'* could heighten the criticality event.

b) Secondary Circuit Failure

During the LOCA event the secondary steam circuit, either the main piping or the bundles of small diameter tubes within the steam generators, could also breach because of pressure shock and/or impact by flying parts of the reactor circuit ejected during the initial fault condition. The introduction of steam from the secondary (turbine) would result in further elevation of the pressure peaks shown in **FIGURE 8**.

c) Plant State

In a crippled reactor in which the primary circuit cooling system is completely disabled the alternate means of cooling are important.

For example, if the reactor plant state is at high power *(Plant State A)* immediately before the LOCA and, particularly for a well irradiated (old) reactor fuel core, if the heat arising from the high rates of radioactive decay exceeds the rate of heat loss through the hull, then the steam formed in the reactor compartment will not cool and condense and a third pressure transient will occur some time one to three hours following the initiating event.

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[15] Moreover, for a primary pipework MDA, if the breach is outboard of the main isolating valves (see **FIGURE 4**) the damaged section of the pipework and its steam generator can be remotely isolated and ECCS applied to the core via the other primary circuit limb.

If the submarine is surfaced then the efficacy of heat transfer through the hull will be impaired because about one-third of the hull surface is out of the water. In this case, the third pressure transient will peak earlier.

d) Steam-Molten Metal Explosion

The sudden mixing of molten fuel (liquid metal) and water can create a phenomenon referred to as a steam-explosion.

Such steam-metal interactions can generate considerable explosive force because the rapid rise in local pressure leads and suppresses boiling of the water, mixing of the metal and water is extremely efficient until the water flashes to steam, generating a very high pressure impulsive shock wave up to 70,000kN/m^2 (~10,000lbf/in^2) and, given the presence of more reactants, the process repeats.[16]

In summary: During a large LOCA there are a number of opportunities for high energy events stemming from thermo-chemical processes and these, particularly relating to an abrupt failure of the reactor pressure vessel, would be very challenging to the hull or secondary containment of the reactor compartment.

3) SURETY OF CONTAINMENT SYSTEMS – EFFICACY OF SOURCE TERM RELEASE

As previously discussed, there are three levels of containment each of which has to be breached in order for radioactivity to release into the public domain.

These containments are the i) fuel and fuel cladding, ii) reactor primary circuit and iii) reactor compartment.

For the purposes of examining the mechanisms available to release the fission products held within the fuel following a severe LOCA, it is assumed that the accident-initiating event also contributed to a failure of the reactor compartment containment.

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[16] Such water-steam explosions are believed to have significantly contributed to the massive damage of the Chernobyl reactor.

Fuel and Fuel Cladding

In the Royal Navy PWR1 fuel design, 24 fuel elements or modules (**FIGURE 2**) comprising, in total, about 220kg of highly enriched (97.3%) uranium-235 make up the fuel core. At the time of refuelling, optimally after eight to ten years of in core service, the fissile uranium-235 content has reduced to about 50kg most of which has been reduced to radioactive fission products.[17]

The form of the fuel is packs of thin, wafer like plates of uranium alloyed with zirconium, metallurgically bonded to a zirconium alloy clad. The entire radioactivity created by the fissioning of the fuel[18] is confined to within the fuel element envelope enclosed by the cladding and this becomes available for release (once that the cladding has failed) in three regimes:-

a) Fuel Clad Gap

If, for whatever reason, the cladding fails then the fission products present in the small gap between the cladding sheath and the fuel *'meat'* are immediately available for release.

This is known as the *'gap inventory'* and comprises all of the fission products that, during normal operation, have migrated from the internals of the fuel meat to the small gap between the fuel plate and its cladding sheath, the cladding gap.

Although little information is available on the rates of fission product migration through the RN uranium-zirconium dispersed fuel matrix, it is generally acknowledged that this fuel behaves similarly to civilian research reactor fuel in that the fraction of the total inventory present in the cladding gap increases with the degree of irradiation.[19] **FIGURE 9** shows the trends for increasing gap inventory for increasing irradiation or *'burn-up'*.

Other empirical data[20] relates to how much of the gap inventory is released at the internal temperature of the fuel meat (~up to 1,300°C) for low burn-

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[17] A component of the U-235 converts to U-236 by absorption of neutrons and to stunt excess reactivity the fuel includes a dispersed gadolinium neutron 'poison' that burns off proportionately to the depletion of U-235 content.

[18] Here we are only concerned with the fission products of the fuel but the reactor itself becomes radioactive because it is irradiated with neutrons – this *activated* radioactivity, although significant in itself at about 7,000TBq, is a small proportion of the total release potential for the fuel at 2,746,000 TBq,

[19] In fact, dispersion plate fuel does not have a cladding gap since the fuel itself, a refractory, is dispersed in a continuous matrix of diluent, here zirconium, with these being metallurgically bonded with the zirconium alloy cladding. Here the 'cladding gap' inventory refers to the fission products immediately available for release which are in close proximity to the cladding.

[20] Gittus J H *PWR Degraded Core Analysis*, ND-R-610 (S) UKAEA.

up uranium oxide fuel (TABLE 5). This shows that the entire radioactivity of the noble gases, halogens and alkali metals available in the gap is released but that the gap inventory itself is a small proportion of the total radioactive inventory available within the fuel.

TABLE 5 GAP INVENTORIES AND RELEASE FRACTION AT 1,300oC

FISSION PRODUCT	GAP INVENTORY FRACTION OF TOTAL CORI	GAP RELEASE FRACTION OF GAP INVENTORY	RELEASE FRACTION OF TOTAL CORE INVENTORY
Xenon - Krypton	0.005	1.0	0.005
Iodine - Bromide	0.005	1.0	0.005
Caesium - Rubidium	0.005	1.0	0.005
Antimony etc	0.005	0.003	0.000015
Strontium- Barium	0.005	0.0001	0.0000005
Uranium oxide dust			0.0005

In other words, if the accident did not proceed beyond cladding failure the greater part of the fission product inventory would remain trapped within the fuel meat for a low burn-up fuel.

If the fuel burn-up is high, that is it had been in the reactor core for some time (up the eight to ten years for a RN submarine), then not only would the total fission product inventory be larger, but a greater proportion of this would be available for immediate release from the cladding gap (FIGURE 9 - approximately proportional to the extent of burn-up).[21]

Even for highly irradiated fuel, providing that the fuel temperature is maintained near its normal operating temperature, the release from the clad gap is constrained to less than 1% of the total fuel core inventory. Hence the Royal Navy's somewhat optimistic adoption of the iodine released source term given for its pipework failure LOCA MDA of TABLE 1.

b) High Temperature and Fuel Melt

Under LOCA conditions where the fuel is being starved of coolant, the temperature of the fuel determines the rate of release of fission products.

Self-heating[8] of the fuel above 1,200 to 1,300°C is accompanied by a greater proportion of the core fission products being released until a temperature of

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[21] A number of factors result in the clad gap inventory increasing with burn-up. Each fission effectively increases the volume of the fuel, so the fuel matrix tends to swell and crack and the fission product gases increase the pressure within the cladding, so a sudden removal of the external pressure acting on the fuel cladding provides a driving potential for the contained fission products to liberate to the outer surfaces of the fuel.

~1,800°C is reached at which point the zirconium cladding and fuel melt will commence and rapidly advance, as shown by **TABLE 6**.

TABLE **6** RELEASE FRACTIONS FOR ABNORMAL HIGH TEMPERATURES AND EVENTUAL FUEL MELT OVER **10** MINUTES

FISSION PRODUCT	RELEASE FRACTION OF TOTAL CORE INVENTORY AT FUEL °C					
	1,300	**1,400**	**1,500**	**1,600**	**1,700**	**1,800**
Xenon - Krypton	0.10	0.24	0.44	0.70	0.93	1.0
Iodine - Bromine	0.10	0.24	0.44	0.70	0.93	1.0
Caesium - Rubidium	0.10	0.24	0.44	0.70	0.93	1.0
Antimony etc	-	-	-	0.0015	0.006	0.03
Strontium- Barium	-	-	-	-	-	-

TABLE 6 shows that the noble gases and volatile fission products, iodine and caesium, are increasingly liberated with increasing temperature. The release rates relate not just to temperature but the period of exposure to abnormally high temperature.

The exposure period for the trials of **TABLE 6** was limited to just 10 minutes so, in effect, in the aftermath of a large LOCA incident in which the fuel is starved of coolant, a very substantial part, if not virtually all, of the fission product inventory could be released first from the fuel and then from the breached reactor primary containment within 10 or so minutes of the triggering incident.

Reactor and Hull Containments

As previously noted, here it is assumed that rupturing and or breakdown of the two final barriers of containment (the reactor primary circuit and the reactor compartment) have accompanied the LOCA incident.

Failure to the reactor compartment could occur in a number of different ways,[22] each of which will provide a different degree of retention of the quantity and range of radionuclides release to atmosphere. Here the worst case is considered to be failure of the topside hull section of the reactor compartment so that the release is direct to atmosphere.

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[22] Essentially, three options are available:- the compartment hull fails topside with the submarine surfaced this provides a direct release path to the atmosphere; and/or the breach could be below waterline in which sea water intrusion provides the main pathway for the release; and/or the fore/aft bulkheads of the compartment could fail which means the remainder or compartments of the submarine act as a secondary containment.

Obviously, in the high temperatures of the aftermath of the LOCA, subsequent fuel melt and possible fuel-steam interactive processes some proportion of the volatile fission products will be captured and retained by the surfaces and remaining contents of the reactor primary circuit and reactor compartment. The processes that provide for this are complex but, generally, include solubility capture of fission products by any remaining water/vapour in the circuit and reactor compartment; adhesion of fission products onto particles and subsequent dispersion therewith; and plating onto surfaces of condensates of volatiles, by chemical and physical means.

Fuel-Reactor Release Phase

The first phase of the aerial transport of radioactivity out of the containment may be categorised into three distinctly different groups of fission products:-

a) **Noble Gases**

The noble gases, krypton and xenon, have low solubility in water and water vapours so, effectively, all of the noble gas inventory will be released to atmosphere.

b) **Halogens**

Iodine will be expelled from the fuel predominantly as iodine ions and, if high temperature steam is present, the zirconium alloy cladding reacts with the steam liberating hydrogen which, in turn, will react with the iodine to form hydrogen iodide

c) **Particulates**

The role of remnants of the uranium-zirconium fuel meat is important in determining the efficacy and extent of the dispersion of the radioactive release of the remaining fission products released from the fuel.

