

KURSK SUBMARINE SINKING

AN ASSESSMENT OF POTENTIAL NUCLEAR HAZARDS

THE KURSK FOUNDATION
Фонд Курск

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Preface

Following an offer by the Netherlands Government to assist the Russian Government with the neutralisation of any danger emanating from the sunken nuclear submarine 'Kursk', the Kursk Foundation was established. Its aim is to provide assistance to the Russian Authorities responsible for the 'Kursk project'.

In the past six months, the Foundation created an international information basis regarding the 'Kursk', funded the initial feasibility to salvage the Kursk, and called on the international community to provide support to the 'Kursk' project.

Following the decision by the Government of the Russian Federation to lift the 'Kursk' in September 2001 with the assistance of a Mammoet-Smit International Joint Venture, the Kursk Foundation was requested by the Russian Authorities to support their lifting plan. The Board of the Foundation subsequently decided to request full details of the Mammoet-Smit lifting plan – which are publicised on 27th July 2001, - and assistance by the Russian Authorities and the industries involved for an independent safety evaluation by Dr. Ir. Carel Prins, Board Member of the Kursk Foundation, nuclear expert and former Technical Director of the Dutch submarine construction company. Dr. Prins was supported in his work by independent experts from navies and naval industries of different nationalities. His report primarily focuses on the nuclear hazard of the salvage plan.

The Board of the Kursk Foundation, in its meeting of Thursday, 26th July 2001, discussed the report by Dr. Prins on the basis of three points of departure:

- safety for personnel
- safety for the environment
- a minimum of experimental techniques during the lifting process.

The Board subsequently decided to fully approve the Prins report and its conclusions. With the publication of the complete text of this document, the Foundation hopes to have contributed to a necessary and responsible international debate of the lifting of the Kursk. With this, it considers its primary tasks as completed.

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1 INTRODUCTION

From the time the Kursk Foundation was established the nuclear hazard of the submarine Kursk has been its primary concern. The nuclear hazard comes only from the two reactors onboard the submarine. There is a clear declaration by the Russian authorities that there are no nuclear weapons onboard.

In view of the envisaged lifting operation the Kursk Foundation wanted to have an understanding of the state of the reactors and make clear in its own mind that they were shut down and safe for the envisaged lifting, transportation and landing of the vessel. The Paper is the Foundation's expression of its current understanding.

In consideration of its independent position the Kursk Foundation adopted a broad view of all the possible scenario's and circumstances and then took them through the analysis. Furthermore the Foundation wanted primarily to use open information from Russian and non-Russian sources to arrive at its conclusions. It expresses its gratitude to official Russian and industrial sources for additional information received in the form of consultations (St. Petersburg/London), written comments and documents.

In parallel and separately from this study the industrial consortium engaged in the lifting of the submarine made its own evaluation and collected its own data, using a specialist consultant with longstanding expertise in the nuclear technology involved. (Ref. 7)

As a matter of course, the Russian authorities have made their own investigations and analysis to get a clear understanding of the nuclear hazard. They have stated that the nuclear reactors were fully shut down.

This Kursk Foundation study examines and postulates the possible behaviour and condition of the submarine between normal operation and becoming inert on the seabed. Layout or operational information on the class has partly been made available by the Russian authorities. To avoid ambiguities a baseline view is established of the layout and crewing of the vessel.

The transient behaviour of the submarine at the time of the second explosion and the key subsystems having relevance to the behaviour and present state of the nuclear reactors are examined and discussed. Finally, the interactions of the potential states of the various subsystems and consequent potential hazards are highlighted.

Throughout, the basic assumptions are that the crew was well trained and efficient and that the vessel was well constructed and maintained.

The firm conclusions of the Kursk Foundation are based primarily on its own analysis and on information received from the Russian authorities - basically the results of radiation monitoring - which has been verified by other sources.

This paper focuses on the state of the nuclear reactors. Obviously the risks of the lifting operation in terms of its effect on the reactors demands close scrutiny. The industrial consortium is responsible for the planning and implementation of the lifting operation and for an assessment of remaining munitions hazards. The Kursk Foundation has taken notice of their plan and agrees that, provided that the checks proposed by the consortium's specialist are adopted and implemented, the necessary precautions are in place to assure the safe condition of the reactors throughout its execution.

