# RECOVERING THE KURSK
## NUCLEAR HAZARDS

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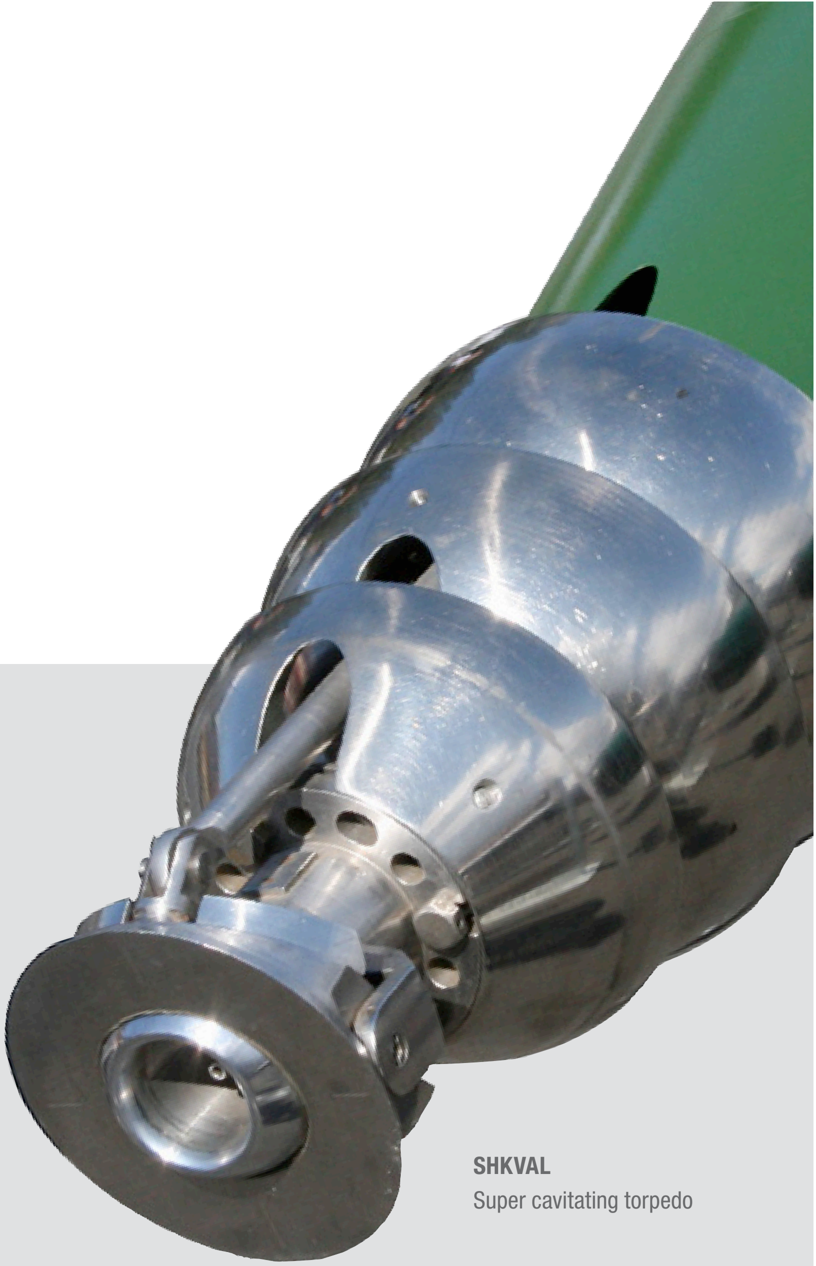
### ABSTRACT

The Russian Federation nuclear powered submarine Kursk sank in August 2000 with the loss of all 118 lives on board. In May 2001 the Russian Federation entered into a contract with the Dutch consortium Mammoet-Smit for the recovery of the Kursk on the condition that it had to be completed within that year. The consortium prepared for this World-first salvage of a nuclear powered and conventionally armed submarine that was very substantially damaged lying at 110m in the icy waters of the Barents Sea. Working at sometimes breathtaking pace, Mammoet-Smit prepared, lifted and transported the wreckage of the Kursk delivering her to a floating dock at Rosljakovo, about 200km south of the foundering site, in just over six months from the contract date. 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.