This is because the fuel melt process will result in rapid oxidisation of some part of the fuel core generating very small oxide particles. These uranium oxide particles provide a readily available platform or mechanism for the means of ejecting, dispersing and eventually depositing a range of solid fission products. Although much determined by physical-chemical conditions, particle size distributions for uranium oxides formed under extreme LOCA conditions can be very small indeed, ranging down to

<0.01μ[23] which is well below the upper threshold of respirable particle size for humans (>5 to 10μ).

Very little is published on the rates of fuel oxidisation under melt conditions and nothing is available in the public domain for the uranium-zirconium alloyed fuels used in the RN PWR1 reactor.

In an extreme LOCA, which results in a fuel melt, almost the entire inventory of noble gases and halogens will be released from the fuel and reactor containment and a substantial proportion of the caesium and a small fraction of strontium and barium will release in a superheated vapour state – the release path to air for these components of the radionuclide inventory will be very efficient.

Of the remaining solid fission products, including up to 10% of the iodine inventory, these are likely to attach to uranium oxides[24] and release in a particulate state.

Fractional Release from the Containment to Atmosphere Phase

For the particulate component, there are two, subsequent temperature related mechanisms that serve to stem the release of the total inventory of the reactor core.

If the escaping fission products are immediately cooled, then both particulate matter and unfixed fission products have a tendency to *'plate out'* onto or stick to the hull structure and other surfaces. A similar retention mechanism occurs when a steam atmosphere condenses whereby the water vapours and condensates capture a high proportion of the solid fission products. Combined, these circumstances might result in approximately 90%, or more, of the solid fission products being retained in the immediate locality of the reactor and its secondary containment.

For the fission products adhering to or combined with the airborne fuel oxides, cooling will promote settling an deposition of the particles and, similarly, particles will agglomerate and settle more rapidly. However, the heat generation of radioactive decay itself can be sufficient to counter atmospheric cooling and maintain the particles airborne, thus extending the period of airborne dispersion.

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[23] 1μ = 0.000001 meter equivalent aerodynamic diameter.

[24] Or the fission products themselves may convert to volatile oxides in an oxidising atmosphere – this applies to tellurium and ruthenium.

In Summary: The processes and mechanisms that determine how much of the available source term of fuel fission products release to the atmosphere are complex. Generally, it is axiomatic that the higher the temperature and energy generated by the LOCA and associated processes then the greater the release and the less likely it is that the magnitude of the release will be confined to the cladding gap inventory.

4/5) RELEASE PLUME DISPERSION AND EXPOSURE/HARM TO SUBJECT GROUP

In the immediate aftermath of reactor LOCA the dispersion and deposition of the radioactive plume will be determined almost wholly by the prevailing weather conditions and, to a lesser extent, by the nature of the ground terrain.

The extent of radiation exposure to those individuals within the path of the plume will be determined, for external radiation dose, by the effectiveness of any shielding and the duration of the exposure and, for internal radiation dose, the uptake of specific species of radionuclides, how these might be concentrated in particular body organs, and how efficiently the body can purge those organs of radioactivity.[25]

In other words, contingency planning can only serve to mitigate the consequences of the radioactive release in terms of controlling and minimising the external and internal uptakes of radiation to individuals caught within the release plume.

6) MITIGATING THE HEALTH DETRIMENT BY COUNTERMEASURES

DEVPUBSAFE[26] sets down background information and guidance on the actions to be taken by the Ministry of Defence and the (civil) local authorities in the event of a nuclear submarine accident.

In a general sense *DEVPUBSAFE* provides a reactive rather than proactive approach to contingency planning. This is because, first, it does not identify the type and severity of containment damage of potential incidents and accidents that might evolve to a radioactive release and, secondly, it does not identify the amount and quality of the radioactive release emanating from all foreseeable accidents.

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[25] Internal radiation gives rise to 'critical groups', that is certain members of the population who by age, occupation and/or habit are more are risk. Obviously, the only effective barrier to internal uptake is to provide those at risk of exposure with respiratory protection.

[26] Issue 1, Amdt 0, July 1999 but excludes PART B.

Accident Damage Severity

For accident damage severity *DEVPUBSAFE* defines three accident severity categories of which **Category 3**[27] includes for a release of radioactivity to the environment. Although the detailed scenario of the **Category 3** accident is not identified, this type of accident would result from the severe loss of coolant accident (LOCA) previously identified in this Review.

However, the sequencing to reach the most severe **Category 3** accident, as implied by *DEVPUBSAFE*, is that the submarine reactor accident cascades from an initiating event, through to a primary containment failure and finally to failure of the secondary containment[28] over some undefined time period.

The implication from this is that all reactor accidents are relatively leisurely events that cascade in some predefined orderly manner, each stage of which will serve to implement a further set of countermeasures and actions.[29] Although the MoD undertakes to implement the *'local'* plan in full following the declaration of a reactor accident, irrespective of Category, there is little acknowledgement that certain **Category 3** incidents, particularly stemming from a reactor pressure vessel LOCA with fuel melt, would not effectively cascade through the categories or, if such did, the whole cascade would be compressed into a very short time frame of a few minutes.[30]

Nature and Magnitude of Potential Radioactive Releases

DEVPUBSAFE does not define the (radioactive) source term of the reactor in any detail whatsoever, other than to obliquely refer to the radio-iodine species via the issue of potassium iodate tablets (PITs).

Instead, for the implementation of countermeasures in the Pre-Planned

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[27] p1-8 *DevPubSafe*, "**Category 3** – an event which has led to the release of fission products from the fuel to the environment outside the pressure hull".

[28] para 1.15 *DevPubSafe*, *"A Category 1 report might refer to an initial event, to be followed by a Category 2 report as a hazard inside the submarine was detected, and Category 3 as monitoring outside the vessel detected that a release had occurred."*.

[29] P26-28 of Section 2, Part A DevPubSafe assumes the cascading of the incident through severity Categories 1, 2 and 3.

[30] For example, the 1957 Windscale accident took several hours to develop but those operating the atomic pile did not realise what was happening, so although the 'category' of events were cascading in seriousness, the operators did not realise that counter actions were necessary. At Three Mile Island in 1978 the operators misunderstood what was happening and implemented the wrong counter actions. At Chernobyl in 1986, the cause of the accident was rooted in actions taken 24 or more hours before the explosion, only when the train of events approached terminated did the operators realise that something was desperately amiss, but by then little less than one minute remained before the reactor was completely destroyed.

Countermeasures Zone (PPCMZ), it is the reactor fuel Category status that triggers countermeasures and, quite differently, for the Extendibility Zone (EZ) countermeasures are related to the projected consequences of radioactive release and exposure in terms of Emergency Reference Levels (ERLs).

DevPubSafe Countermeasures Triggers

For safeguarding members of the public three countermeasures are identified in the so-called Pre-Planned Countermeasure Zone (PPCMZ), which extends within a 30° downwind sector over a 2 km radius from the Dockyard (**FIGURE 10**) and the Extendibility Zone (EZ) beyond. However, for these two zones quite different means and criteria are adopted for triggering the countermeasures set out in **TABLES 7A** and **7B**.

TABLE 7A *DEVPUBSAFE* COUNTERMEASURE TRIGGER IN PPCMZ

	PPCMZ	
COUNTERMEASURE	CATEGORY	TRIGGERS
SHELTERING	1 - likely to or has resulted in fission product leak from fuel	Public advised to shelter and PITs distributed[31] at onset of Category 1 incident
STABLE IODINE TABLETS - PITs	2 - has resulted in a radiation hazard fission product leak from fuel	Public advised to take PITs when Category 2 incident declared[32,33,34]
EVACUATION		not specified

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[31] It is not at all clear how what resource has been allocated to the distribution of tablets to the considerable number of individuals who have not received stable iodine tablets via pre-distribution. The City of Plymouth refers this to the Devon and Cornwall Health Authority but all that it notes is that *"Naval personnel will distribute Potassium Iodate Tablets door to door in a 30 degree downwind sector"*. Although *para 2.8.3* states that the distribution of PITs will be carried out automatically by personnel from within the Naval Base the numbers of and the training of these personnel is unknown – importantly, the distribution of PITs to the public has never been rehearsed under realistic conditions.

[32] The radioactive half-life of iodine-131 is such that its presence in the fuel of a reactor that has been shut down for a significant period (6 months) is greatly diminished. Accordingly, it may not be necessary to implement this prophylactic measure for incidents involving a reactor during refuelling, unless the incident involves a significant criticality event in which radio-iodine is generated.

[33] It is not at all clear in *DevPubSafe* how the iodine dose is to be determined. This is important since when monitoring I-131 following a reactor release knowledge of the other radio-iodine species is necessary – this assessment may be simplified by considering the species I-131 and I-133. For the release from a reactor that has been recently shut down, where there is a dose contribution from other iodine species (together with Tellurium-132 which decays to I-132) and these are in relative equilibrium (say, after one year of continuous reactor operation) the dose contribution from these other iodine isotopes is about 0.46 relative to that of I-131 – in this case the ERL based solely on I-131 monitoring for the Thyroid would be reduced by about one-half to accommodate the dose from the other iodine species. Where the release is from an operating (or very recently operating) reactor, I-131 monitoring alone would require the ERL to be reduced tenfold in account of the short half life iodine species present.

[34] Interestingly, firefighters of the local authority fire services are required to retire from the active scene if their individual dose exceeds 50mSv (or up 100mSv for lifesaving) in any one incident and that female firefighters are not permitted to attend any incident where there is risk of radiation exposure.

In setting out the approach to protection of the public within the pre-planned countermeasure zone (***Section 2.9.8***) *DEVPUBSAFE* states:-

> "..
>
> *Following declaration of a nuclear reactor accident, the local civil authorities and emergency services will be advised to implement countermeasures immediately, rather than waiting for monitored results*
>
> .."

but then rather confusingly adds that sheltering and distribution of PITs would be automatic at **Category 1** and that the public would be advised to take the PITs at **Category 2**.[35,36]

This means that for the PPCMZ the Royal Navy does not relate to the radiation exposure dose of individual members of the public, but to the **Category** assessment of the reactor fuel condition for the implementation of specific countermeasures. Since the definition of **Category** is vague (see **Section 1.14**) and, moreover, it unlikely that the Royal Navy would wish to share sensitive information about the condition of a submarine propulsion reactor with a local authority, members of the public in the PPCMZ are entirely dependent upon the uncorroborated assessment of naval personnel for their well-being.

Nothing at all is set out in *DEVPUBSAFE* relating to the means and criteria by which this assessment is undertaken, how much cognisance is given to critical groups within the public population, its hierarchy of reporting within the MoD organisation at Devonport and beyond, and its eventual communication to the local authorities.

