RISKS AND HAZARDS IN RECOVERING THE NUCLEAR SUBMARINE *KURSK*

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SUMMARY

In August 2000, the Russian Federation nuclear powered submarine *Kursk* sank in the Barents Sea with the loss of all 118 crew. In May following, the Dutch consortium Mammoet-Smit was contracted to recover the *Kursk* on condition that it had to be completed within that year. Working at a sometimes breathtaking pace, in just over six months the wreck was prepared, lifted, transported and delivered to a floating dock at Rosljakovo, about 200km south of the foundering site. Throughout salvage, a specialist nuclear team continuously assessed the radiological and weaponry hazards. For this, a radical and fast moving approach to developing a unique safety case had to be undertaken and, in doing so, normally sensitive areas of military secrecy had to be overcome; the differing approaches to safety assessment of East and West had to be harmonised; and, most of all, the radiological health and safety of the two or so hundred salvage personnel involved had to be assured.

This paper tracks how the nuclear and other hazards of the *Kursk*, its nuclear reactors and weaponry were assessed and monitored throughout the recovery and salvage program, and it provides an insight into the reasons why the *Kursk* sank.

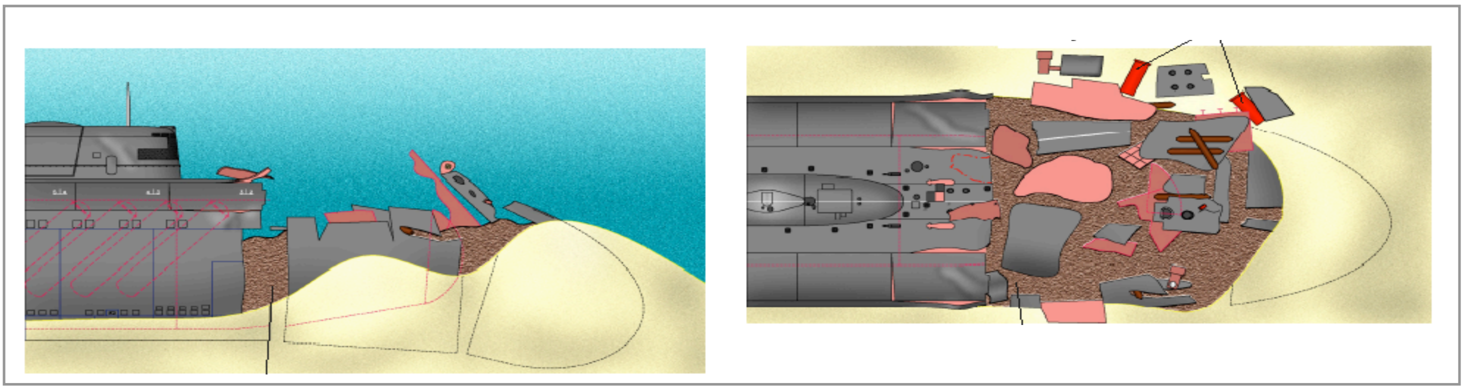
1 THE FOUNDERING OF THE *KURSK*

On Saturday, 12 August 2000 and exactly at 7.29.50 GMT a small and relatively insignificant seismic disturbance was recorded by a Norwegian seismological station. It was followed one hundred and thirty five seconds later by 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.[1]

The debris field from the first explosion suggests that this was located 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 (conventional) 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, at the same time, sending a reverberating hammer blow through the compartments towards the stern. Structural and flood bulkheads N^o 2 and 3 were ripped through, with N^o 4 buckling and subsequently collapsing under the hydrostatic flooding loads. N^o 5, the forward reactor compartment bulkhead, and the remaining bulkheads through to the ninth compartment remained intact.