**SHKVAL**
Super cavitating torpedo

### 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 with a much more significant event, equivalent to about 3 to 3.5 Richter scale. None of those at the recording stations in Norway, Finland, Scotland, Canada, Alaska and elsewhere realized that this second explosion marked the death knell of an advanced nuclear powered submarine in the Barents Sea.

During the morning of 14 August the rescue centre at Bodø in northern Norway received rumor of an accident on board a then unknown Russian submarine somewhere north of Murmansk. This was the first inkling in the West of a very serious situation, the details of which were to unfurl over the following hours when it became apparent, and was subsequently confirmed by the Russian Federation (RF) Northern Fleet headquarters in Severomorsk, that a submarine had foundered. At about 16.30 that day the Norwegian Moscow embassy was notified by the Russian Federation authorities that there had been an accident to a submarine - that boat was the OSCAR II (RF PLARK class), cruise missile armed and nuclear powered submarine Kursk. It is now known that Kursk left her home base in the Uraguba bay on 10 August, with a total complement of 118 men aboard, two of whom were torpedo designers. She was heading out to participate in sea exercises east of the Rybatschi Peninsula about 200km north of Murmansk. Kursk was assigned to an area of the sea cleared as a torpedo range under the supervision of the battle group command cruiser Pyotr Veliky, where she was to test fire two unarmed, prototype torpedoes from the forward port 650mm diameter tube that had been specially adapted for the trials.

It was the second firing that went so wrong. Speculation is, and it can only be speculation because the damage to the forward compartments was so great, that the gas generating system of the second prototype torpedo reacted with its main propellant, burning and exploding with an equivalent power to that of 100 to 200kg of TNT.

The prototype torpedoes were of the super cavitating type. This type of deep diving, high-speed torpedo 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 hydrogen peroxide and, probably, the second prototype torpedo that initiated the sinking was an antisubmarine weapon (ASW) being deep diving and powered by a lithium-fluoride internal propulsion system.

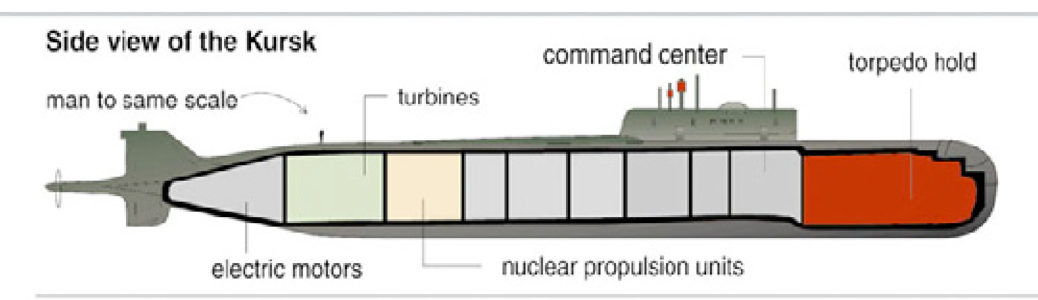
The damage sustained from this first explosion, which alone the Kursk could have withstood, can be pieced together from the first