The complete dependence upon Royal Navy personnel to trigger the countermeasures in the public domain, based upon their assessment of the fuel condition, which is unavailable for independent scrutiny, could be a serious shortfall of the *DEVPUBSAFE* plan.

Extendibility Zone EZ – Countermeasure Triggers

The triggers for implementing the countermeasures in the EZ are set out on the left-hand side of TABLE 7B as Site Specific Intervention Levels. These triggering thresholds are a *DEVPUBSAFE* adaptation of the NRPB ERL levels

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[35] **Section 1.14** of *DevPubSafe* defines a Category 2 event as *'an event which has led to a radiation hazard as a release of fission products from the fuel'* although how it is subsequently referred to in the text suggests that it should be *'an event which has led to a radiation hazard as a release of fission products from the reactor primary circuit'.*

[36] Note that no trigger to initiate evacuation in the PPCMZ is given.

shown on the right-hand side of the table.

TABLE 7B *DEVPUBSAFE* COUNTERMEASURE TRIGGER IN EZ

	EZ					
	SITE SPECIFIC INTERVENTION LEVELS		NRPB EMERGENCY REFERENCE LEVELS			
	WHOLE BODY DOSE EQUIVALENT [37] - mSv					
			LOWER		UPPER	
COUNTERMEASURE			BODY	ORGAN	BODY	ORGAN
SHELTERING	Lower ERL - 3		3	30	30	300
STABLE IODINE TABLETS- PITs	Upper ERL – 300 Thyroid	Lower ERL - 30 where practicable Thyroid	-	30 Thyroid	-	300 Thyroid
EVACUATION	Upper ERL - 300	Lower ERL – 30 where practicable	30	300	300	3000

In effect, *DEVPUBSAFE* proposes to initiate countermeasures in the outer EZ by adopting the lower ERL levels (as projected avertable doses) as the triggers and, if this is not practicable, to implement the countermeasures to avert the upper ERL dose.

This approach does not exactly follow the recommendations of the NRPB on the basic principles to be adopted for ERL countermeasure implementation, since it recommends that:-

First, the introduction of countermeasures should occur only if these are expected to achieve more good than harm, so the countermeasure action and its triggering threshold has to be justified. Second, the quantitative criteria used for the introduction of countermeasures should be such that the protection of the public is optimized.

Obviously, the countermeasure triggers used in the PPCMZ (the **Category**) are not formally *justified* nor are there any requirement in *DEVPUBSAFE* that these are *optimized.*

For triggering the EZ countermeasures the Radiation Health Cell notifies the local authority of the projected avertable doses so that the local authority itself can consider implementing the countermeasures. In the

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[37] These are the ERL thresholds set down by the NRPB. The lower ERL is the dose level below which the countermeasure should not be introduced because it would be very unlikely to be justified to do so. If estimated averted doses exceed the lower ERL, implementation of the countermeasure should be considered but is not essential. The upper ERL is the dose level at which every effort to be made to introduce the countermeasure unless it would clearly contravene the principles of *justification* and *optimisation* to do so. The ERL principles are intended to be used as one of the major inputs to the establishment of emergency plans and as guidance for actions when an accidental release or other emergency has actually occurred.

case of the City of Plymouth, there is nothing in **Chapter 4** of *DEVPUBSAFE* requiring Plymouth to consider *justification* and *optimisation* procedures prior to countermeasures being introduced.[38]

Reliance upon Radiation Monitoring and Dose Exposures Calculated Therefrom

Using the ERL lower dose limit as the trigger points requires either direct measurement or a reliable means assessment of the radiation dose uptake of the individuals at risk being in place in the immediate aftermath of the accident.

Consider two aspects of a major radioactive release and how these might affect those at the Barne Barton School about 1.3km from the Dockyard basin[39]:-

Radiation Shine from the Radioactive Plume

FIGURE 11 shows the whole body dose exposure *-v-* distance profile expected to arise for individuals exposed (within buildings) to a radioactive plume passing through the area following a RPV failure LOCA that includes an immediate core melt.

For the two hour sheltering period assumed, pupils and staff sheltering within the school buildings[40] would receive whole body equivalent dose exposure in excess of the Lower ERL for evacuation, so evacuation of the school might be considered to be justified.

Although the radiation dose assessment includes for shielding factors from buildings, it does not include for deposition from the cloud to the ground and building surfaces, or for how a complex urban streetscape determines the final dispersion pattern. Such variations could result in significant

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[38] Also, there is no consideration of the radiological protection of City and other civilian personnel involved in the countermeasures in the PPCMZ and EZ areas other than the general statement (**Section 2.9.7**) that *'emergency services and other non-Naval Base personnel, are to be maintained at a level which is As Low As Reasonably Practicable'*. The NRPB recommends that workers involved in implementing countermeasures and taking other actions to protect the public in the event of an accident should be allowed to receive doses equal to the currently recommended limits for occupationally exposed persons and, in exceptional circumstances, to receive doses which are above these limits, provided that doses are always kept below the thresholds for serious deterministic effects. This requires agreement with those personnel and volunteers and it may be necessary to filter out high-risk individuals (eg women of reproductive age), so some form of justification and optimisation of the deployment of these individuals in the active areas is required.

[39] Or from the RAFT ammunition facility which is about the same distance from the School.

[40] The dose uptake for individuals sheltering within buildings depends of the structure and design of the building, the ventilation rates and the activity of those sheltering.

increases in the dose exposure, with intolerable levels of exposures doses in excess of the upper ERL limit for whole body equivalent exposure.[41]

Unless NEMT radiation monitors could access the site early in the development of the incident (themselves also subject to radiation exposure) to determine the actual dose receipt, there would be further justification to evacuate the School.

Thyroid Dose Uptake

FIGURE 12 shows the levels of thyroid dose uptake *-v-* distance for various levels of radio-iodine release – dose uptakes for adults and children are given for a range of releases from 4 to 4,000TBq of equivalent iodine-131 which represents the range of release expected for a low severity accident during which only the fuel cladding gap fission product inventory is released.

At the location of Barne Barton school a relatively small release of radio-iodine (40 of TBq I-131 equivalent) will exceed the ERL upper limit.[42,43]

Importantly, the RPV LOCA scenario (which is beyond the MDA assumed by the Royal Navy) compresses the time between the initiating event and failure of the submarine hull to a few minutes. Once released, the time for the plume to arrive at the school under a stiff breeze of, say, 3m/s would be about 7 minutes. Thus, those in and about the school locality would be committed to the evacuation countermeasure since the lower ERL of 30mSv have been committed to within 10 or so minutes from the onset of the accident.

There are a number of shortfalls and/or apparent omissions in *DEVPUBSAFE* that suggest that effective contingency plans, particularly for a speedy evacuation,

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[41] The prediction of the dispersion of relatively low level plumes passing over and through urban areas is very unreliable because of the terrain 'roughness', wind and thermal effects and, in the near field, the plume may not be sufficiently developed for reliable analytical prediction. For example, following the Chernobyl explosion the deposition at Pripyat (about 6 kilometres from the stricken nuclear plant) varied considerably with adjacent streets varying in radiation levels by x1,000 and more. This type of patchy patchy dose-distance profile in which pockets of population could be subject to very high levels of dose would not be unexpected to apply in the urban areas surrounding the Dockyard at Plymouth.

[42] In fact, the 400TBq release of radio-iodine simply relates to the Royal Navy's 100 hour *Standard Core History* given in **TABLE 1** but, other than this low inventory core produces a 'manageable' iodine release, there seems no other reason to adopt it to be typical of a RN submarine reactor core.

[43] The *Risk Factor* for Thyroid Cancer is (NRPB) 0.0025 per Sv applied to low dose rates but for high dose rates the *Risk Factor* is multiplied x3 and, generally, for children who are considered a *'critical group'* the *Risk Factor* is doubled. For example, if it is not possible to avert the Upper ERL thyroid dose of 300mSV then that individual will run the risk of contacting thyroid cancer of 300mSvx0.0025x2 = 0.0015 or 1 in 666.

would not be in place in sufficient time for the RPV LOCA scenario. These include:-

Section 17 sets out the evacuation contingency plan but it is not sufficiently detailed to provide an insight into how quickly and effectively the evacuation countermeasures could be put in place.[44]

Section 2.12 states that the MoD Naval Emergency Monitoring Team (NEMT) will continue monitoring but it is not clear whether NEMT (Devonport) is sufficiently resourced to extend its monitoring capability into the public sector. Obviously, in the short time scales afforded by an RPV LOCA additional or *'back up'* from Hinkley Point and Winfrith[45] will not be available.

NEMT's orders were originally defined by MOD document BR 3025[46] to include for *"Revised Emergency Reference Levels"* by selective sampling over which there is doubt relating to the accuracy and reliability of the techniques employed.[47]

According to BR 3025, the MoD segregates its post accident monitoring into three stages:-

Stage I

Stage I monitoring measures the direct gamma shine from the submarine hull at a number of preselected monitoring points. Providing that the submarine is berthed this is likely to be undertaken automatically by the Dockside Installed Radiac System (DIRS). Some delays may occur if the submarine is not berthed and, particularly, where the hull shine is obstructed by another vessel or building.

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[44] For example, if public service vehicles are to be involved a schedule of dose limitation has to be agreed for the drivers and attendants on the vehicles; suitable wheel, body and interior decontamination has to be available for each trip, and decontamination and reclothing centres have to be established at an uncontaminated set down point for the evacuees.

[45] At Winfrith, all active reactors have now been closed down for several years and, at present, there is little other nuclear activity carried on there. Accordingly, it is unclear how much resource Winfrith could offer in the aftermath of an emergency at Plymouth.

[46] BR 3025 (c1976) may now have been superseded and it refers specifically to NEMO (Naval Emergency Monitoring Organisation) – the BR documents are generally not available to organisations outside the MoD because permission for their release follows through a vetting system in which the sanction of a *'Sponsor'* is required but to determine if the documents are available, first, the documents have to be ordered so that the Sponsor may consider the request.

[47] See Footnote 33 for the reasons why it is necessary to identify individual species of radionuclides in the release plume.

Stage II

This stage of monitoring is to establish whether a fission product release has occurred, to determine the direction of the release plume, local deposition of radioactive particles and if the release is continuing. Some part of this release monitoring is likely to be undertaken automatically by the Perimeter Monitoring System (PMS) but the ground contamination dose rates and smear samples will require NEMT health physics personnel involvement.