The second seabed debris field provides clues to the remaining seconds of the *Kursk* and for all those crew present in the forward five compartments. The *Kursk* came to rest relatively upright lying on the seabed at



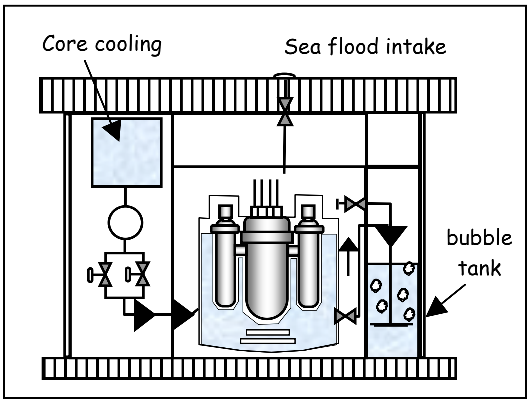
1 The bow damage showing failure of both flood and pressure hulls- internally the damage extended into the boat, collapsing lateral bulkheads into through to N^o 5 Compartment - the red cylinders are gas bottles about 110m depth, with the stem buffered against a sediment bank at an angle of 2^o bow down and with the hull pitched to the port side by 1.5^o. The major part of the second debris field lay 20 to 30m starboard of the wreck, whereas the pressure hull damage indicates that the major blast direction was upwards and to the port side, with this anomaly suggesting that the second explosion occurred when the Kursk was about 30 to 35m above the sea bed.[2]

When operating submerged, up to twenty-three crew members would be stationed aft of the reactor compartment attending to the steam raising and electricity generating plant generally dispersed about compartments N^o 7, 8 and 9 with, at all times whilst the reactors are operational, there being two crew members present in the reactor control room which is located at the higher deck level immediately aft of the reactor compartment. All of these individuals survived the two explosions and sought refuge in the sternmost N^o 9 compartment surviving for, it is believed, two to three hours in very cramped conditions on existing oxygen supplies and oxygen breathing apparatus canisters. Whether they perished by hypothermia, nitrogen narcosis or simply lack of oxygen is not known.[3]

2 *KURSK* K141 - TYPE, CONSTRUCTION & WEAPONRY

Kursk, a Krasnodar (NATO Oscar II) class guided missile submarine designed by RUBIN [4] and commissioned into service in 1996, was a very large submarine (~19,000t submerged, 155m length and ~11m beam inside the flood casing). Oscar II class submarine structure comprises double hull construction with nine interconnected watertight compartments, all being normally accessible except for the twin reactor compartment N^o 6 which is passed through via a radiation shielded corridor. The outer 8 to 18mm carbon steel (flood) hull casing of carbon steel plates is sprung off the externally ribbed 50mm high carbon steel externally ribbed, pressure hull by webs and struts. The void between the casing and pressure hull varies from 1 to 4m within which is located ship's equipment, sonar and the cruise missile silos. The entire outer hull and conning tower is sheathed in 40 to 80mm thick acoustically tuned, synthetic rubber tiles serving to both attenuate machinery noise from within and to reduce the reflective echo from incoming sonar signals.

Located in the sealed reactor compartment N^o 6, the power plant comprises two, integrated type pressurized water reactors (PWR - OK 650b) each of ~200MW thermal output 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. Each reactor pressure vessel is housed within a sealed 25m^3 capacity water shield tank that was resiliently mounted to absorb shock from the operational submarine when in battle situations. Nuclear plant emergency shut down is via control rod injection by mechanical spring and pneumatic drive and core cooling was via a relatively conventional ECS with a supplementary bubble tank. As an ultimate safeguard the entire reactor compartment was capable of being flooded with seawater via valves set into the pressure hull.



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

The *Kursk* had an armament capacity for 24 ship-to-ship cruise missiles (SN-19-GRANIT - NATO *Shipwreck*) armed with 760kg main charge conventional explosive, but nuclear capable for low-yield warheads. The missiles were housed in individual pressure sealed silos, pitched forward at 40^o arranged in two rows of twelve, each covered by six hatches on each side of the sail (conning tower). Torpedo munitions comprised 24 torpedoes held in open rack magazines, potentially including torpedoes of nuclear capability, firing from 2x650mm and 4x533mm torpedo tubes in the bow (N^o 1) compartment. The armaments could also include ASW Harpoon-type rockets and seabed mines also deployed from the forward torpedo tubes.

Kursk was the latest and most modern attack submarine of the Russian Federation Navy, being assigned to the Northern Fleet operating out of the Kola voyaging into the Barents Sea and beyond. She could make 28+ knots when running deep and 15 knots on the surface, being capable of full operations at 600m depth.

