

Forensic Assessments of the Nuclear Propulsion Plants of the Submarines HMS *Tireless* and RF Northern Fleet *Kursk*

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SYNOPSIS

In May 2000, whilst operating submerged deep in the Mediterranean off the southern coast of Sicily, the Royal Navy nuclear powered submarine HMS *Tireless* developed a serious fault in the primary circuit of her nuclear reactor, she surfaced, shut down her nuclear propulsion system and made way under emergency diesel power to Gibraltar for investigation and repairs which were to occupy almost 12 months. In August of the same year, the Russian Federation Northern Fleet nuclear powered and nuclear weapons capable submarine *Kursk*, whilst at periscope depth just north of the Murmansk inlet in the Barents Sea, experienced a catastrophic explosion in her forward torpedo compartment, sinking with a total loss of the 119 crew members on board.

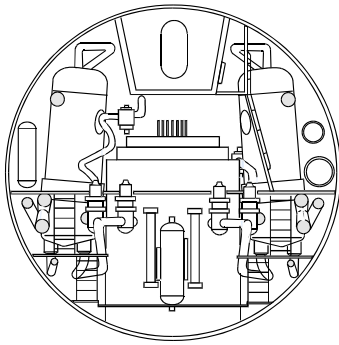
This paper reviews the determining aspect for both projects, being the need to assure continued nuclear safety in the absence of the opportunity for fully detailed scientific examination of the damaged plant. Forensic assessments had therefore to make best use of limited indirect evidence, backed by experienced judgement, to deduce limits to the potential damage and define safeguards to ensure that these limits were not infringed during both the repair and recovery processes leading to resumption of nuclear operations of *Tireless* and the world-first salvage of a nuclear-powered submarine the *Kursk*.

1 MARINE NUCLEAR POWER PLANTS

Nuclear, pressurised water reactors (PWR) provided the main propulsion power for both of these submarines. Essentially, the PWR heats water to below saturation conditions in excess of 240 bar, transferring this heat to raise steam in a secondary circuit to drive the boat's turbines, providing power to boat auxiliaries and the main propulsion system.



1 HMS *Tireless* rides out heavy Irish Sea Swell



2 Reactor Compartment - reactor shield tank centre, flanked by 2 steam generators

In *Tireless* (~5,200t submerged, 85m length and 9.8m beam) the heat provided by the single 70MW_t reactor¹ raises steam in a secondary circuit via two steam generators each feeding a geared turbine, in all generating about 15,000 shaft horsepower at the single pump jet propulsor (essentially a ducted propeller with stators). The reactor connects with the two steam generators via large diameter (~360mm) stainless steel piping that follows a relatively torturous path in the confines of the isolated reactor compartment that is positioned amidships. This ‘dispersed’ arrangement has a number of advantages, including protecting the steam raising plant from neutron irradiation embrittlement in and nearby the reactor nuclear fuel core, the relative ease at which parts of primary circuit can be quickly isolated by automatic valves in the event of a leak, and accessibility for repair.

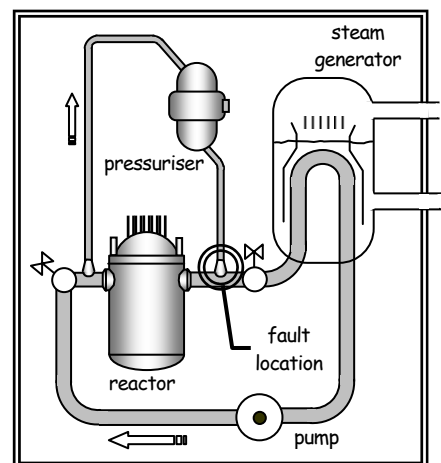
Kursk, a Krasnodar (NATO Oscar II) class guided missile submarine commissioned into service in 1996, was a very large submarine (~19,000t submerged, 155m length and ~11m beam inside the flood casing), being powered by two ‘integrated’ OK-650b nuclear reactors, where the steam raising pods are close-coupled to the reactor pressure vessel, generating a total shaft power of 98,000 shp via two contra-rotating swept propellers. The moderately enriched uranium fuel cores each comprise about 200 thin-shelled zirconium-uranium alloy, tubular elements, with this type of fuel being generally less robust to power changes than the western flat plate highly enriched uranium ceramic-metal dispersed *cermet* fuel. The OK-650b power train design compensates for this by continuously draining 15 to 20% of the full power rated steam directly to the condenser bypassing the turbines, but switching this directly to the turbines when combat conditions dictate, thus allowing the nuclear plants a more leisurely time to catch up with the power demand (like the make-up steam drum on conventional steam raising plant).