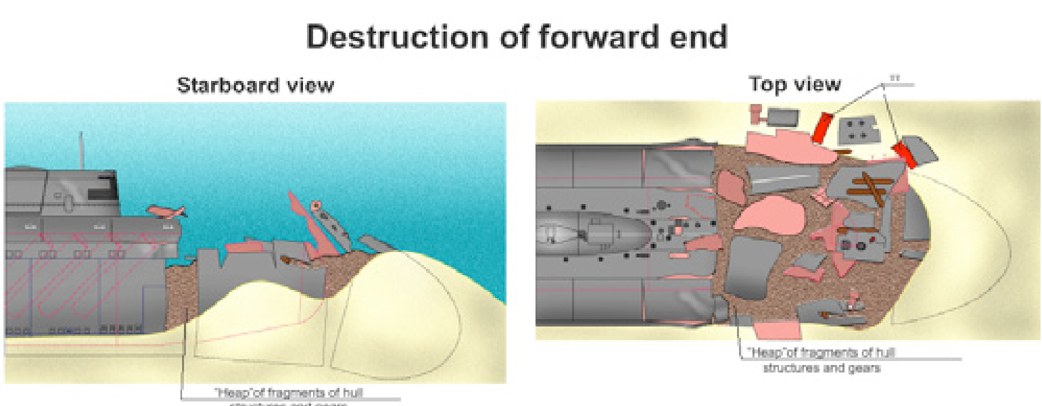
of the two seabed debris fields. The debris included plates from the outer (flood) casing and, significantly, components of the port hydroplane hydraulic mechanism and the forward ballast and trim tanks. At the time of the first explosion, Kursk was positioned for torpedo firing, at periscope depth in the sub surface layer where to assist with depth control and, to avoid porpoising, she would have been trimmed to negative buoyancy, maintaining her sea depth by driving hydrodynamically against her forward planes at up to about 6 knots. The centre of the first explosion seems to have been ahead of the foremost section of the pressure hull suggesting that the torpedo was loaded into the firing tube so, if the inner torpedo hatch was and remained closed, the damage to the bow compartment would have been minimal. However, the sonar trace taken by the nearby RF cruiser Pyotr Veliky shows continuing activity following the initial explosion spike, which could be interpreted as severe burning and jetting of the torpedo propellant system into the weapon stowage compartment (Compartment No 1).

It is clear from the 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 rack. 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 No 2 and 3 were ripped through, with No 4 buckling and subsequently collapsing under the hydrostatic flood loading. No 5, the forward reactor compartment bulkhead, and the remaining bulkheads through to the ninth compartment remained intact.

The second seabed debris field (at 69°36,99N, 37°34,50E) provides clues to the remaining split 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, with the stem buffered against a sediment bank at an angle of 2o bow down and with the hull pitched to the port side by 1.5o. 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.

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 traveled 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.




When operating submerged, twenty-three crewmembers of the Kursk would be positioned aft of the reactor compartment. These crewmembers attended to the steam raising and electricity generating plant generally dispersed about compartments No 7, 8 and 9. At all times whilst the reactors are operational there are 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 stern most No 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. What is known is that a number of the crew members subsequently recovered from the No 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.

## CONDITION OF THE KURSK

Two expeditions to the Kursk site were undertaken jointly between the Russian Federation Navy and the Norwegian Radiation Protection Authority. The first of these expeditions was in August, immediately following the sinking, and the second in October 2000 during which twelve of the twenty-three casualties in the stern compartment were recovered.

These two expeditions, particularly the latter, established the radiological regime in and around the Kursk. Air, sediment and seawater samples were taken and analyzed, and water samples within the submarine, from compartments No 3, 4 and 7, were collected and sealed in cans for subsequent gamma spectrometry. Similarly, the remote operated vehicles (ROV) and the diving personnel were rigged to monitor dose rates at various locations about the casing of the submarine (Amundsen Ingar, 2001). The preliminary results from these two expeditions did not indicate the presence of radionuclides that may have been released from the submarine reactors or, potentially, from any nuclear weapons carried on board.

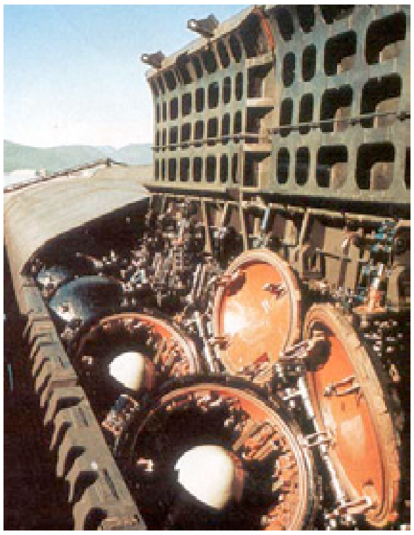
The presence of nuclear weapons on board the Kursk at time of the sinking was of particular concern. In 1989, another Russian Northern Fleet submarine, Komsomolets, which was lost in the Barents Sea at about 1,700m was leaking from both its single reactor and from two nuclear tipped torpedoes loaded in the bow tubes at the time of the foundering. For the Kursk, the Russian Federation Northern Fleet confirmed that at the time of the foundering no nuclear weapons were on board. At this stage, no attempt was made to sample within the sealed reactor compartment, nor was any significant monitoring undertaken of any thermal gradients in the flood hull in the vicinity of the reactor compartment.