In the immediate aftermath of the release, the Local Emergency Monitoring Team (LEMT) could undertake Stage II monitoring during the period of up to one hour that the mobile NEMT team has prepared and arrived on site.

Stage III

Stage III monitoring is to determine the extent and magnitude of ground contamination in the public areas surrounding the Dockyard. Under Stage III checkpoints are located radially about the dockyard in 60° sectors, although in practice these follow the roads radiating from the Dockyard out to a distance of 20 to 30km.

DEVPUBSAFE provides no information whatsoever on how NEMT undertakes off-site monitoring, how it arrives at the dose exposures necessary to trigger the ERL countermeasures and, importantly, on how and in what form this information is to be passed to the civilian authorities. Unless the monitoring and dose assessment practices of BR 3025 have been substantially revised, then the monitoring must be confined to ground contamination so, it follows, gamma shine dose from the overhead release plume (**FIGURE 11**) and Thyroid dose for inhalation of the iodine content of the release (**FIGURE 12**) must be extrapolated from the PMS, which may or may not have gamma spectrometry capability.[48]

In fact, monitoring activities within the Dockyard are likely to dominate the initial stages of the emergency response to any accident. This approach is set out in a Royal Navy training course on submarine reactor accidents[49]:-

"...

> *Stage III monitoring is started as soon as emergency monitoring teams (LEMO or NEMT) can be spared from Stage I or Stage II monitoring, or on the arrival of "back up" monitoring teams from CEGB, UKAEA etc. This should*

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[49] *Reactor Accidents Course Notes*, Royal Naval College Greenwich, Department of Nuclear Science and Technology, 1976

> *be some six hours or so after the initial report and may take several days to complete, depending on the number of teams that can be deployed for this task.*
>
> . . ."

In fact *DEVPUBSAFE* states that during the early stages of the aftermath of the incident both on-site and off-site situations are under the direction of the Military Co-ordinating Authority (MCA) and the Incident Commander (IC). Immediate off-site response is co-ordinated by the MCA who is expected to provide the local authority with relevant information relating to emergency countermeasures.

In effect, the military MCA dominates the administration of the accident response, particularly in the early stages, and it is not until the representative of the National Radiological Protection Board arrives that any independent validation of the response is available.

NUCLEAR SAFETY AT DEVONPORT - CONCLUSION

This Review identifies and assesses the potential severity of a loss of coolant accident on board a Royal Navy nuclear-powered submarine when in the approaches to, manoeuvring within or berthed in the Dockyard basin.

The extreme of accident severity identified is whereby the reactor pressure vessel structurally fails and there is an immediate loss of primary coolant which results in the rapid development of a series of pressure pulses which, together with a fuel melt and a liquid metal-water explosion, breaches the submarine hull and permits a release of radioactive fission products to the atmosphere. The contingency planning response, as outlined by *DEVPUBSAFE*, for this and other severely damaging accidents, raises a number of issues and shortcomings:-

1 Barne Barton School

The projected radioactive release from a seriously damaging RPV LOCA, particularly where the accident progresses from initiation to release in a few minutes, would not provide sufficient time for adequate countermeasures to be implemented to safeguard individual members of the public in the PPCMZ.

With unfavourable weather conditions sweeping the radioactive plume through the general area of Barne Barton School, the deteriorating radiological situation could require evacuation within a very short period of time. In other words, the composite countermeasure of sheltering and PITs would be inadequate in that the external radiation shine element itself would be sufficient in itself to require immediate evacuation. In fact, in all but low levels of radio-iodine release it is probable that the ERL for iodine uptake would also require evacuation in the immediate aftermath of the accident.

Since the decision to evacuate Barne Barton School would be made by the City of Plymouth local authority it is surprising that *DEVPUBSAFE* documentation does not provide sufficient detail to determine if the City has an evacuation plan in place and, if so, how and at what point in the accident aftermath this would be implemented.

2 Royal Navy Resources/Priorities

Under *DEVPUBSAFE THE* Royal Navy is committed to providing a number of essential services in the aftermath of the accident.

Although *DEVPUBSAFE* identifies these services it does not provide information on the size and capacity of the resource to provide and manage each service. Examples of this are the number of personnel available for the distribution of PITs in the PPCMZ, and the number of Naval Emergency Monitoring Teams available for immediate monitoring of the PPCMZ and areas beyond.

In providing the radiological monitoring role, particularly as to where and how the initial monitoring is to be undertaken, the Royal Navy adheres to the pre-planned priorities of the Ministry of Defence Book of Reference (BR) 3019. Yet, BR 3019 is not publicly available (see **APPENDIX 1**) so it is not at all clear when the public areas of the PPCMZ and Extendibility Zone would be monitored. Another publicly restricted BR document, BR3025, assigns least priority to monitoring of public areas.

The failure of *DEVPUBSAFE* to define the resources in terms of specific demands and the secrecy over how the resources available are to be prioritised raises a number of concerns over the readiness of *DEVPUBSAFE*.

3 Reliance of Local Authorities Upon the Royal Navy

For the implementation of evacuation and all other countermeasures, the local authorities seem to be overly dependent upon the Royal Navy for radiological information and advice. This is particularly so for the PPCMZ where the countermeasures are triggered by the Royal Navy's assessment of the reactor fuel condition.

Projecting the assessment of the condition of the fuel to the radiological hazard this represent to members of the public is absolutely critical in safeguarding public health and property. The procedures employed for this assessment[50] and the means of communicating it through the MoD organisational structure to the local authority are not included within the *DEVPUBSAFE* documentation and, in the main, are not publicly available (see **APPENDIX I**).

This almost blind reliance of local authorities upon unpublished Ministry of Defence procedures, criteria and judgements leaves much of the Royal Navies commanding role in implementing *DEVPUBSAFE UNCHECKED* at a critical stage in the implementation of countermeasures – under *DEVPUBSAFE THERE* is no provision to check and corroborate the Royal Navy's decision-making until the involvement of the NRPB, which will be several hours or more into the accident aftermath.

On one hand, it might be noted that *DEVPUBSAFE* is the outcome of military planning - it follows a military hierarchal structure and adopts what might be assumed a military rationale. On the other hand, the purpose of *DEVPUBSAFE* is to protect the health and property of members of the local community who may not, under accident conditions and at times of high stress, act in accord with expectations of *DEVPUBSAFE.*

The tacit assumption that the public will behave as expected, particularly in the absence of any direct public involvement in past yearly exercises, might indeed be the fatal flaw of *DEVPUBSAFE.*

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[50] The procedures are set out in a series of MOD documents (BR 3030 – Radiological Controls, BR 3020 Radiological Protection, BR 3019 Nuclear Reactor Accidents, BR3025 – Naval Emergency Monitoring Organisational Orders) none of which seem to be available in the public domain.

APPENDIX I

PARLIAMENTARY QUESTIONS

Nuclear-powered Submarines

Mrs. Gilroy: *To ask the Secretary of State for Defence (1) if he will list the maximum design accidents assessed by the Nuclear Powered Warships Committee following a near instantaneous loss of primary circuit coolant which are in place for the Swiftsure and Trafalgar nuclear powered submarines in operation near and in the Devonport Royal Dockyard; what is the anticipated frequency of MDA per reactor year; what is the core inventory in terms of the fission products Kr, Xe, I, Te, Cs, Sr, and Ru for the nominated MDA for a reactor that (a) is at Plant State A and (b) has recently been derated to Plant State B on the basis of the Standard Core History for the average reactor in-core life for the currently operational Core Z fuel charge; if he will place in the Library copies of his Department's BR1, BR 3018, BR 3019, BR3020, BR 3025 and BR 3030 documents and where appropriate the documents that have superseded them; and if he will make a statement;] (2) if, in relation to the refitting and refuelling of Royal Navy nuclear-powered submarines at Devonport Royal Dockyard, he will provide the Reference, MDA or Design Basics Accidents (a) applicable to periods (i) when the boat is under repair in the dry dock facility, other than when refuelling, (ii) when the boat is being defuelled in preparation for refuelling for the nuclear reactor, including the transition of the irradiated fuel to the dockyard storage locality and (iii) when the boat is out of commission and awaiting decommissioning without and with irradiated fuel in the reactor core and (b) relating to the treatment, packaging and storage of past and present arisings of radioactive waste undertaken and held at the Dockyard; and if he will make a statement ?*

17 May 2000

Mr. Spellar: Response plans for a nuclear accident during submarine operations, including refitting, refuelling, fuel and waste handling, within HM Naval Base and the Royal Dockyard, Devonport are firmly based on detailed analysis and comply with appropriate legislation (in particular the Ionising Radiations Regulations). Probabilistic techniques are employed where appropriate in this analysis.

The radioactive inventories and source terms used in this analysis are classified, because they are related to sensitive information about the design of naval propulsion reactors. I am, therefore, withholding this information under Exemption 1 of the Code of Practice on Access to Government Information. However, work is underway within my Department to respond to the forthcoming Radiation (Emergency Preparedness and Public Information) Regulation (REPPIR) which are expected to require that some aspects of the hazard assessments are made available to the public. Some information of this nature is already available in the document DEVPUBSAFE.

I am placing a copy of Joint Service Publication JSP392 (Instructions for Radiological Protection , which replaced Book of Reference BR3020) together with BR3030 Vol. 1, in the Library of the House. The other documents listed are classified and I am, therefore, withholding them under Exemption 1 of the Code of Practice on Access to Government Information.