3 *Kursk* heading out for her last patrol in the Barents Sea

2 TIRELESS FAULT

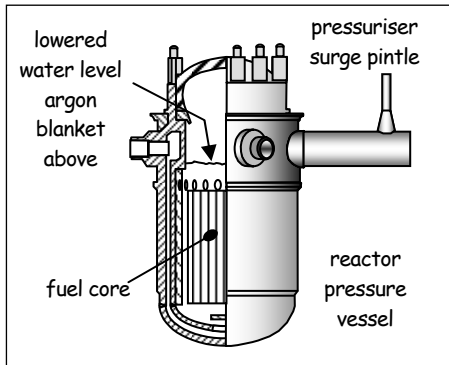
The fault in the reactor primary circuit of *Tireless* was first detected by the *leak-before-break* systems on board the submarine when she was submerged. The leak was located in the immediate locality of the welded pintle tee-junction of the pressuriser surge pipe and the main outlet pipe feeding from the reactor to one of the steam generators. The reactor was shut down following prescribed procedures, and the leakage rate estimated. It was then decided at high level within Ministry of Defence (MoD) and communicated back to the boat that the reactor could be restarted and the boat continue nuclear operations. However, after a few hours of running the leakage



4 Schematic - Dispersed Nuclear Plant Main Components

increased to an intolerable rate, suggesting rapid development of the leakage path, so much so that the nuclear plant was shut down again with the primary circuit being progressively depressurised whilst *Tireless* made for the Port of Gibraltar under her standby diesel plant.

If the fault had been allowed to develop further then *Tireless* would have been at very real risk of catastrophic failure of the surge pipe junction which, being located inboard of the primary circuit isolation valves, could allow the reactor pressure vessel to rapidly depressurise and starve of coolant. Uncontrolled loss of coolant at this locality could have resulted in boiling of the coolant remaining in the reactor vessel, overheating of the nuclear fuel (even with the nuclear process shut down because of the continuing residual heat from fuel decay), the possibility of fuel melting and, in the extreme, a violent explosion leading to a radioactive release within a few minutes.^{2,3}

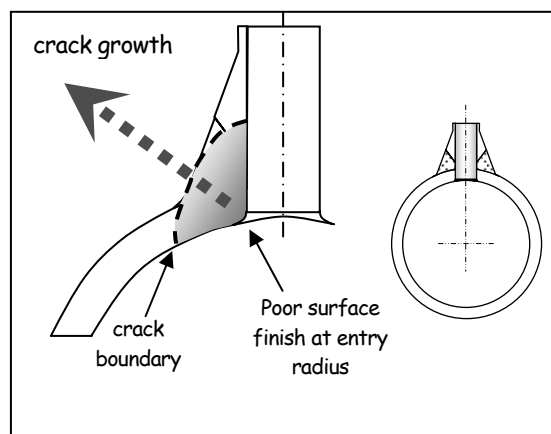


5 RPV and Surge Pipe Pintle

The challenge for the forensic analysis was that the inspections had to be undertaken in a radioactive environment, with the sources of radioactivity being deposited layers of radioactive crud⁴ adhering to the inner surfaces of the pipework, together with the intensely radioactive fuel core that could not be removed, having to remain in situ within a meter or so of the fault location. In ideal circumstances, the investigation and repairs would have been completed in a refit dockyard, such as Devonport, where the fuel could have been removed and the magnetite-based crud scoured out by an acid etch solution.

Moreover, work in earnest could not begin until the decay heat in the fuel core had reduced sufficiently to permit the reactor primary circuit to be drained down to a level to empty the main pipe at the pressuriser junction and isolate it by insertion of an inflatable bladder.⁵ For the reactor fuel to sufficiently decay to reach *thermal rollover*, the point in time at which the residual heat could be dissipated by natural heat loss, 40 days passed during which very little non-destructive and no intrusive examination could be undertaken. However, there was a great deal to do during this period, particularly in developing the nuclear safety case between the navy's nuclear regulator (CNNRP)⁶ and the design authority (Rolls Royce Marine), and the Expert Panel of specialists⁷ acting on behalf of the Government of Gibraltar had to be satisfied that the in-port repair and eventual restart of the reactor would be safe (of acceptably low risk).