2 CONCLUSIONS

The Kursk Foundation has deliberately sought and analysed information from a variety of open sources and, where Russian information has been provided, has so far as was appropriate looked for independent verification. Until this Paper was on the point of publication, such Russian information was essentially limited to verbal consultations, documentation and site radiological measurements, which have been independently verified. It follows that the conclusions reached are based more on engineering judgement rather than mathematical analysis at this time.

Nevertheless, it is considered that the conclusions given are justified and robust.

The principal conclusion, that the reactors are shut down and safe, has independently been confirmed by the consortium consultants, and has also been stated by the Russian authorities.

The sinking and its aftermath:

There is firm evidence that:

- The vessel suffered two internal explosions in its forwardmost compartment, the first of 0.02-0.1 tonnes TNT equivalent and the second of about 5 tonnes TNT equivalent.
- Both occurred with the vessel submerged, the boat being at periscope depth initially. (Russian sources put the submarine at 30 m depth before the incident and at about 100 m as the second explosion occurred)
- The first explosion started, according to Russian sources, flooding of the forward compartment and killed the crew present quickly.
- The second explosion almost instantaneously wrecked and flooded the forward two compartments and killed everyone in them.
- Compartments from the fourth compartment, including the Reactor Compartment, aft did not flood quickly and the crew in them survived for several hours.

There is circumstantial and persuasive evidence that:

- the damage created by the second explosion was significantly diminished between the explosion site and the forward Reactor Compartment bulkhead and more so aft of that compartment
- in the view of western observers the crew may have taken recovery action after the first explosion (which would imply that the vessel was not critically disabled at that time through damage or death) to bring the vessel to the surface.
- dependent on the actual submarine's depth and whether the crew did indeed take recovery action, the vessel transiently may have assumed a sudden and large bow-down trim angle after the second explosion.

Nuclear Issues

The reactor and its systems were unquestionably subjected to heavy shock loads. The design limits are not in the public domain. The reactors in their shield tanks are resiliently mounted to the hull construction. Whether the shock loads were within these limits has to be judged on the available evidence of the temporary survivors. It is deemed to be within the limits. Russian sources state that the shock loads did not exceed the design limits.

If the boat underwent a sudden and large transient inclination it is reasonable to assume that the shallow depth prevented exceeding of the design limits.

It is almost certain that the Reactor compartment is now flooded, subjecting everything in it to sea pressure and potential corrosion.

The power level immediately before the first explosion was reported to be 20 to 25 % . The power level before the second explosion is not known but - given the time available - is not thought to have been much higher. Whether it was reduced in a controlled manner and whether a controlled (automatic) shutdown followed is not a documented event, and has to be taken into account during lifting operations.

Continuous site monitoring outside the submarine hull since the sinking has shown no evidence of other than natural radiation levels, which is more than strongly suggestive of a subcritical reactor and limited, if any, damage to systems and components. This is consistent with the findings and analyses of this paper and the evidence of the References and communications to the Author.(Ref. 7) Moreover independent measurements of the Norwegian Radiation Protection Authority and, most recently, by divers of the salvaging company corroborate this evidence.

The conclusions drawn are thus that:

- the reactors are sub-critical.
- the likelihood of them becoming critical through any effects from raising/transportation is so extremely remote as to be disregarded.
- the likelihood of the raising/transportation process exacerbating any radioactive leakage hazards, which may exist as a result of the sinking is remote.
- the greater hazard probably lies in leaving the submarine where it is and doing nothing.

3 OPERATIONS AND EXPLOSIONS

3.1 Status before explosions

Whereas there are differences between open sources about the submarine layout, a reference baseline for this analysis is adopted in Appendix 5.1.