## RF NORTHERN FLEET SUBMARINE KURSK K141-TYPE CONSTRUCTION & WEAPONRY

The Kursk is a SSGN (cruise missile armed, nuclear powered) submarine, designated by NATO as an OSCAR II class, commissioned from Sevmash shipyard, Severodvinsk in 1995. Designed by RUBIN, The Russian State Marine Engineering Design Bureau in St Petersburg, the Kursk was 154 m long and 18m beam over the casing or flood hull, with a 11m diameter internal pressure hull, and of submerged displacement 24,000 tons (surface 11,500t). The submarine structure was of double hull construction with nine interconnected watertight compartments, all being normally accessible except for the reactor compartment No 6 which is passed through via a radiation shield corridor. The outer hull casing comprised 8mm steel plates supported off the pressure hull by webs and struts. The inner pressure hull was an externally ribbed cylindrical form fabricated from 50mm thick high yield steel plate. The void between the casing and pressure hull varied from 1 to 4m within which was located ship's equipment, sonar and the cruise missile silos. The entire outer hull and conning tower was clad with 40 to 80mm thick synthetic rubber tiles serving to both attenuate machinery noise and reduce the reflective echo from incoming sonar signals.

The power plant comprised two, integrated type pressurized water reactors (OK 650b) each of ~200MW thermal output located in the sealed reactor compartment No 6. The reactors were arranged in line, in foreaft fashion, each in its own pressure sealed sub-compartment. Each reactor pressure vessel was housed within a sealed 25m3 capacity water shield tank that was resiliently mounted to absorb shock from the operational submarine when in battle situations. The steam generators were clustered immediately around the RPV with the main circulating pumps above with just over 1m head to assist in natural circulation in the event of pump failure. Fuel comprised annular elements of uranium-aluminum cermet or dispersion type fuel clad in zircaloy, zoned between 20 to 45% (core equivalent 30%) enriched U-235 of 48 assemblies, totaling about 200kg U-235 per reactor core. Gadolinium burnable poison was integrated within the fuel and control was via boron/hafnium absorbers. Nuclear plant emergency shut down was via control rod injection by 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.

The Kursk submarine 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 40º 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 (No 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 Northern Kola voyaging into the Barents Sea and beyond. With 49,000 shp through the two 7-blade propellers, she could make 28+ knots when running deep and 15 knots on the surface, being capable of full operations at 600m depth.

## MAMMOET-SMIT RECOVERY PLANS

From about January 2001, the Russian Federation Navy and the Kursk designers, RUBIN, jointly asked 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. This was in order to comply with the promise of President Putin to the relatives of the crew. The first consortium formed, Smit-Heerema-Halliburton, withdrew because Halliburton believed the end of the year recovery deadline could not be safely achieved. In mid May 2001, the Russian Federation and RUBIN, jointly contracted Mammoet-Smit (M-S) to recover the Kursk within the year deadline. Although the salvage plan was to be produced by M-S the Russian Federation Navy was to provide a floating dock where the submarine was to be finally berthed. The M-S strategy was to effect the recovery in three phases, these being:

Phase 1: 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 No 1 bulkhead to sever the most damaged part of the submarine. Then, to give a stable and predictable lift and to mount the rigs, to cut 26 holes through the casing and pressure hull either side of the vertical centerline of the main hull for the subsequent insertion and clamping of the lifting fittings. The positions of these holes were selected by the RF to minimize hull bending during the lift and none were positioned in the reactor compartment. This also included the modification of the Giant 4 barge by preparing 26 tubes through the barge hull so that the strand jack system, used to lift the submarine, could be fitted.