In fact, throughout this cool down and preparatory period the assumption had been that the fault was a single crack originating and confined within the pintle weld, that had grown from a flaw overlooked in the original build NDE radiographed certification of the weld and, importantly, that for the repair it would be sufficient to remove and replace just the pintle of the smaller diameter pressuriser surge pipe. However, once access for an in-pipe cctv viewing system had been established, the cracking was discovered to be very much more extensive, comprising two distinct centimetres long vertical fractures originating in the parent metal of the larger primary circuit pipework, and spreading upwards and outwards into the wall of the main pipe and pintle weld. The extent of the cracking required approximately one-quarter of the uppermost section of the primary circuit pipe at



6 Pressuriser Surge Line Pintle showing 1 of 2 thermally induced cracks

required approximately one-quarter of the uppermost section of the primary circuit pipe at

the cracked junction to be trepanned out resulting in the need for a complete in situ reconstruction of the surge pipe junction.

CNNRP concluded upon fuller inspection of the removed trepanned section, the cracking to have arisen from thermal fatigue resulting from slugs of cooler water cycling in and out of the mouth of the pressuriser surge pipe⁸ over many years of operation, although the final detailed results of the analysis of the removed pintle-main pipe section were never revealed to the Expert Panel advising the Government of Gibraltar.⁹ In the absence of proof otherwise, it may have been that the failure cause was more complex, resulting from a combination of thermal fatigue¹⁰ and thermal striping,^{11,12} the latter being relatively short-term in development. Another possible contributory factor to the cracking was the very poor (grooved) finish of what should have been a smooth, radius edge of the main pipe cut-out leading into the surge pipe, possibly containing latent crack initiators that could have developed over years of service.

Whatever the cause of the cracking, the implications of this were very significant because by then, over three months since the enforced lay up of *Tireless*, an entirely new repair strategy had to be developed and proven; *Tireless*, her boat and on-board weapon systems had to be maintained safe¹³ for a repair lay-up that was to be much longer than originally foreseen; and, because the nature of the defect was most probably generic, the other six boats of the *Trafalgar* class and the two or more remaining boats of the *Swiftsure* class (all fitted with basically the same PWR-1 nuclear plant) had to return to the UK refit yards for inspection and urgent modification.¹⁴

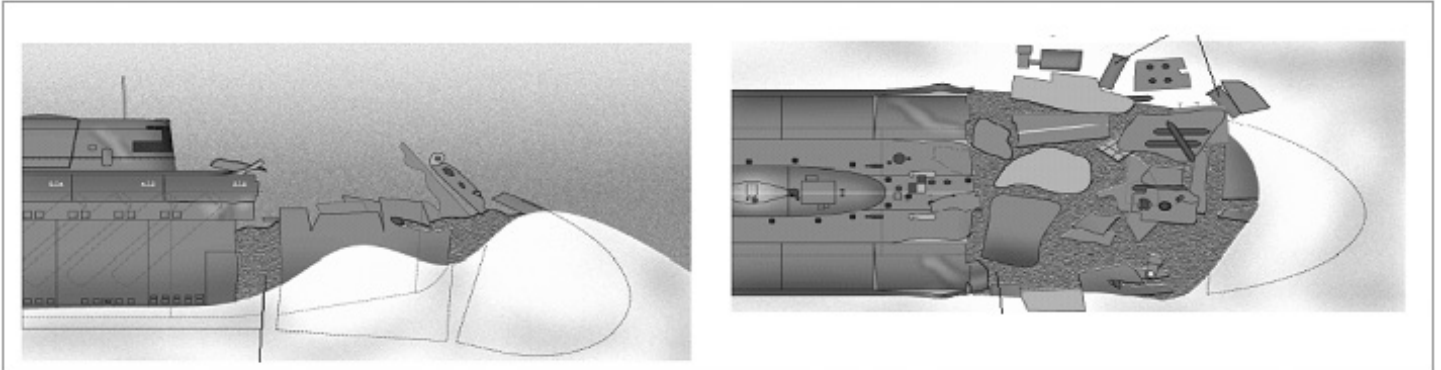
Working up the new repair plan and the decision to replace the pintle design with a one-piece forged swept branch connector (a *Sweepolet*) further delayed progress on *Tireless* until November, thereafter there was stay-over whilst another *Trafalgar* class submarine was adopted as the lead boat to demonstrate the ease and validity of repair at the fully equipped Devonport Dockyard in the UK. *Tireless* was eventually fitted with the *Sweepolet*, passed NDE and the cold hydro test, being readied for nuclear power operations to leave the Port of Gibraltar on 8 May 2001, almost a year to the day that she ignominiously limped into Gibraltar under her emergency diesel power.