FIGURES AND DIAGRAMS

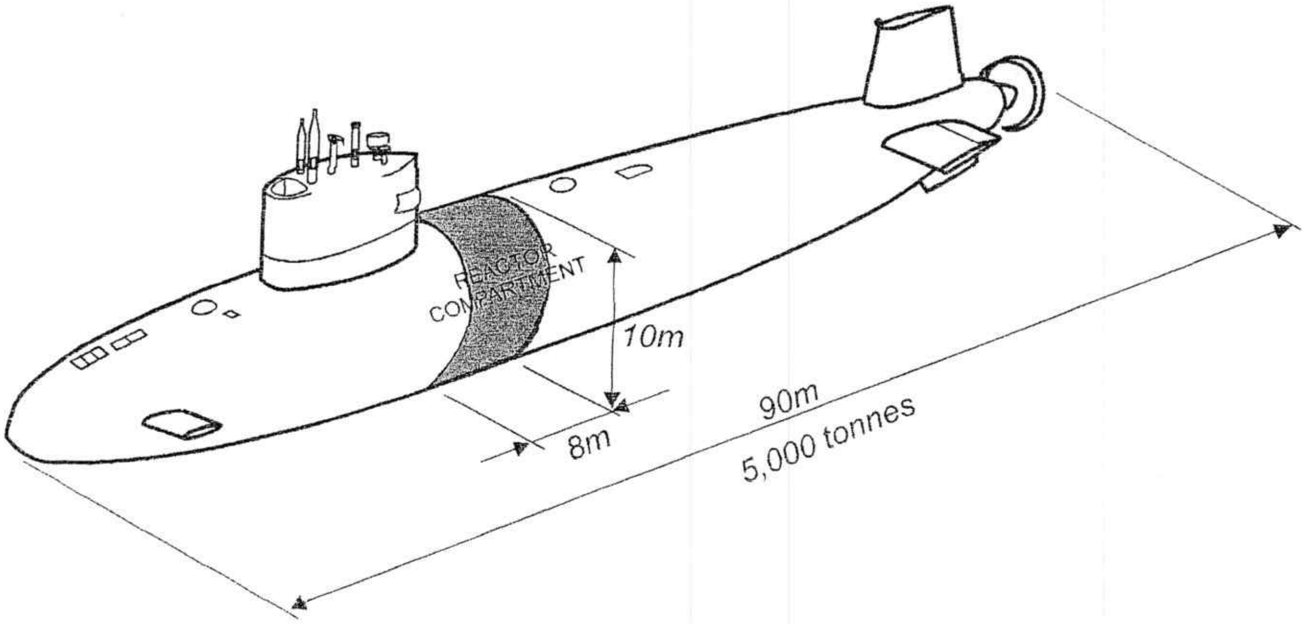

FIGURE 1 - SWIFTSURE CLASS OF NPS

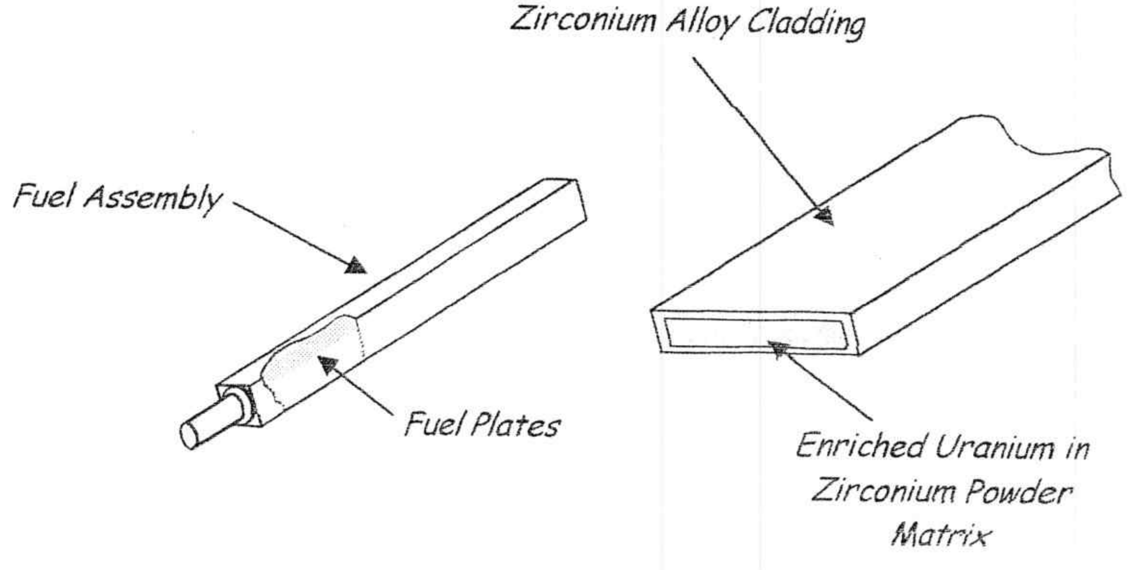

FIGURE 2 - HIGHLY ENRICHED URANIUM DISPERSED PLATE FUEL

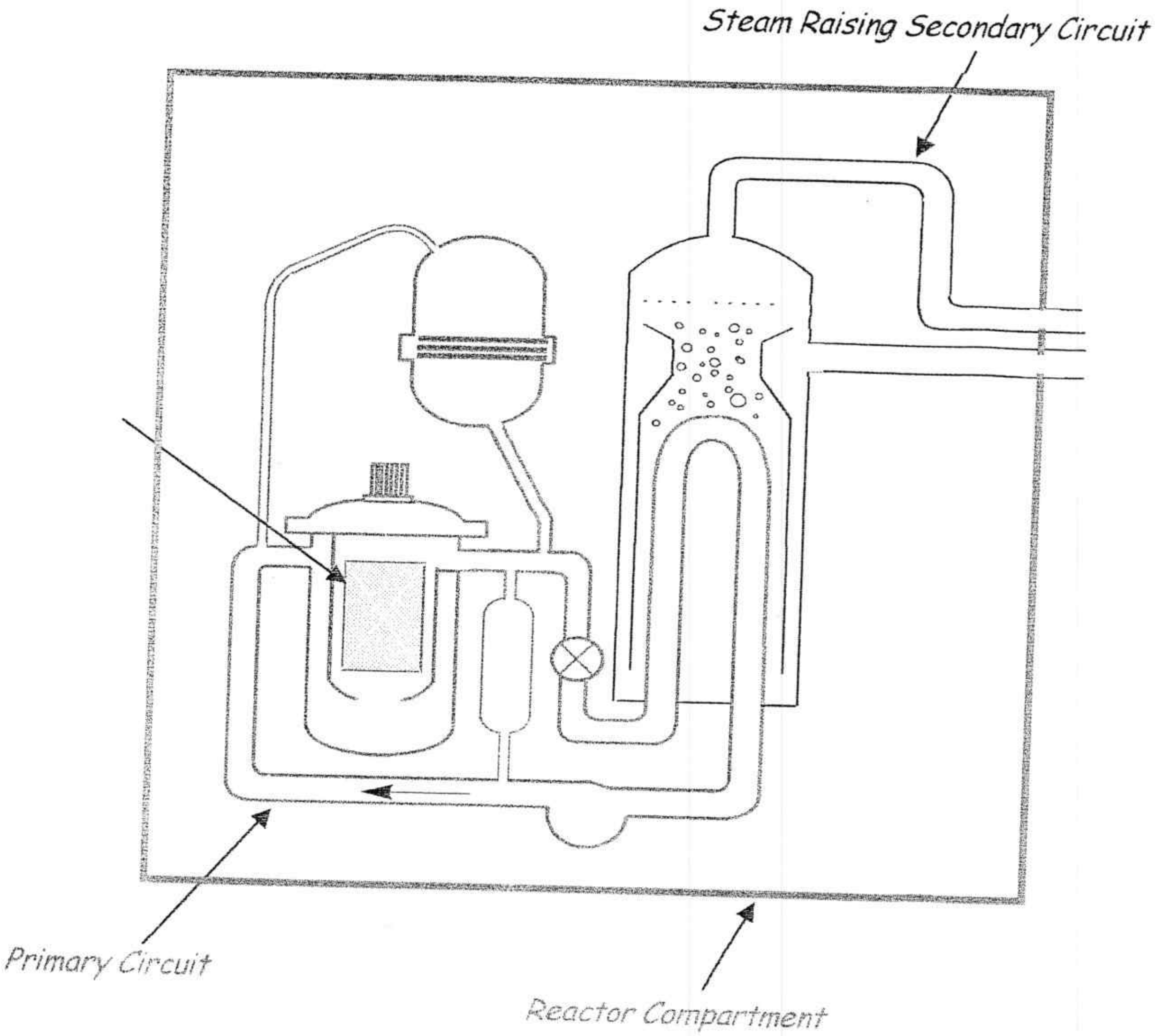

FIGURE 3 - REACTOR COMPARTMENT COMPONENTS