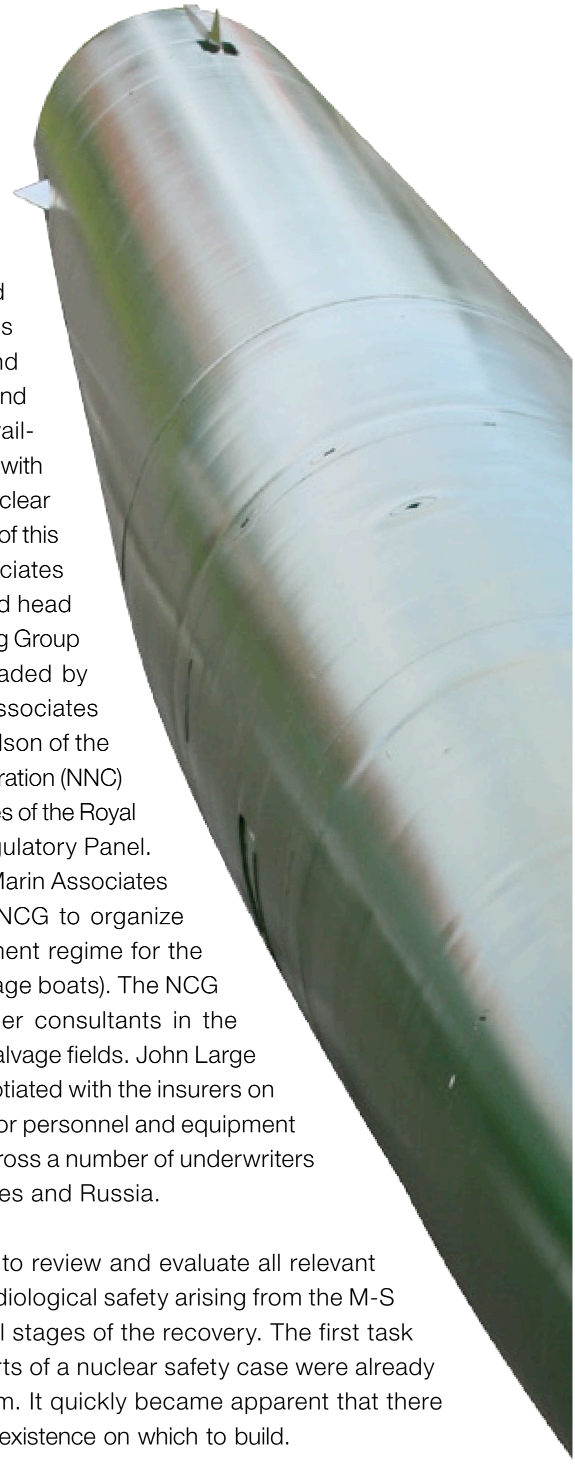
Phase 2: Installation of the 26 lifting fittings, the lowering through the pre-inserted tubes in the barge hull and connecting of 26 sets of lifting cables, each comprising 54 strands of seven twisted wires each 6mm diameter and the raising of the Kursk using Mammoet's strand jack system. The cables would then hold the Kursk against a pre-fitted inverted cradle under the barge during transit to a floating dock near Murmansk.

Phase 3: The fitting of two large pontoons, one under each side of the barge, to lift it entirely out of the water to give sufficient clearance of the underslung Kursk over the cradles when entering the floating dock, the lowering of the Kursk onto the cradles, followed by demobilization and withdrawal of all M-S equipment and personnel.

Severing the remains of No 1 compartment deployed a heavy cable carrying thick-walled tubular sections coated with a very coarse (~25mm) abrasive. Reciprocating motion was to be provided by two 30 tonne hydraulic rams attached by suction anchors to the seabed.

The strand jack system relies on two collets on each strand, the upper collets being hydraulically lifted/lowered as a cable group. Additional hydraulics activate the collets under computer control, the timing of the collet activation determining whether the strands are raised or lowered. Each cable lifting system was to be supported by four pneumatic cylinders with 4m strokes and with a large nitrogen gas reservoir, the pressure being matched to the cable load so that large movements due to swell (within the cylinder stroke limits) would have minimal effect on the cable loads.