3 KURSK

At almost exactly at 07.30 GMT on 12 August, 2000 a small and relatively insignificant seismic disturbance offshore in the Barents Sea was recorded by a Norwegian seismological station. It was followed one hundred and thirty five seconds later with a much more significant event, equivalent to about 3 to 3.5 Richter scale. This second explosion was the death knell of the Russian Federation Northern Fleet nuclear powered submarine *Kursk*.

Kursk was participating in torpedo firing trials; she had fired the first of two prototype and unarmed rounds and was readied to fire the second under the supervision of the range ship, the cruiser *Pyotr Velikiy* – it is believed that the unintended mixing of the torpedo fuel components of this second round exploded in the confines of the outer port torpedo launch tube. The debris field from the first explosion suggests that the damage was ahead of the foremost section of the pressure hull and that only a small section of the non-structural casing (or flood hull) had been damaged. However, the sonar trace taken by the nearby *Pyotr Velikiy* showed a continuing activity representative of severe burning and jetting of the second prototype torpedo into the forward weapons stowage compartment, and it is clear from the same sonar records of the very much larger second explosion that this was from five to seven individual events occupying, in all, just over one-fifth of a second. This multi-explosion, equivalent to 2 to 3 tonnes of TNT, is believed to have derived from the detonation of up to 7 fully armed torpedo rounds in the forward port magazine carousel. This massive explosion, inside the pressure hull, dealt a catastrophic blow to the *Kursk*, ripping out a very large section of the

forward pressure hull (10 x 8m area) and outer casing and, at the same time, sending a reverberating hammer blow through the compartments towards the stern. Structural and flood bulkheads N° 2 and 3 were ripped through, with N° 4 buckling and subsequently collapsing under the hydrostatic flooding loads. N° 5, the forward reactor compartment bulkhead, and the remaining bulkheads through to the ninth compartment remained intact.¹⁵



7 Wreck of the *Kursk* – bow flood hull housing the forward seeking sonar has been displaced, the various cylinders are gas storage bottles, and the entire top section of the pressure hull of No 1 and No 2 compartments has been blown away

In preparation for the Mammoet-Smit salvage activities scheduled throughout the summer of 2001, two groups of hazard had to be evaluated, being i) the condition of the two nuclear reactors and ii) the stability of the remaining weaponry on board, particularly the remnants of the torpedoes, either remaining in or blown clear of the bow compartment, and the 23 cruise missiles located in port and starboard silo banks. Then, first, the threat to the nuclear reactors if and when disturbed directly by the Mammoet-Smit salvage operations had to be established and, second, the threat to the remaining weaponry, and thence to the nuclear reactors, had to be evaluated or proven to be adequately countered against. This nuclear and weapons hazard assessment and safety case as undertaken by a team of nuclear and weaponry specialists, the Independent Assessment Panel (IAP),¹⁶ appointed by Mammoet-Smit and approved by the Russian Federation authorities.

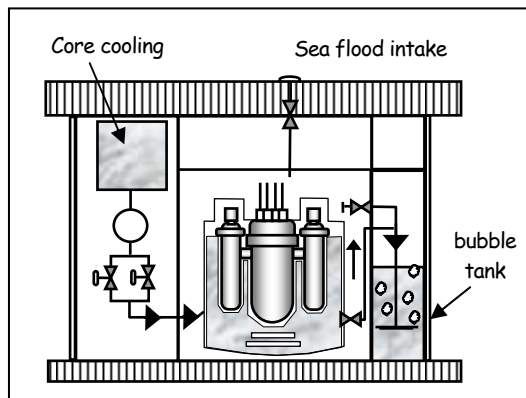
These safety issues were addressed in terms of had both reactors closed down during or after the second explosive event; had the fuel been damaged, that is melted down, following sinking and loss of power; were the reactor-primary circuit and reactor compartment containments intact and reliable; and was there possibility that one or both reactors could resume criticality during salvage operations?

The hurdles that the IAP had to overcome included that all instrumentation channels to the reactor compartment had been lost, and that the reactor compartment was and had to remain sealed for the final lifting operation. However, during the three months or so following the sinking the Russian authorities had completed a number of investigations about the reactor compartment, including monitoring for radioactivity around the sea scuppers of the flood hull (casing), the introduction of a 5-7Mev¹⁷ gamma sensor inserted into the void of the casing to monitor for neutron induced activity in the reactor fuel cores, and temperature sensing from top to bottom of the casing around the reactor compartment to determine any extraordinary heat generation by the reactors being neutron critical.