Ref. 1 states that the vessel had received permission for an “educational” (training or trial?) torpedo launch. To do this it would almost certainly have been submerged at about 22m if at periscope depth but probably not more than about 70m (the water depth is 108m) and be proceeding at a moderate speed. The Russian authorities report that the reactors were at 20 to 24 % of nominal power. After deduction of auxiliary power requirements that would correspond to a moderate speed. Ref. 1 also states that trials of an upgraded weapon were scheduled to be carried out on this vessel, allegedly centred on the replacement of the previous solid propellant with a sensitive liquid fuel. Russian sources indicate battery driven torpedoes were replaced with a new type.

For such an event, or simply for a routine weapon launch, the vessel would be in a high state of readiness, with the crew at their designated positions. Whether it is Russian practice to conduct such trials with bulkhead hatches open or closed is not known. The presence of the Head Quarters team would no doubt lend an edge to this and the presence of factory weapon specialists suggests that something that was not routine was afoot.

3.2 Explosion magnitudes

Whatever the weapon firing intentions, there is incontrovertible evidence, Ref. 3, that on 8 August 2000 the Kursk suffered two explosions.

The first explosion, according to Ref. 1, registered 1.5 on the Richter scale and the second registered 3.5, implying explosions of 0.1 and 10 tonnes TNT equivalent respectively. The forensic seismic study of the University of Arizona, reported in Ref.3, found the second event to be in the 3-7 tonnes TNT region. The seismic recordings were compared with those of known test explosions. The article concludes that the second Kursk explosion is most likely to be close to 5 tonnes of TNT with a ratio of 250 to the first explosion, which puts the first event at 20 kg TNT.

The Richter scale is one of comparative amplitude, in which a change of 1 point represents a 10-fold increase in amplitude. By convention this is taken in earthquake situations to equate to a 30-fold increase in energy, but for the purposes of this paper the energy multiple is conservatively taken as 10, since it is difficult to conceive of an energy multiple less than the amplitude increase for two explosions of similar origin.

Kursk could carry up to 28 weapons (torpedoes) inboard; their warheads ranging from 210 - 450 kg.

According to the Russian authorities the number of inboard torpedoes on the day was 24 and could readily have been several tonnes of explosives, to which must be added the energy stored in the fuel of each weapon. It is thus readily possible to postulate the presence of sufficient explosion potential in the Weapons Compartment for both events. (The actual number of cruise missiles stored in the bins in the double hull, according to Russian sources was actually 22)

For the second explosion to have had the energy release as low as 2 tonnes of TNT, as has been suggested elsewhere, seems very doubtful in view of the seismic evidence. The actual value may seem somewhat academic, since, whatever its TNT equivalence, it was sufficient to rupture the pressure hull.

3.3 Response to first explosion

Since the second explosion evidently occurred in the Weapons Compartment (Compartment I), it is most likely that the first also took place there. There is much speculation on the cause of the first explosion, none of which is germane to the subject of this paper. Its magnitude (0.02 - 0.1 tonnes of TNT equivalent) would certainly disable and probably immediately kill the five occupants. The compartment, presumably to magazine standards, would, in Western practice, be designed to minimise the effects of such an event on the rest of the vessel. It would be an eventuality the crew would have rehearsed.

If the explosion took place with one tube door open, it is possible that the remaining door might have been dislocated or if it happened within the tube that both doors were damaged; Ref. 5 states that an open 533mm weapon tube at or close to the surface could admit 2m³/min, sufficient to progressively affect trim on such a submarine, but insufficient to create a sinking situation. Barring this circumstance the likelihood of large-scale flooding from the first explosion is low. If an armed weapon had exploded in a tube, or in the compartment, the seismic record would presumably have been higher.

More insidiously, the presence of water may have fuelled an existing fire situation and exacerbated the second explosion (Ref. 5-loss of Russian submarine K219 by fire in 1986). A shock wave would have travelled through the vessel, causing people to fall about, at least in the adjacent Control Room, and possibly creating some equipment damage/malfunction.

The Command would probably have no direct knowledge of the state of affairs in the compartment or of the extent of damage other than by observing effects on vessel trim and atmosphere. The compartment would presumably have an automatic suppression system (water/gas) and possibly remote sensing to quell/monitor the immediate situation.

There are two scenarios to be considered for the response to the first explosion. One constitutes an active response from the crew. The other is a passive sequence of events.