3 MAMMOET-SMIT RECOVERY PLANS

In mid May 2001, the Russian Federation and RUBIN, jointly contracted Mammoet-Smit (M-S) to recover and deliver the *Kursk* to a floating dock within the year deadline.[5]

The M-S salvage strategy included three distinct phases:

First, preparatory activities, including surveying, radiation monitoring of the submarine, removal of silt around the area of the intended hull cutting operation, and cutting of the hull just forward of the N^o 1 bulkhead to sever the most damaged part of the submarine.

Then, to provide for a stable lift, cutting 26 holes through the casing and pressure hull either side of the vertical centreline of the main hull for the subsequent insertion and clamping of the lifting fittings or 'grippers' to the pressure hull.

Correspondingly, the 22,000 tonne lift capacity barge, *Giant 4*, was modified with 26 guide tubes passing through the barge hull to accommodate the deck-mounted strand jack system for lifting the submarine, and with its underside modified to form an inverted cradle to which the submarine, once lifted, could be secured.

Second, the installation of each of the grippers into pressure hull and raising the *Kursk* with Mammoet's swell compensated strand jack system. The jacks would then hold the *Kursk* against the inverted cradle under the barge during transit to a floating dock at Rosljako Bay near Murmansk.

3 *The strand jack (inset) mounted within the cable reel platform with the swell compensator rams underneath*

Finally, to transfer the *Kursk* into the floating dock deploying two large, custom-built pontoons, one under each side of the barge, to lift it (about 20,000 tonnes combined) entirely out of the water for sufficient clearance to position the underslung *Kursk* over the cradles when entering the floating dock, then lowering the *Kursk* onto the cradles, followed by demobilization and withdrawal of all M-S equipment and personnel.

4 NUCLEAR & RADIOLOGICAL SAFETY

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), appointed by M-S and approved by the Russian Federation authorities.[6]

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 5-7Mev[7] 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.

The first role of the IAP was to ascertain what parts of a nuclear safety case were already in place and evaluate them, although it very soon became apparent that the RF authorities had prepared no structured case upon which to build.

5 SAFETY APPROACH OF THE RUSSIAN FEDERATION

The RF approach to safety was essentially deterministic with any probabilistic treatment limited to confirming that sequences outside the design basis (which was itself not comprehensively defined) were sufficiently unlikely (eg with an annual probability of less than 10^{-7}). There seems to have been no overall integration of the diverse range of technologies covering nuclear propulsion, weapons systems, life support systems and operational systems, to cover the full spectrum of potential interactions between them. Instead, the strategy seemed to consider deliberately each area in isolation with a definition for each area of a worst-case accident that the other areas must withstand.

The engineering of the *Kursk* was similarly compartmentalized. This was possibly to minimize the need for detailed interface coverage between the various RF design bureaus and production associations. The flaw in this approach was that there could never have been a full recognition of the wide range of potential challenges, failure modes and consequences (including interactions) arising from internal plant failures and external hazards.

6 IAP'S APPROACH AND STRATEGY

The IAP's overall strategy was framed to suit the RF approach by first establishing a datum condition of the *Kursk* taking into account the effects of the explosions and the degradation over a year of submersion. Once established, the stability and residual strength of the datum condition, including the degree of defence in depth that might remain available for the essential reactor safety functions, was framed in terms of limits and conditions for the M-S operations to ensure that the residual strength and stability criteria could not be exceeded, nor the defence in depth totally undermined, together with allowance for unwanted interactions. And, of course, throughout the salvage and recovery operations ensuring that there was an adequate radiological safety management regime in place to protect the M-S employees, its contractors, and the marine environment generally.

In light of this, the IAP set out to work with teams of RF specialists to check how each system had been and could be affected by events and thus establish the limits and conditions that had to be maintained during the M-S recovery operations. The actual and potential interactions of the many systems involved warranted a strong probabilistic evaluation but this was not favoured nor, indeed, practiced by the RF for its own assessment. Instead, the approach of RF analysts and engineers was, predominantly, underpinned by reliance upon passive safeguards (eg containment, dormancy, etc) for which probabilistic treatment is anyway not usually necessary.

However, this reliance required, first, an accurate and reliable assessment of each 'safeguard', particularly the extent to which it may have sustained damage as a result of the original explosions and, then, an account of the degradation that it may have suffered over the year or more that it was submerged in the Barents Sea. Of particular concern to the IAP was the possibility of the *rough-and-tumble* of M-S operations[8] triggering a further explosion (of a torpedo or missile), and the potential consequences to the reactor plant and its safeguards.