These Russian investigations, which pointed to a contained radiological and nuclear situation, had been completed in order to assess the potential environmental impact of the wreck should the reactor

containments fail in the relatively quiescent sunken state. Since that time the decision to salvage the submarine had been taken at the highest political level, so the earlier monitoring of the Russian authorities had to be re-examined in terms of the rough-and-tumble of forces, disturbance and circumstances likely to be generated during the Mammoet-Smit salvage.¹⁸

The IAP set down two prerequisites to be satisfied before recovery operations could commence: The first being robustness of containment of the nuclear materials and radioactivity, and the second requiring continuing stability (nuclear inactivity) of the nuclear fuel cores.



8 Integrated PWR plant (1 of 2) in Compartment No 6 showing schematic of emergency cooling systems

For containment surety, IAP needed to determine if adequate levels of containment had survived the main explosion and, after that over a period of 12 or so months until the salvage operation commenced, the degradation processes of the wreck being abandoned on the sea bed. Of the four levels of containment (fuel cladding, reactor pressure vessel, shield tank and reactor compartment hull), at least two levels had to be intact and, if at all practicable, at least one or the other had to be resistant to a series of postulated causes of failure, such as the submarine impacting on the seabed during the first stages of the recovery lift. Other more threatening scenarios, such as impact by a (60 tonne deadweight) crane falling from the recovery barge

tethered immediately above the wreck had to be precluded (by operating restrictions).

First, the capacity of the passive heat dissipation and emergency core cooling systems to protect the reactor cores was assessed.¹⁹ Observations for the range ship *Pyotr Velikiy* gave *Kursk* to be making a little over 6 knots on its torpedo run and, rigged in combat role, her reactors would have been powered to include for at least a 15% steam dump to the condensers, so all in all about 90MW_t for each reactor at the instant of boat electrical supplies being tripped out and, once and if this had been coped with, thereafter a residual heat of decay of about 10 to 15MW_t reducing (initially rapidly and then slowing over weeks) until equilibrium *thermal rollover* had been reached. The post-incident dissipation of the reactor core residual heat, with the reactors tripped and once that the turbines had spun down and the condensers lost vacuum, in the absence of any energised core cooling systems was considered to be the most challenging phase. This had been analysed by the Russian technicians earlier with the outcome suggesting that some parts of the fuel cores would have been unlikely to have survived the associated temperature excursions without damage. So with the condition of individual fuel element containments (cladding) doubtful but in the absence of any radioactivity emanating from within the reactor compartment, the assessment was that the pressure hull and bulkhead containment in the vicinity of the reactor compartment remained sound, with at least one other containment level (either the shield tank and/or primary circuit) intact.

Second, although both reactors seemed have shut down (from the results of 5-7Mev gamma monitoring), no indication was available that the control rods had actually latched-in. Each control rod mechanism includes a harpoon-like latch, or *garpunnaya zaschyolka*, which holds each rod in place inserted into the fuel core once electrical power to the rod clutches has been isolated. The dilemma here was did the electrical power circuit breakers cut off the power at the instant of the first relatively small explosion, in which case the rods would have most probably fully inserted and latched, or was power available until the second devastating explosion which, if so, may have resulted in the rods being unable to insert and latch in fully whilst the reactor structures were subject

to the reverberating shock running down the hull structure. The expectation is that power supplies would have remained available for the 135 seconds between the two explosions because in combat the design specification for the nuclear plant would require it to continue to operate unabated when under attack from depth charges and other anti-submarine weaponry. Nor is it likely that the submarine commander Gennady Lyachin would have ordered the reactors to close down because continuing propulsive power was required to maintain the trim of the boat and, of course, he and his executive officers would have been totally absorbed assessing the compartment damage reports following the first explosion, a process that on a submarine of this size and complexity would have occupied at least 2 minutes.²⁰

The integrated PWR plants in the *Kursk* were, like earlier Soviet era designs, held in resilient mounts (a requirement for the combat role and silent running) so it was necessary to determine if these mounts had been capable of absorbing the impulsive loading from the second explosion and, importantly, if they could do the same again should any remnants of unaccounted torpedoes detonate during the salvage lift.²¹ Assessment of the impulsive loads was made, in part, by detailed post-mortem examination of the crewmen who had been recovered from the stern section in the weeks following the loss of the *Kursk*. Two crewmen were of particular interest, these being the reactor control room personnel who would have been stationed in the reactor control room abutting the aft bulkhead of the reactor compartment who would have been subject to the shock of first and second explosions carried along the length of the pressure hull. The injuries to these two individuals indicated that the dynamic loading on the resilient mounts were just about at the design limit. Thus, unknowingly, these two crewmen contributed vital information that augmented confidence in the structural condition and stability of the reactor plants and their containments.