## NUCLEAR & RADIOLOGICAL SAFETY



In early June, Large & Associates were engaged by M-S to complete a preliminary assessment of the nuclear hazard and held a number of meetings with RUBIN to discuss and determine the information and data likely to be made available from the RF authorities with respect to radiation and nuclear safety issues. On the basis of this information, Large & Associates was instructed to form and head up the Nuclear Coordinating Group (NCG). The NCG was headed by John Large of Large & Associates with members Peter Davidson of the UK National Nuclear Corporation (NNC) and Commander Huw Jones of the Royal Navy's Naval Nuclear Regulatory Panel. Later Alan Martin of Alan Marin Associates was seconded onto the NCG to organize the radiological management regime for the recovery spread (the salvage boats). The NCG had direct access to other consultants in the explosive, weapons and salvage fields. 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.

The role of the NCG was to review and evaluate all relevant aspects of nuclear and radiological safety arising from the M-S recovery operations for all stages of the recovery. The first task was to ascertain what parts of a nuclear safety case were already in place and evaluate them. It quickly became apparent that there was no structured case in existence on which to build.

## THE RF APPROACH

The RF approach to safety was essentially deterministic. Any probabilistic treatment was limited to confirming that sequences outside the design basis (which was itself not comprehensively defined) were sufficiently unlikely (e.g. 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 design bureaus. 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.

## THE NCG STRATEGY

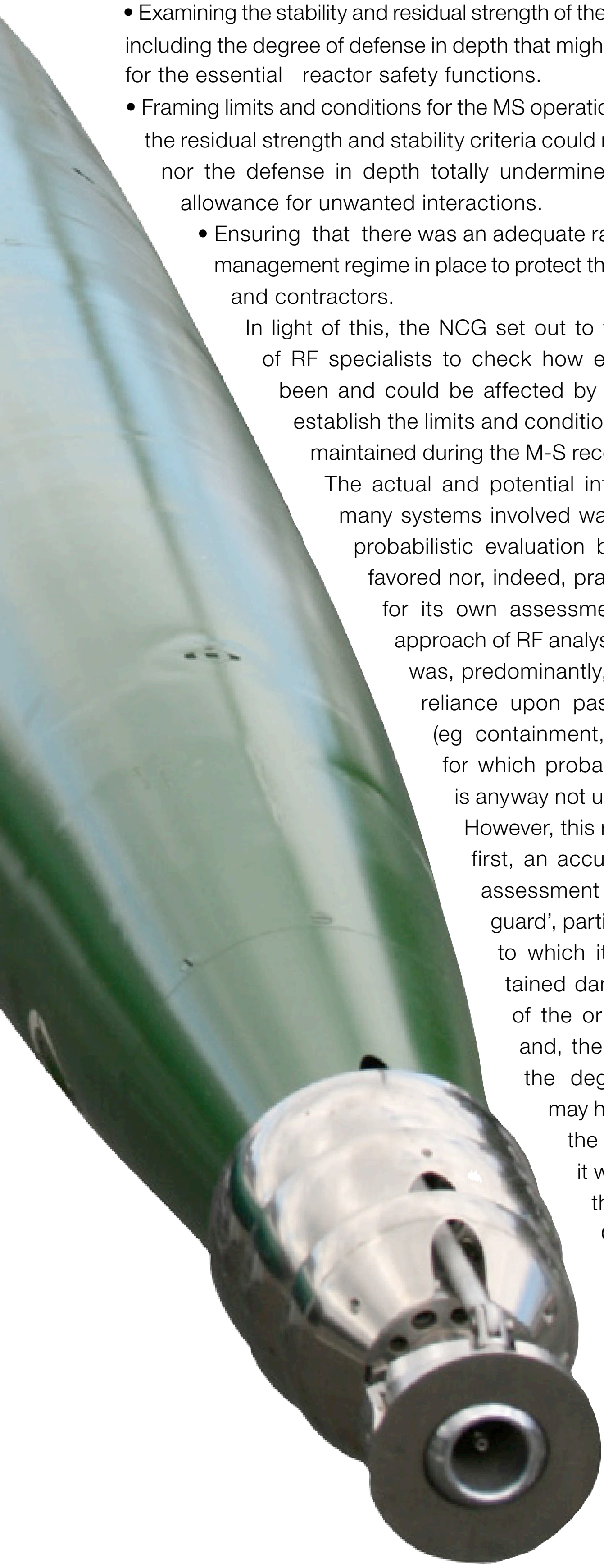
The NCG's overall strategy was framed to suit the RF approach by:

• Establishing the datum condition of the Kursk taking into account the effects of the explosions and the degradation over a year of submersion.

• Examining the stability and residual strength of the datum condition, including the degree of defense in depth that might remain available for the essential reactor safety functions.

• Framing limits and conditions for the MS operations to ensure that the residual strength and stability criteria could not be exceeded, nor the defense in depth totally undermined, together with allowance for unwanted interactions.

• Ensuring that there was an adequate radiological safety management regime in place to protect the M-S employees and contractors.



In light of this, the NCG 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 favored 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 NCG was the possibility of the M-S operations triggering a further explosion (of a torpedo or missile), and the potential consequences to the reactor plant and 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 NCG, 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 NCG 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. In doing this, the NCG had to rely largely on its own judgment and experience.

## ESTABLISHING DATUM CONDITION OF THE REACTOR PLANT AND SAFEGUARDS

The NCG'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.

The determinant of a safe and complete shutdown was, primarily, the ability of each reactor's fuel and shut down systems to function adequately during or immediately following the high levels of impulse loading from the torpedo explosions. Each reactor is supported in a resilient cradle providing shock absorption to cater for an impulse well in excess of 50g, defined by military operations of the boat. To determine the actual loading in the immediate aftermath of the explosions, forensic examination was undertaken on two of the casualties recovered from the stern section, these being identified as the reactor control room operators. These casualties had sustained skeletal damage indicative of body shock loading of just over 50g. This provided a degree of reassurance that the reactor resilient mounts, being below or about the design limit, had not been damaged and that the reactors could have closed down automatically as intended after power supplies had been lost.

Other factors relating to the condition of the reactor systems included:

I.The shock level (~50g) would have also temporarily disoriented the reactor control personnel who would not have been expected to recover for several minutes by which time most, if not all, of the power required for operator intervention would have been lost;

II.The shock would have caused opening of electrical circuit breakers leading to loss of power, eg to the main coolant pumps;

III. Automatic reactor shutdown sequences would have been initiated probably by the above power loss - this sequence causes the insertion under gravity, with spring and pneumatic assistance, of two diverse means of neutron absorption which then lock into place, and the initiation of decay heat removal which makes use of the large thermal capacity of the water in the shield tank - this sequence cannot easily be interrupted by the operator and it was unlikely that its essentially passive role was impeded by the shock loading;

IV. The reactor shutdown and decay heat removal equipment had a design basis for an inclination of the submarine in excess of 45º for

forced cooling during pump spin down, and thereafter a lesser angle of inclination for heat dissipation by natural circulation - the depth of water (108m) in conjunction with the submarine's length (155m) precluded a larger inclination - in view of the perceived accident sequence it is probable that the maximum trim angle was much less than 45º, although this may have been exceeded for a few seconds or more when the hull responded to the expansion of the explosive gas products; and

V. the design provides four barriers to the escape of fission products (or particulates) from the nuclear fuel. These comprise the fuel assembly cladding, the reactor primary circuits, and the reactor shield boundaries.

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:

I. The reactors remained shutdown;

II. There was effectively no contamination (eg fuel particulate) in the shield tank, suggesting that the reactor primary circuit containment is complete;

III. There is no contamination between the shield tank and the pressure hull, suggesting that the shield tank containment is complete; and

IV. The lack of any thermal gradient indicated that no significant heat was being generated in either of the reactor compartments.