On one hand, all that the RF could offer was its assertion and confidence that the M-S salvage of the *Kursk* could be undertaken within the RF's sometimes rather qualitatively defined limits of each of the 'safeguards' but, on the other hand, its engineers and technicians were enthusiastically responsive to any demands placed upon them by the IAP, often responding in detail once trust had been established, and explaining their sometimes brilliantly simple solutions to problems, as they were identified.

In the light of this, the IAP had to conclude that it was not in a position to provide a traditional assessment or review but, instead, had to weigh these RF statements to assess whether, when put together, they provided a sufficiently coherent and persuasive safety demonstration to enabled each of the staged hold points of the salvage programme to be removed.[9] In doing this, the IAP had to rely largely on its own judgment and experience.

7 REACTOR DATUM CONDITIONS/ SAFEGUARDS

The IAP's strategy required a detailed assessment of the potential damage to the containment, fuel and nuclear shutdown/hold down components of the two nuclear reactor systems. These two prerequisites (robustness of containment and continuing nuclear inactivity) had to be satisfied for all stages of the salvage operations.

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.[10] 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.

To assess the condition of the reactor fuel cores, the capacity of the passive heat dissipation and emergency core cooling systems to protect the reactor cores was assessed.[11] 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.[12]

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.

Although both reactors seemed have shut down, 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 was 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.[13]

To confirm the state of the reactor the RF deployed gamma spectroscopy in the range 4 to 8 MeV (characteristic of reactor operation) in the lower regions outside the pressure hull and the thermal gradient in the flood hull space was profiled to detect any thermal input. Negative results suggested that, in all probability, that the reactors remained shutdown; there was effectively no contamination (eg nuclear fuel particulate) in the reactor shield tank, suggesting that the reactor primary circuit containment was complete; there was no evidence of contamination between the shield tank and the pressure hull, suggesting that the shield tank containment was complete; and the lack of any thermal gradient indicated that no significant heat was being generated in either of the reactor compartments.

On this basis, the IAP's criterion that at least two of the reactor containments be in place was satisfied.

8 Munitions Datum Conditions

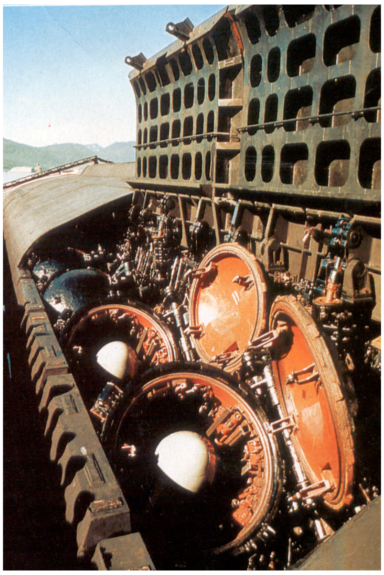
Torpedoes: At the time of sailing the *Kursk* was carrying 24 torpedoes, two with dummy warheads, the remainder with conventional explosives, and all stored within N^{o} 1 compartment. Analysis of the acoustic data from the cruiser *Pyotr Veliky* suggested that around seven torpedo rounds were destroyed as a series of explosions in rapid succession. The survey of the second debris field revealed a number of torpedo components but these, collectively, did not account for the remaining 12 or so armed rounds. These missing rounds could have been hidden within the hull, particularly in the mangled wreckage of what remained of the bow compartment and some could have been thrown into the wreckage of the second compartment.[14] Some or all of the rounds could have burnt or frazzled during the explosions, some might have fragmented, and others might remain intact and hidden under the submarine hull from her post-explosion descent from 30-35m above the sea bed.

Such was the uncertainty surrounding the presence, state and stability of these missing torpedo rounds that an explosion from this source had to be considered a credible fault condition at any time during the lift operations. That considered, however, factors in mitigation included the dispersion of the remaining torpedoes and fragments of torpedoes, made a sympathetic detonation less likely; that if it did occur, detonation would be unconfined and not directed through the hull towards the reactor compartment (compared to the original explosion that was initially confined by the pressure hull); and that the design basis capability of the reactor plant to withstand shock remained available (to an undeclared amount).