By mid-September IAP was satisfied that it had addressed the major issues of nuclear safety in the salvage of the *Kursk*: Sufficient levels of containment of the radioactive and fissile fuel cores had survived intact, all external signs indicated that both reactors had close down, and that the reactor resilient cradles should have withstood the explosive shocks and be in a condition to withstand and attenuate shock transmission from a further torpedo explosion postulated possible during the early phases of the salvage lift. That said, a number of other uncertainties remained although IAP considered these to be sufficiently compensated for by the radiological sheltering and countermeasures in place to safeguard the Mammoet-Smit salvage personnel, to enable the final recovery operations to proceed.

Kursk was lifted from the seabed on 8 October 2001 and then, slung under her lifting barge, transported to Roslyakov in the Belokamennaya Bay (Murmansk) where she was transferred into a huge floating dock. The lift, sea transport and docking operations were comprehensively monitored for radioactive release and nuclear activity – nothing radiologically untoward was detected.

4 CONCLUSIONS

At the best of times, inspection of nuclear reactor plant is difficult because of the persistent radiological environment, more so for the nuclear propulsion plant on board a submarine because the spatial restrictions are so tight and demanding. So much so for both *Tireless* and *Kursk* projects where access was not entirely available, in the case of the *Kursk* entirely denied, so each of the post-incident assessments requiring a great deal of sound engineering judgement to arrive at the correct forensic analysis.

For *Tireless*: The decision to restart the reactor seems to have been entirely misjudged because it was based upon a belief that the then assumed single crack had either stabilised or would run itself out within the confines of the weldment and, once the plant had been restarted, the developing leak-

before-break information seems to have been misinterpreted allowing the two cracks (as subsequently found by inspection of the removed trepanned section) to enter over a few hours the rapid propagation phase²² before the reactor was shut down again and depressurised. And then, during the initial and early stages of the *Tireless* investigation the engineering judgement faltered because assumptions were drawn only from a set of prescribed fault conditions (the in-service inspection *League Table*),²³ apparently there being little flexibility and scope for the navy regulators to look beyond these.²⁴ Thereafter, and until physical access into the junction internals was possible, the investigation and preparation of the repair procedure continued on the basis that a hidden defect had initiated a single crack, with the investigators seemingly unaware of the possibility of the rapid onset of cracking being thermally induced, and/or generated from the poor surface finish of the original fettling of the surge line junction.²⁵ Once that the fault (although not necessarily its direct cause) had been correctly identified action was swift, with the introduction of the swept branch connector, the *Sweepolet*, and the inspection and modification of all of the Royal Navy's submarines fitted with the PWR-1 nuclear propulsion plant.

Kursk was an entirely different kettle of fish. Here the IAP was probing into the secret design of an advanced military vessel that, just a few years earlier would have been deployed in the forward brigades of the Cold War. As the IAP prepared its nuclear safety case, working with its Russian Federation counterparts, for some topics the information was so sensitive that if the IAP got it wrong they were met with denials, but when they got it right this was greeted only with silence. Most frustrating at all, although the IAP did get it right and this world-first salvage of a nuclear-powered submarine was raised without any radioactive spillage to the environment, they never knew the margin of their success because as soon as the *Kursk* had been lowered onto the cradles of the floating dock at Roslyakov, passing into Russian Federation Northern Fleet hands, the all enshrouding Russian military secrecy descended once again.

¹ HMS *Tireless* (a Trafalgar class) was commissioned in 1985 and is powered by a third generation nuclear reactor, being a development of the United States S5W propulsion reactor originally purchased by the Royal Navy for its first nuclear submarine *Dreadnought* commissioned in 1963. The latest generation of highly enriched uranium 'Z' fuel core is capable powering the submarine over 10 or more years.

² There are two potential sources of explosion: If the fuel-steam temperature of a partially boiled off reactor vessel reach ~1,000°C, there is risk of detonation of the hydrogen liberated by the oxygen stripping reaction of steam and the zirconium of the zircalloy cladding of the fuel plates, and if the fuel becomes molten and drops into the remaining water in the bottom of the reactor pressure vessel, then the risk of a very severe metal-water explosion.

³ Nothing is published in the open literature on the loss of coolant accident (LOCA) scenarios for submarine nuclear plant, although the classified Royal Navy *Books of Reference* provide details of the scenarios that have to be planned for and, more specifically, *MAPC Hazards of a Reactors Accident* (Royal Naval College, Department of Nuclear Science and Technology (S)CM/13/88/WM, October 1992) describes three severities of incident, the worst of which results in a major release to atmosphere from a surfaced submarine within 10 to 20 minutes. Civil PWR LOCA scenarios have been published, see *Loft Core Damage Test Lauded*, Nuc Eng Int 1985 and Gittus J, *PWR Degraded Core Analysis*, ND-R-610(S), UKAEA 1982, although these relate to uranium dioxide fuel cores of much lower U-235 enrichment (2 to 3%).