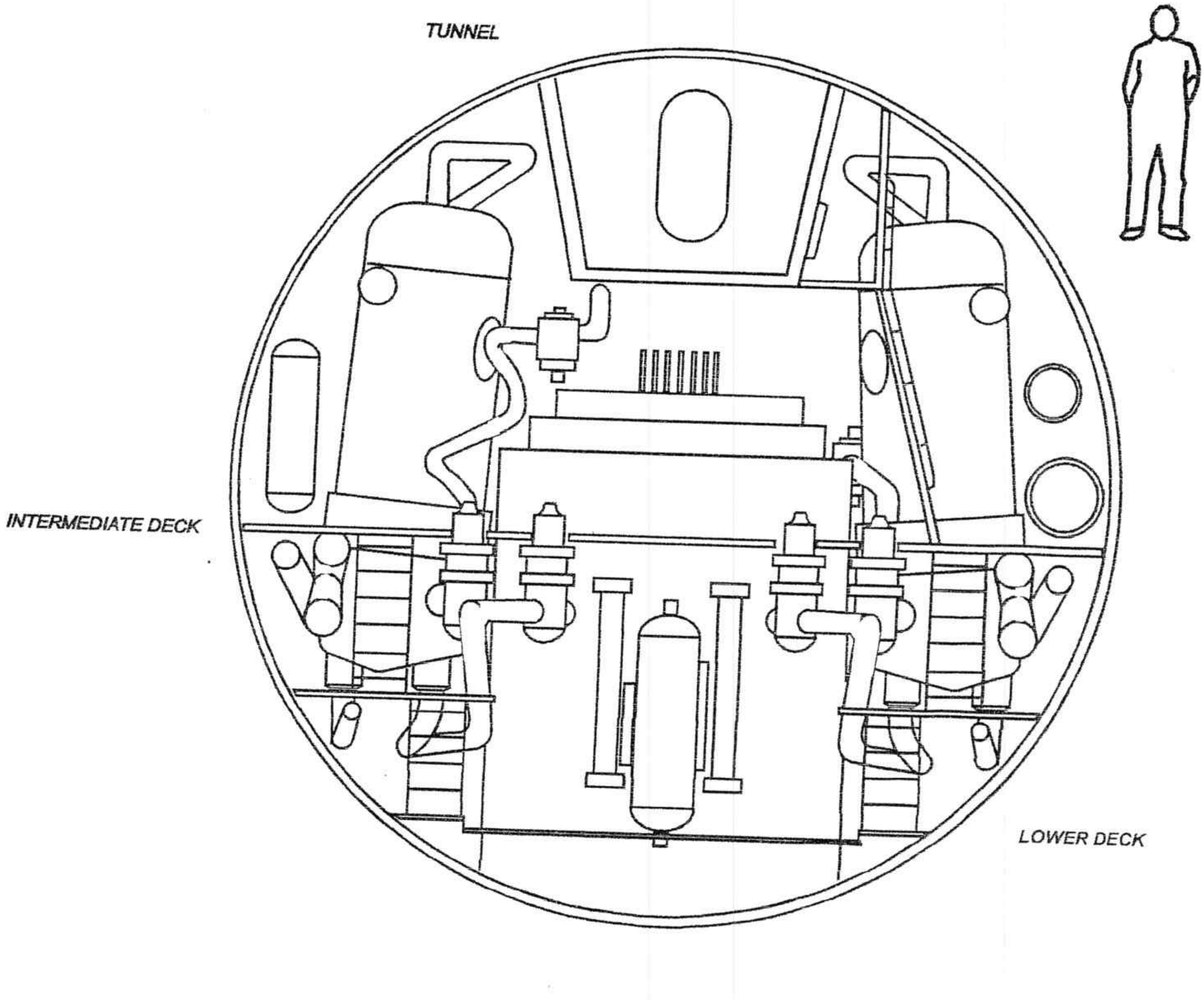

FIGURE 4 - SWIFTSURE/TRAFALGAR CLASS SSN REACTOR COMPARTMENT - SHEAR

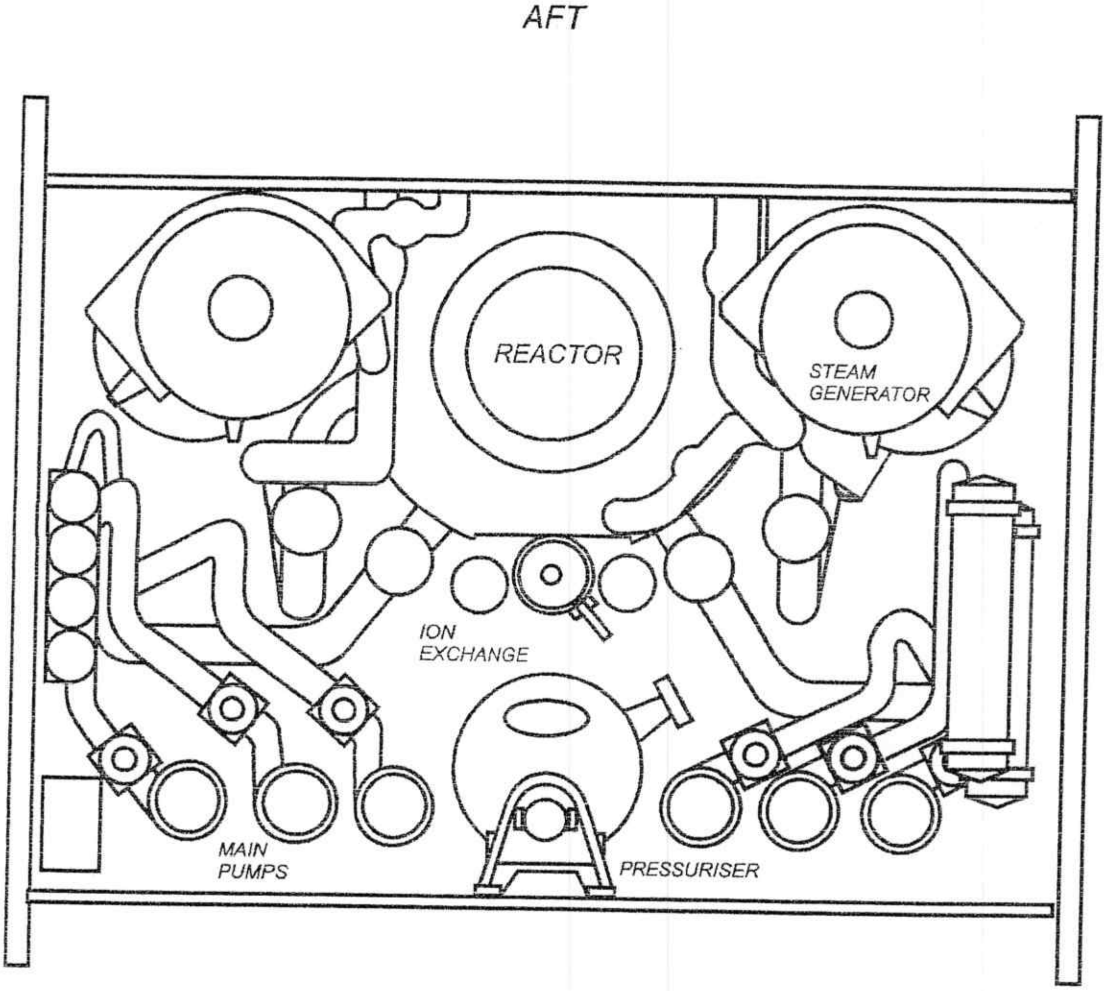

FIGURE 5 - SWIFTSURE/TRAFALGAR CLASS SSN REACTOR COMPARTMENT - PLAN

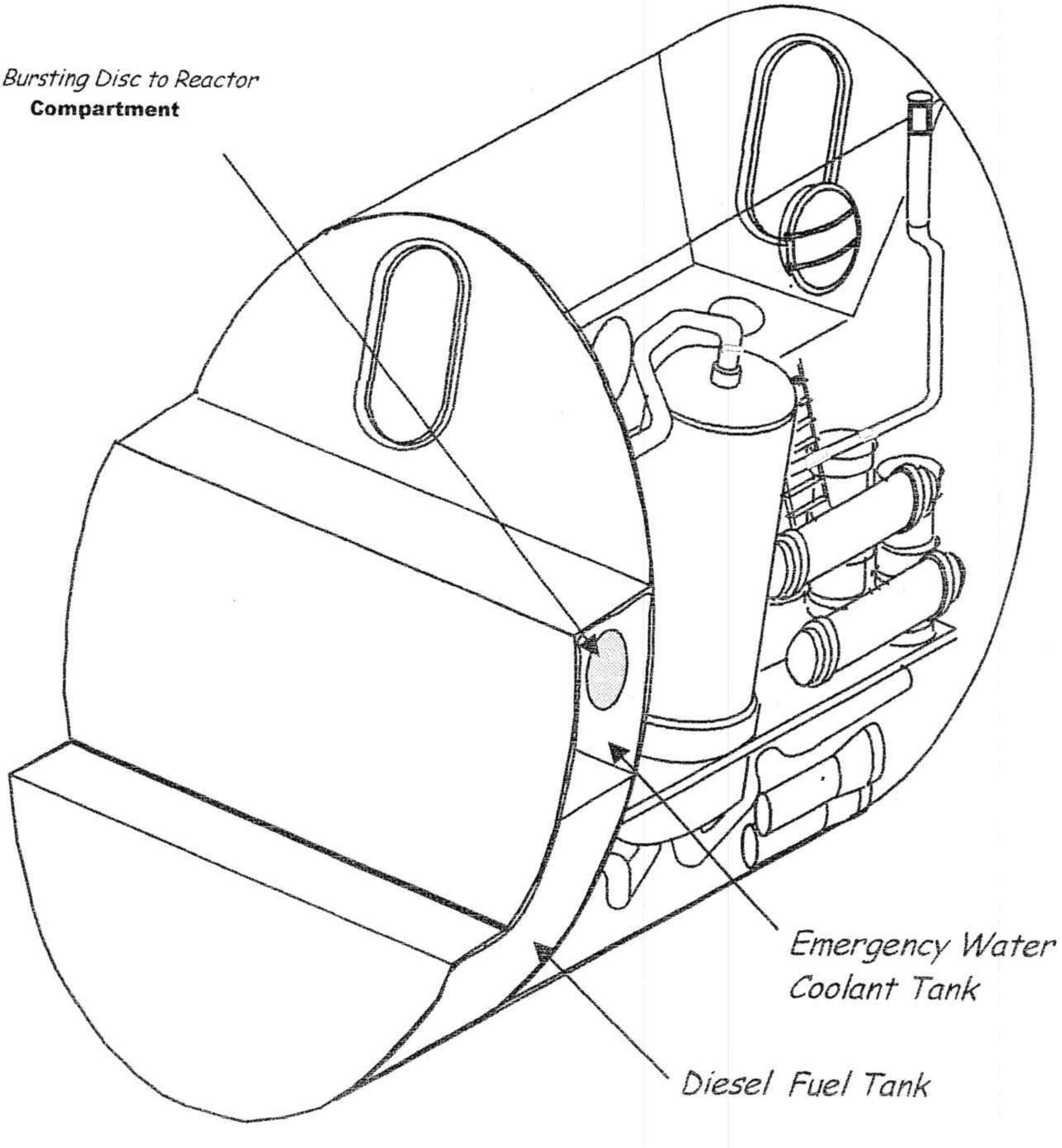