The IAP nominated a fault condition whereby the equivalent of two torpedo rounds (~450kg TNT in total) simultaneously detonated during the bow separation operation or the lifting operation. The IAP sought assurance, with explanations, from the RF of each reactor's capability to withstand such explosive loading. In addition, an analysis of the effect of the explosion gave the strength requirements of the hull plating of the attending barges and the length limitation for smaller vessels attending the barges, a requirement that these be larger that the sea surface bulk cavitation and gas bubble diameters that would put smaller surface vessels at risk of sinking. Also, the analysis provided the minimum lashing requirements for the heavy equipment operating on the barge decks, particularly the two 60t crawler cranes working on the *Giant 4* lifting barge, in account that these could topple into the sea and descend onto the *Kursk* in the reactor compartment area or onto the cruise missile silos.

Missiles: At the time of loss, the *Kursk* was armed with 23 SS-N-19 GRANIT cruise missiles with conventional explosives. These missiles were located in forward slanting silo tubes, 12 either side of the submarine, the first being just behind N^{o} 1 compartment and within 3m of the cut line that was to isolate the bow wreckage, and the last two missiles being some 30m ahead of the reactor compartment.

Unlike a torpedo round explosion, which was considered to be credible and tolerable, full detonation of a single 760kg missile warhead could not be tolerated at any stage of the lift, conveyance from the wreck site and transfer to the floating dock because this would have imperilled all of those personnel manning the salvage vessels and had the potential to result in a release of radioactivity to the marine environment and hence to the M-S personnel. Thus, it was absolutely essential to determine the most unstable condition for the missile systems and the main fill and ejection charges and if any of the five AFS latches[15] had been enabled by the foundering explosions and the subsequent M-S recovery operations.



4 Starboard Missile Bank Forward - Silo Hatches Open

This was determined by a series of trials in which fully assembled missiles were subject to a range of conditions simulating the impulse and vibration environments. Particular regard was given to the vibration spectra that was to be generated by the M-S cutting technique deployed to sever the bow section, since there was a possibility that a sympathetic vibration could not only result in the release of the cap of the first starboard side missile silo which had been damaged during the original explosion, but it could also override one of the acceleration/deceleration sensitive latches of the weapon firing system.

9 Potential Faults in the M-S Operations

Pressure Hull Lifting Sockets: Lifting of the *Kursk* to be secured to the underside of the *Giant 4* lifting barge required the cutting of 26 holes (each ~1m diameter) through the outer hull casing, the removal of any equipment and ship's services in the flood hull space, and cutting through the structure of the pressure hull, thereafter clearing to a depth within the pressure hull to allow for the insertion and fixing of the grippers.

5 Giant 4 with the Kursk slung underneath awaits entry into the floating dock at Rosljakovo – two sinkable pontoons were deployed to raise Giant 4 for the necessary clearance into the floating dock

The potential fault scenarios primarily related to cutting through the submarine ship's services occupying the cavity between the casing and pressure hull. Although engineering drawing details had been provided and location trials had been conducted on the sister boat *Orel* (K226), the as-built *Kursk* services installations were found to be markedly differ from the 'design' and/or from the actual installations on the *Orel*.

Difficulties for the saturation divers undertaking these tasks (surveying the locations and setting up the robotic, high pressure grit cutting equipment) included encountering pockets of explosive gases (three relatively small gas burns/explosions were experienced), and contamination by, particularly, hydraulic gels and asbestos products used in the acoustic tiling bonding system to the outer casing. Procedures had to be introduced for the divers to decontaminate themselves of oils and fibres before entering the saturation chambers on board the diving ship Mayo for shift breaks over each diver's spell of two to four weeks under a full saturation environment.

Lift, Sea, State and Other Factors: Limits on sea state had to be imposed during the lift and transit phases of the recovery operation.

First, lifting operations could not proceed at sea state swell (peak to peak) heights greater than 2.5m because of the limit ram stroke of the Mammoet swell compensation system acting on the strand jacks - this system maintained a uniform cable tension during the lift. The entire 110m lift was scheduled for at a minimum period of 10 hours so a fair weather window of at least this was necessary to ensure safety throughout the lift. If weather conditions deteriorated during the lift then the lift would have to be abandoned and the *Kursk* lowered back to the seabed.