⁴ CRUD – so called *Chalk River Unidentified Deposits* – generally, the radioactive deposits that build up on the inner surfaces of the primary surface pipework, valve seats, etc.

⁵ On the reactor side of the junction, sufficient water cover (under an argon gas blanket) was maintained over the fuel core which, by that time, continued to generate a steady 10kW_t which was naturally dissipated through the reactor shield tank to the hull and surrounds

⁶ CNNRP - *Chairman Naval Nuclear Regulatory Panel*, comprising serving naval officers and staffed by MoD personnel. There is also the *Defence Nuclear Safety Committee* (DNSC) that seems to finally sanction arrangements for nuclear safety, although the membership details of the DNSC are not publicly available.

⁷ The Government of Gibraltar appointed an independent Expert Panel to advise of safety throughout the repairs, the panel comprised Large & Associates, the National Nuclear Corporation and Ove Arup – the comments and opinions expressed in this paper are solely those of the author.

⁸ To maintain and trim the required primary circuit pressure (ie to prevent boiling in the reactor fuel core) the steam bubble held in the pressuriser is either electrically heated or cooled with a water spray (from the primary return coolant), the pressure adjustment being transmitted down the surge line to the main primary circuit pipework. Thus, when the reactor is required to respond rapidly, such as when in combat mode, slugs of cooler water pulse down the pressuriser surge line – the greater robustness of the Z fuel core to thermal cycling has improved the propulsion performance but, seemingly, in permitting a greater combat response the thermal fatigue of the pressuriser pintle was overlooked. There could also have occurred hydraulic siphoning and resonance within the pressuriser circuit to similar effect.