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

## ESTABLISHING DATUM CONDITIONS FOR THE MUNITIONS

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 No 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 15 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 (which was subsequently shown to be the case when the internals of the wreck was dried out and inspected at Rosljakovo). Some or all of the rounds could have burnt during the explosions, some might have fragmented, and others might remain intact and hidden under the submarine hull.

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. Factors in mitigation were:

I. the dispersion of the remaining torpedoes and fragments of torpedoes, made a sympathetic detonation less likely;

II. 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);

III. the design basis capability of the reactor plant to withstand shock remained available (to an undeclared amount); and

IV. any fragment revealed during silt clearance etc, be removed by the RF, using remotely operated equipment to at least 70m from the submarine - torpedoes and fragments within the cut zone would also be removed.

V. the silt clearing equipment was unlikely to cause detonation of a torpedo or explosive fragment.

The NCG 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 NCG sought assurance, with explanations, from the RF of each reactor's capability to withstand such an explosion. 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 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 No 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.
Relevant features of the SS-N-19 missiles are:

I. the propellant fuel is kerosene, with a small (7 Kg TNT equivalent) powder charge for ejection from the silo to the turbojet firing altitude above the sea surface.

II. the launching 'trigger' or arming and firing system (AFS) comprised five independent degrees of protection or latches;

III. each missile was held within shock mountings within the silo, which itself had the same material characteristics and strength as the submarine pressure hull; and

IV. the missile could be launched only after the silo cap had been opened, which required hydraulic actuation that was no longer available.

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 imperiled 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 had been enabled by the foundering explosions and the subsequent MS recovery operations.

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.

## ESTABLISHING THE POTENTIAL FAULT CONDITIONS DURING 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 lifting clamps.

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 fibers 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 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. The local seabed at the Kursk site 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 reserve, if the stern lift failed to break suction, a line tethered to two tugs was to be passed under the stern of the Kursk with the tugs operating in a seesaw fashion to work the hawser towards the stem. The risks associated with this method included detonation of any torpedo munitions trapped under the hull or, in the event of a hawser failure, whip lashing against the exposed cruise missile silo on the forward starboard side.

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.

## BARGE AND DIVING SUPPORT VESSEL 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 NCG 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 were:

- expansion of the air/gas bubble drives a discharge of 150m3 of water from the reactor compartment via the 6mm diameter instrumentation hole (a known open route into the reactor compartment), taking 36 hours.
- 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 3x1012 Bq (Becquerel). Allowing for dilution in the sea, the total effective dose to a barge crewmember would be less than 1 μSv (at less than 0.1 μSievert/hour). Further development of this model analysis concluded that:
- a larger leak path would not significantly affect the above conclusion.
- 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, 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.

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.

## OVERVIEW

In completing its task, the Nuclear Coordinating Group adopted the following principles to ensure that the preparatory and recovery operations would not present an unacceptable nuclear or radiation risk to those involved with the recovery and, generally, to the marine environment (NCG 2001):

- Limits and Conditions: A clear set of limits and conditions had to be established for all of the operations to ensure that credible hazards would not challenge the capability of the structures, systems and components involved, both on the Kursk and or the Giant 4.
- Degradation and Recovery Operations: The limits and conditions safeguarding the structures, systems and its components would have to account for damage sustained during the sinking, the degradation over the year on the sea bed, and for forces and circumstances introduced by the Mammoet-Smit recovery operations.
- Defense in Depth: There should be a number of separate safeguards in place at all times against all of the significant hazards.
- Tried & Tested Technology: Since the deployment of novel procedures and processes introduces additional risk, preferably tried and tested technology should applied.
- ALARP: the risk should be reduced to As Low As is Reasonably Practical.
- Radiological Management Regime: Radiation doses to those personnel involved in the recovery operation should be controlled below the limits for Class B radiation workers (as defined for the UK).
- In Contingency: Contingency plans should exist in the unlikely event of a significant radiological release, particularly for mitigating the impact upon the marine environment.

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.

## A SUCCESSFUL RECOVERY

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 postincident nuclear safety case, members of the Nuclear Coordinating Group 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. This demanding and unique approach was shown to be sound because there was no radiological release or significant radiation hazard to any of the M-S personnel or contactors during any part of the recovery operations.

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