Second, during the transit phase when the *Kursk* was held against the under hull saddles of the *Giant 4* and making way for port to dock with the floating dock, excessive sea state could result in slapping and pounding of the upper casing hull against the saddles and high forces being transmitted into barge frame. In these circumstances, either the *Giant 4* would have to make for sheltered waters or the *Kursk* would have to be lowered to the seabed until clemency resumed. For one particular spell of the open sea transit, over a period of 3 to 4 hours, the distance to the coast and the sea depth precluded both of these options.

Other factors that had to be accounted for included excessive suction binding the *Kursk* to the seabed. This was because the local seabed comprised silty clays for which M-S had calculated a suction or hold down force of between zero and 11,000 tonnes. To break suction, the plan was to apply a steady but disproportionately higher lift tension to the stern group of lifting cables allowing, over time, this to overcome the suction. This required demonstration that the damaged pressure hull could absorb the bending moment being applied, particularly at discontinuities in the hull form where the forward bulkheads had been blasted through.

In the event, there was no suction, the first movement of the *Kursk* being lateral as the lifting forces allowed her to slip sideways impelled by the tidal stream.

10 Barge - Diving Activities - Radiation Risk

As well as the pre-prepared arrangements for response to a serious mishap to the *Kursk* during recovery (ie torpedo explosion, falling equipment, etc), the barge and support vessel crews had to work under a strict radiological management regime. This regime was administered by a radiation adviser overseeing shifts of health physics monitors surveying and managing contamination, dose receipt and recording, sheltering and other dose mitigation countermeasures.

The IAP cooperated with the RF over analysis of a hypothetical radioactive release from the reactor compartment at the stage when the lifting *Kursk* approached close to the underside of the *Giant 4* barge - this was assumed to be the point at which the barge crew were most at risk of radiation exposure. The conditions assumed for this analysis included expansion of the air/gas bubble drives a discharge of 150m^3 of water from the reactor compartment via the 6mm diameter instrumentation hole (a known open route into the reactor compartment), taking some 36 hours; that the discharged water contains fission and activation products released from fuel corroded for 14 months by seawater, as determined by a representative test, amounting to some 3.10^{12} Bq which, allowing for dilution in the sea, the total effective dose to a barge crewmember would be less than 1 μSv/hour;[16] and if the same amount of fission and activation products were not discharged by the bubble expansion, but remained at the top of the reactor compartment.[17]

To mitigate these risks and those from uncontrolled criticality, discharge of radioactivity or direct radiation resulting in unacceptable levels of exposure, emergency arrangements to protect personnel, including evacuation by the RF Northern Fleet vessels and aircraft, were agreed with the RF Northern Fleet. These actions, triggered by an emergency reference level (ERL) protocol, applied to all personnel present on board M-S vessels.

11 A Successful Recovery

Mammoet-Smit had contracted to raise the *Kursk* in May 2001 and in just six short months, on 23 October, the *Kursk* was lowered from *Giant 4* onto the cradles of the floating dry dock at Rosljakovo - a quite remarkable and World-first achievement.

The recovery of the *Kursk* was a success that derived from a tragedy. The successful and almost trouble-free recovery of the sunken nuclear powered submarine *Kursk* was completed by a group of commercial organizations and not by its military operator. This was because the Russian Federation itself did not possess the resources and expertise to do this and, moreover, it had never planned to do so.

In planning and carrying through the entire recovery operation, the Dutch consortium Mammoet-Smit engaged quite remarkable levels of ingenuity of approach to this unique problem. Their strategy of building on their experience of their equipment and of salvage operations in general proved to be sound and ultimately successful.

Because there was insufficient time to generate and evaluate a conventional post-incident nuclear safety case, members of the Independent Assessment Panel had to arrive at judgments drawn from their experience in nuclear safety, weaponry and engineering. Moreover, in doing so they had to cross the divide between East and West, accounting not just for the different approaches to nuclear and engineering technologies, but also how the safety reasoning of the original designs could be integrated into the salvage scheme. 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.