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- 9 The position of the Expert Panel was that it was to advise the Government of Gibraltar on the safety assessments of the repair procedure and the eventual restarting of *Tireless's* reactor in the Port, so working to this brief it could not insist on access to, nor was it given, all of the facts that resulted in the failure itself.
- 10 The formation of the alpha-prime phase in the ferrite component is the primary factor involved in the thermal aging of cast stainless steel at PWR operating temperatures. Because only the ferrite phase is embrittled by long-term service at PWR operating temperatures, the overall thermal aging of cast stainless steel piping depends on the amount and morphology of the ferrite present. Pressure and thermal stresses imposed during system transients, including heat up and cool down, cause low-cycle fatigue damage. On civil PWR power stations there have been no reported failures, not even discovered cracks, in existing primary circuit main coolant piping mainly because the main coolant piping does not, unlike submarine PWR plant, experience significant transients. However, civil PWR branch lines have suffered from thermal fatigue cracking caused by the phenomena not accounted in the original fatigue design - see Shah, V N et al *Review of Industry Efforts to Manage Pressurized Water Reactor Feedwater Nozzle, Piping and Feeding Cracking and Wall Thinning*, NUREG/CR-6456, Nuclear Regulatory Research 1998
- 11 In nuclear, thermal and many process plants, there are pipe or Tee junctions where hot and cold fluids are mixed together during normal operation. This mixing of hot and cold fluids, under certain operating conditions, may result in significant fluctuation or oscillation in the local fluid temperature, commonly referred to as 'thermal striping' (rapid-thermal-cycle-induced fatigue). Thermal striping of plant components has recently caused cracking and failure of piping in operating plants in Japan and France. One of the fundamental limitations in understanding thermal striping is calculating the rapidly changing fluid temperature at the material surface. Limitations of both the single-phase computational fluid dynamics turbulence models in handling simultaneous momentum transport and energy transport, and of the ability to calculate the behaviour of the structure being thermally striped, prevent understanding and prediction of the material's performance. Thermal striping is reported to be particularly aggressive when the frequency of temperature oscillation is in the range 0.1 to 5Hz – the hydrodynamics (ie organ pipe frequency) of the pressuriser surge pipe may well have a resonance in this range – see Lee J I et al *A Parametric Study of High Cycle Thermal Fatigue Caused by Thermal Striping*, Center for Advanced Nuclear Energy Systems, Department of Nuclear Engineering, Massachusetts Institute of Technology, 1998.
- 12 Nuclear Energy Research Advisory Committee (NERAC) Subcommittee on Long-Term Planning for Nuclear Energy Research Long-Term Nuclear Technology Research and Development Plan June 2000
- 13 The torpedo and other bow launched weapons could only be unloaded with a specialised arming facility not available in Gibraltar and some of the weapons systems remaining on board had passed the so-called validation or shelf-life date, for which re-assessment and certification was required. Also, the repairs required the attendance at Gibraltar of the Royal Fleet Auxiliary *Fort Rosalie*, together with security and protection forces.
- 14 On 1 November 2000 Secretary of State Hoon announced that HMS *Splendid* and *Superb* also required the *Tireless* repair, and *Sceptre*, *Sovereign* and possibly *Superb* were withdrawn from service around that time for undisclosed repairs. In effect, the Royal Navy's entire hunter killer (SSN) flotilla was laid up and was not totally effective for about two years following the fault discovery on *Tireless*. It may have been, although it is not known, that certain classes of US Navy boats were also affected, also having similar nuclear propulsion plant on board.
- 15 Davidson P, Jones H, Large J H, *The Recovery of the Russian Federation Nuclear Powered Submarine Kursk*, Society of Naval Architects and Marine Engineers, World Maritime Technology Conference, Int Conf, Sans Francisco, October 2003
- 16 A consortium of the Dutch companies Mammoet and Smit International. Large & Associates were appointed to establish and head up the IAP to determine and set the radiological and weapons safety parameters during the salvage, this team included the same NNC personnel involved for HMS *Tireless* Expert Panel and a submariner Commander seconded from the Royal Navy.
- 17 The energy level of any neutron activity distinct from radioactive decay of the fuel.
- 18 *Rough-and-tumble* inasmuch the submarine was never designed with salvage in mind.
- 19 The OK-650b has three emergency systems to reduce the consequences of the most extreme incidents. Of these, should the pressure in the reactor compartment exceed 0.15MPa (arising from failure of the reactor primary circuit) then the containment space is vented into bubbling tanks which feed the cooled excess back into the compartment for recycling through this pressure suppression system if necessary. The second system relies upon power being available to operate two of three pumps that flood the reactor core if the circuit pressure drops below a preset level, delivery core flood water at 10MPa or much lower if power is drawn from battery reserves and/or if only the accumulator powered water supply is utilised. The third system of protection, applicable when there is a loss of electrical supplies, simply leaves open the path to the steam turbines and condenser banks.
- 20 It is now known from inspection of the N° 2, 3 and 4 compartments that there raged a very intense fire in these compartments in the time between the two explosions, so the crew and command in the forward and midship sections may have been incapacitated before the second explosion.
- 21 A further torpedo explosion during the salvage lift was assumed for the nuclear safety case because only 7 of the 24 live torpedo rounds on board at the time of the sinking could be accounted for. Therefore the possibility of a further torpedo explosion during the recovery had to be considered to be a credible event and potential causes avoided by setting operating restrictions, such as limits on the swell at the time of initial lift to avoid the possibility of the boat bouncing on the sea bed.
- 22 As recently as January 2000 the limitations of leak before break (LBB) have been identified to include situations where "ageing mechanisms or crack growth is not understood or not coherent with LBB hypothesis (e.g.: large crack growth extending circumferentially before longitudinally)", see *European Safety Practices on the Application of Leak Before Break (LBB) Concept*, EUR 185-49 EN, January 2000 and Keskinen R: *Technical Substantiation of the Leak-Before-Break concept*, STUK, Helsinki 1999.
- 23 The in-service inspection sites are defined in terms of risk being the product of consequence and probability yielding a *League Table* for the safety case which is generally in accord with ASME XI - see Taylor, S et al, *Integrating NDT Qualification with Design and Manufacture of Submarine Reactor Vessels* 3rd Int Conf NDE in Relation to Structural Integrity for Nuclear and Pressurized Components November 2001, Spain.

²⁴ The Design Authority for the nuclear propulsion plant is Rolls Royce Marine but there is also the involvement of the private dockyard at Devonport and the Navy regulator CNNRP in the in-service repair and inspection regimes, although the demarcation of the roles and responsibilities of each of these parties was at times unclear to the specialist panel.

²⁵ The difficulty with *Tireless*, at least during the earlier phases of the investigation, was that the forensic reasoning seemed inflexible and unable to consider any possible causes that had not been previously established in the fault *League Table* which, in itself, suggests that the surge line-main pipe junction was not previously identified to be at risk of failure. This apparent omission from the *League Table* is, since it is located in part of the primary circuit that cannot be isolated from the reactor, quite remarkable.