FIGURE 6 – REACTOR COMPARTMENT BOUNDARIES

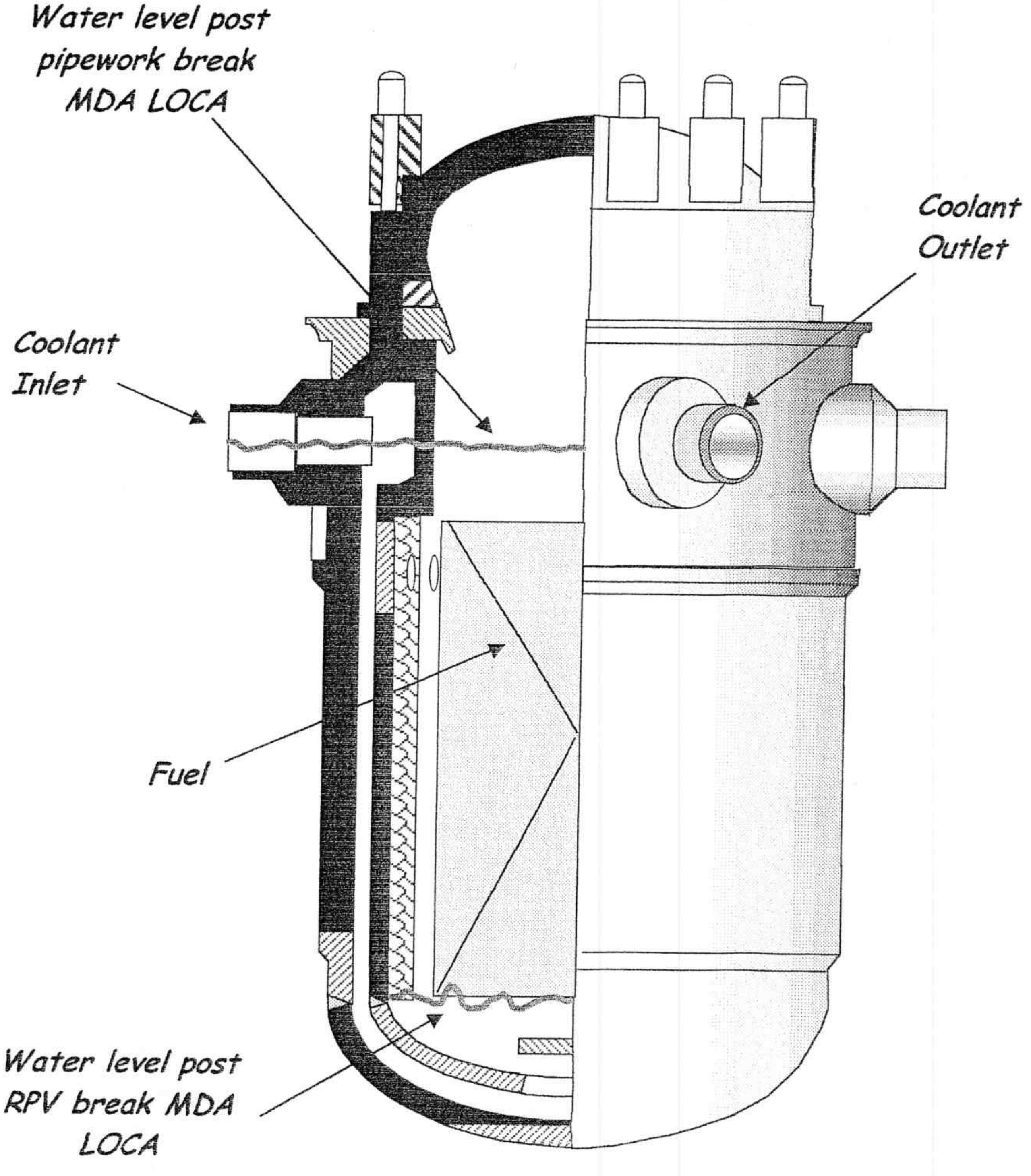

FIGURE 7 – FUEL COOLANT COVER POST PIPEWORK AND RPV LOCA SCENARIOS

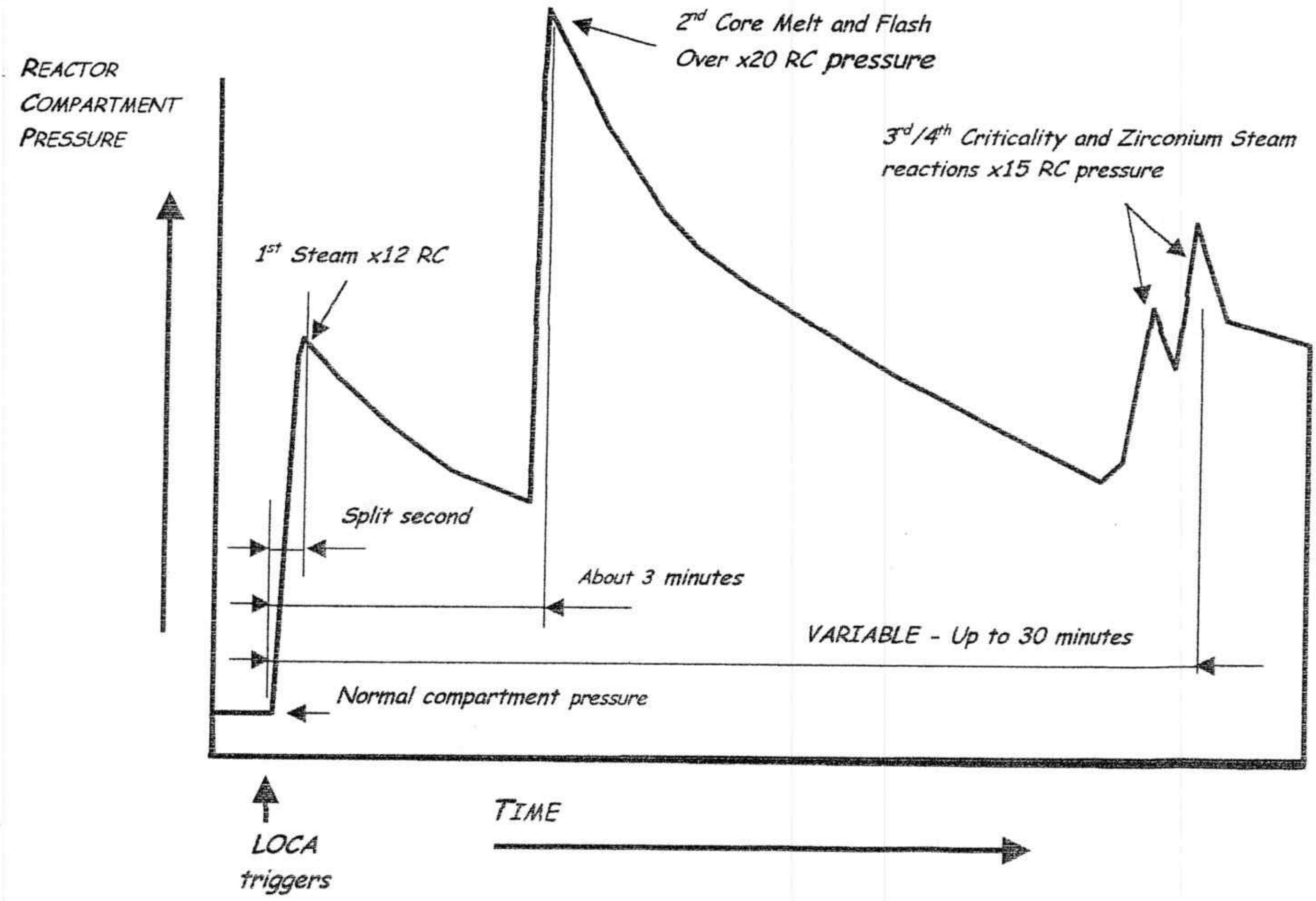

FIGURE 8 – SECONDARY CONTAINMENT PRESSURE TRANSIENTS V TIME
(not derived)