6 The Wreck of the Kursk Rising in the Well of the Floating Dock at Rosljako

ACKNOWLEDGMENTS

Acknowledgement to present this paper is given to the salvers Smit International and Mammoet, the cooperation of personnel of the Russian Federation Northern Fleet and Rubin was essential and, particularly, the efforts and judgements of the other IAP team members, particularly Peter Davidson and Cdr Huw Jones, has been greatly appreciated.

This paper is dedicated to the suffering and memory of all those lost on board the *Kursk*.

REFERENCES & NOTES

1 The prototype torpedoes were of the so-called super cavitating type or *Shkval*. This type of deep diving, high-speed torpedo initiate cavitation at its tip and then envelops itself in a gas envelope generated at its bow with, essentially, the gas being replenished at the same rate as its progress through the water. The gas generating agent was probably hydrogen peroxide and, probably, the second prototype torpedo that initiated the sinking was an anti-submarine weapon (ASW) being deep diving and powered by a lithium-fluoride internal propulsion system.

2 A most telling clue to the dying moments of the *Kursk* was the final position of a 4 by 2m section of forward section casing (the outer flood hull) on the seabed to starboard of the stern, having travelled the 154m length of the hull to its final resting place. This casing plate must have 'swum' from the point of the second explosion through the water down to the seabed; thereafter she drifted down and settled on the seabed at a depth of 110m - analysis of this gives the *Kursk* at 30-35m above the seabed at the instance of the plate detachment.

3 What is known is that a number of the crew members subsequently recovered from the N^{o} 9 compartment had sustained quite severe body burns and the water-filled compartment was strewn with dust and ash - the surviving crew had closed the compartment hatch thereby isolating themselves in this final refuge. The source of the fire has not been established, although a survivor trying to recharge an oxygen regenerator plate in the compartment could have sparked it.

4 RUBIN - the Russian State Marine Engineering Design Bureau in St Petersburg.

5 In January 2001, the Russian Federation Navy and the *Kursk* designers, RUBIN, jointly invited a consortium of companies from the West to tender for the entire recovery of the wreck (with the exception of the totally devastated forward compartment) and, specifically to complete the salvage within the year. The first consortium formed, Smit-Heerema-Halliburton, withdrew because Halliburton believed the end of the year recovery deadline5 could not be safely achieved.

6 John Large of Large & Associates was appointed to establish and head up the IAP to determine and set the radiological and weapons safety parameters during the salvage. This team included NNC safety engineer and a submariner Commander seconded from the Royal Navy, and the IAP had direct access to other consultants in the radiological protection, explosive, weapons and salvage fields – total IAP team strength was between 4 to 8 depending on the stage of the project. John Large also represented and negotiated with the insurers on behalf of Mammoet-Smit for personnel and equipment cover that was ticketed across a number of underwriters at Lloyds, the United States and Russia.

7 The energy level of any neutron activity distinct from radioactive decay of the fuel.

8 *Rough-and-Tumble* inasmuch that the submarine was never designed with salvage in mind.

9 Nuclear Coordinating Group, *1st, 2nd and 3rd Stage Reports of the Nuclear Coordinating Group*, Report Ref No R3065-1B/C/D, throughout 2001

10 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.

11 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.

12 Thermal Rollover is the stage in time when the continuing decay heat of the reactor fuel core can be dissipated by entirely passive means,

13 It is now known from inspection of the No 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 amidships sections may have been incapacitated before the second explosion.

14 Which was subsequently shown to be the case when the internals of the wreck were dried out and inspected at Rosljakovo a number of torpedo remnants were found

15 AFS - Arming and Firing System of five independent degrees of protection or latches. Relevant features of the SS-N-19 missiles included the pre-tanked propellant kerosene fuel, the small (7 Kg TNT equivalent) powder charge for ejection from the silo to the turbojet firing altitude above the sea surface; and the missile could be launched only after the silo cap had been opened, which required hydraulic actuation that was no longer available.

16 A becquerel (Bq) is 1 disintegration or the rate of radioactive decay per second which replaced the traditional unit of the Curie (1 Curie = 3.7 1010 Bq) and a µSv/hour is a unit of radiation dose in terms of the tissue absorbed dose equivalent.

17 Although the 2m of seawater that will fill the space between the pressure hull and the casing would reduce the dose rate to a barge crew member to a few µSv/hour, during the final lift-out operation to place the *Kursk* in the floating dock this shielding would be lost.