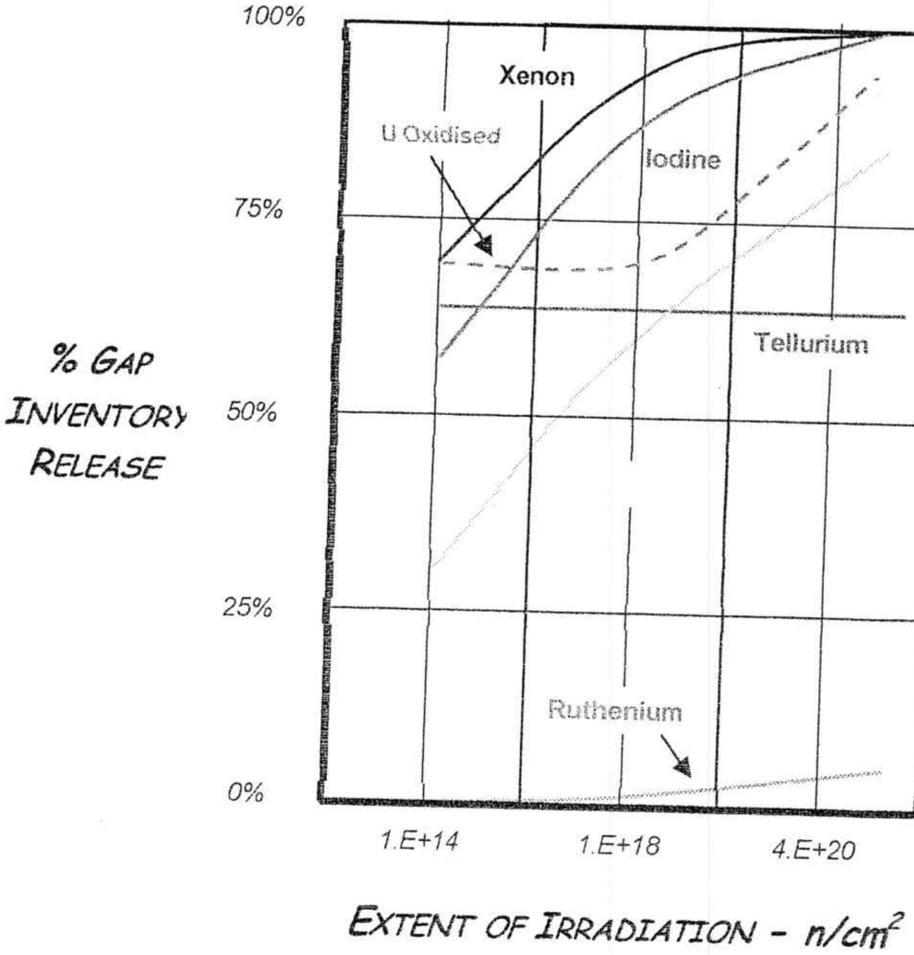

FIGURE 9 – GAP INVENTORY RELEASE V FUEL BURN-UP

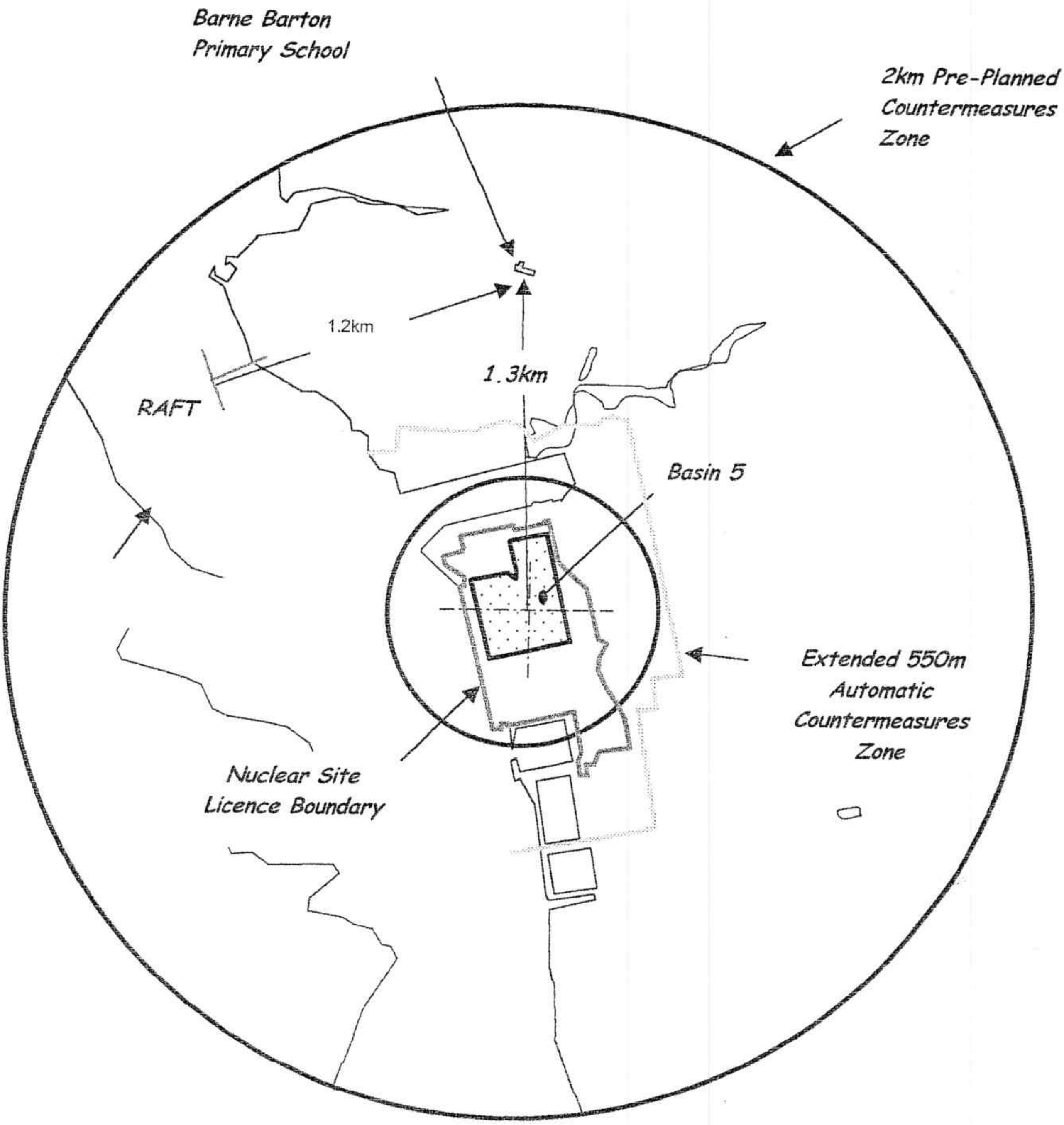

FIGURE 10 – *DEVPUBSAFE* ERL COUNTERMEASURE ZONES

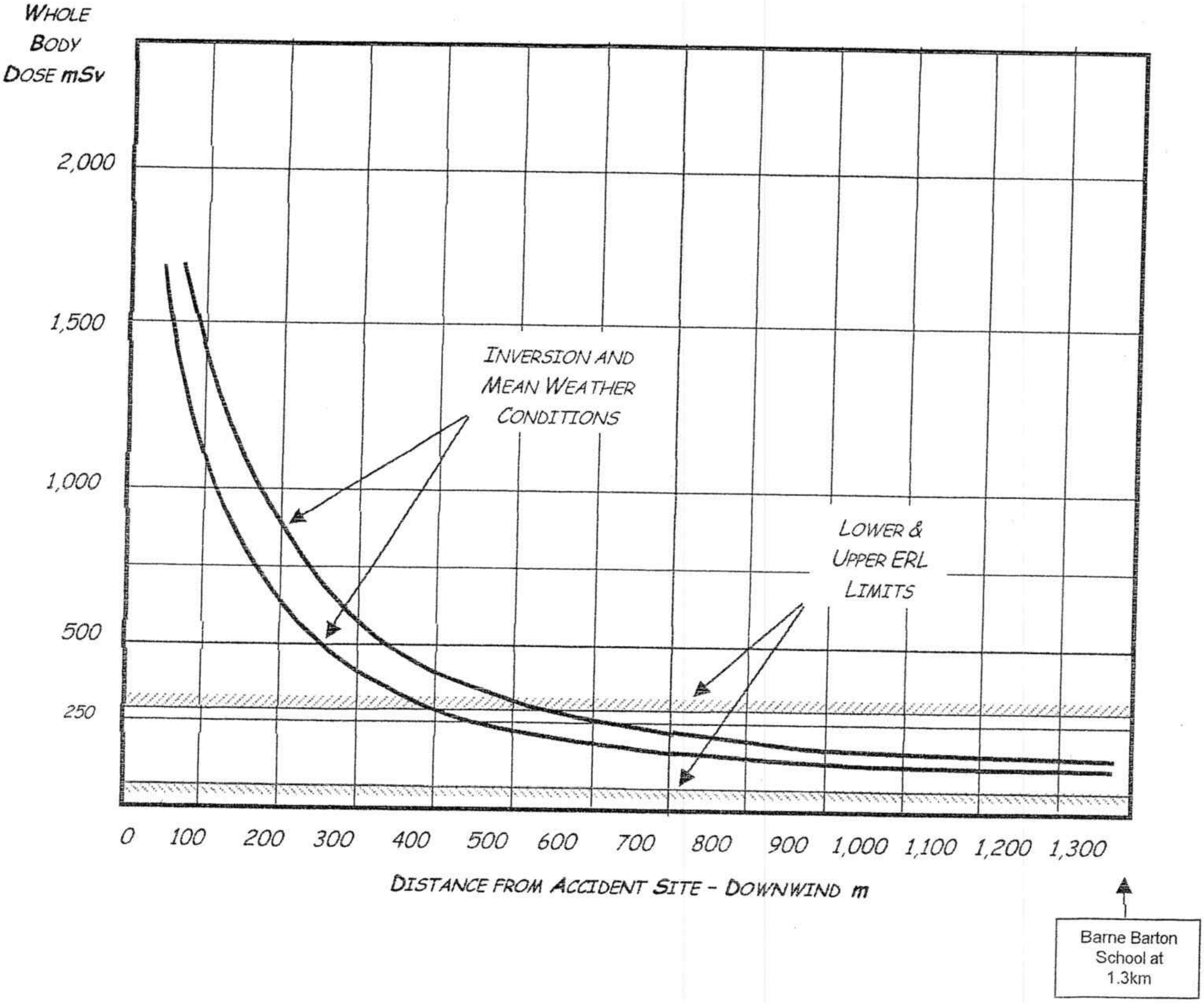

FIGURE 11 – WHOLE BODY DOSE FROM THE PASSING OF A 400,000 TBq PLUME RELEASE OF GASEOUS AND VOLATILE GAMMA EMITTERS – SHINE ONLY - NO DEPOSITION – REDUCED FOR BUILDING SHIELDING

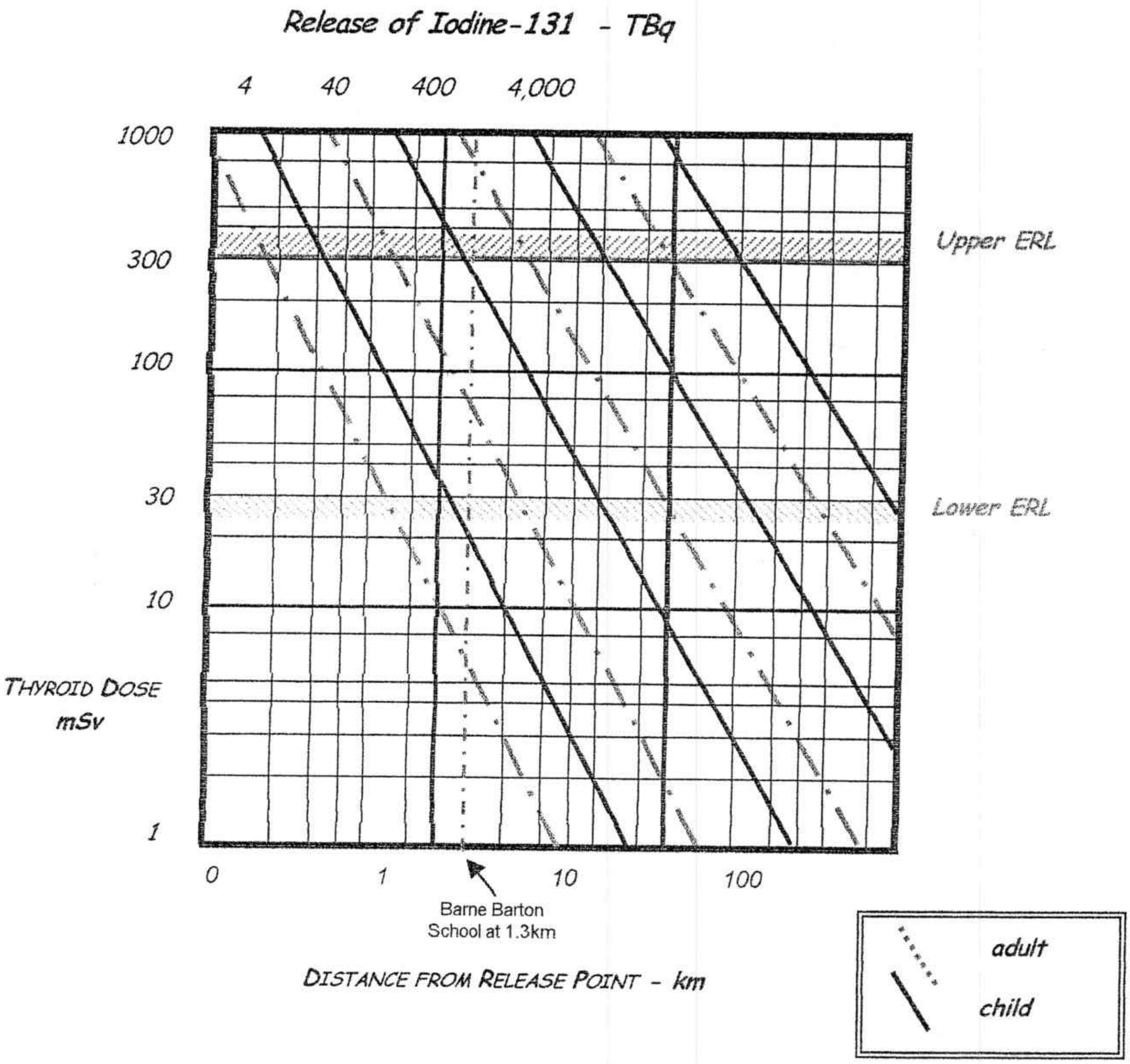

FIGURE 12 – THYROID DOSE FROM EQUIVALENT I-131 DEPOSITION