Active scenario

A logic reaction would be to get to the surface through closing compartments, blowing of the main ballast tanks and possibly through propelling the submarine there. If at periscope depth with no evident trim change there would probably be no order to change propulsion power. If deep then increased power would be demanded, ahead if there were no trim changes or perhaps astern if there was a bow-down problem. Whether 108m water depth would permit or necessitate such an action is unclear.

There is evidence (Ref.1) that at least one and possibly all of these operations occurred. If at periscope depth when the explosion occurred the vessel could have reached the surface, assuming typical submarine characteristics, in less than 1 minute from its initiation (presumably shortly after the explosion); from 70m it would probably be at the surface in under 3 minutes.

In summary, 2 minutes after the first explosion, immediately before the second explosion it is likely that under the active scenario:

- the reactor was operating normally and perhaps moving to a high power level; there would be no reason to shut it down, nor is it likely that the magnitude of this explosion would have caused it to shut down automatically. Even if full power had been ordered immediately after the first explosion, it is unlikely that this would have been achieved in the intervening two minutes.
- the submarine was on or very close to the surface in near-normal trim
- the Weapons Compartment crew were dead and the state of affairs in it was unclear to the Command
- elsewhere equipment and systems were generally functioning normally.

Under the active scenario this would have been a trained-for emergency situation but not a disaster, with no reason yet to release distress buoys or emergency signals. There would also be no time, if that would have been practice, to send a signal to the Fleet advising of the situation.

Passive scenario.

The passive scenario assumes that the fire in compartment I and the start of flooding of this and following compartments prevented the crew from taking any action. The boat would develop a bow down tilt but this would be limited in view of the amount of water intake in relation to the displacement of a boat this size. The supposition is that the boat would start to sink to the bottom under an increasingly negative buoyancy. Assuming the hatches in the bulkheads were not closed the water entering compartment II and III may have caused the battery switchboards to short and possibly enter the battery compartments, which are taken to be in Compartments II and III. The result would be that the reactor circulation pumps would stop and subsequently the reactors scrambled.

The boat without further propulsion could have sunk to the sea bottom at a shallow angle and borrow its bow into the sand. In this case just before the second explosion took place the situation would be:

- the submarine is on the bottom
- the reactors are automatically shut down.
- The crew is disoriented from fire and smoke and the flooding continues

3.4 Second explosion

The second explosion occurred 2 minutes and 14 seconds after the first, was clearly centred on the Weapons Compartment with a most probable magnitude not less than 5 tonnes TNT equivalent.

It tore open (the top of) the Weapons Compartment, resulting in near instantaneous, massive and uncontrollable flooding.

The force of the explosion would be applied to the compartment's deck, to the bulkhead with the Control Room and to the pressure hull. It clearly ruptured the pressure hull over much of the compartment. The bulkhead would be no stronger and so would also have failed, as must the compartment deck.

If the shock wave and moving/falling equipment didn't kill the crew in these surrounding compartments then the incoming water would have done so very rapidly. Without the Control Room the vessel lost any possibility of co-ordinated action.

How far such severity of damage and death went is presently unclear, but that all the crew of Compartments VI, VII, VIII and IX "survived" (Ref.1) strongly suggests that these compartments were not as catastrophically affected. The shock that humans can endure is in general much less than the design shock limits of the vital systems such as the reactor plant. The cause of the death of these temporary survivors was not caused by injuries from shock, which supports the assumption that the shock loading of the reactor plant was within the design limits.

The effects of the second explosion are different for the active and the passive scenario.

Active scenario

Whether the operators at the Primary controls in Compartment V or those associated with Reactor Compartment (VI) had the means or presence of mind to shut the reactors down is a critical matter, as is whether the reactors shut down automatically. These matters are examined in following sections of this paper.

The effect of the massive and rapid flooding forward would be potentially to give the vessel quickly a large bow-down angle; this would be exacerbated if, as is likely, the aft Main Ballast Tanks remained relatively intact and had been "emergency blown", as depicted in Figure 1. Indeed it is not inconceivable that the stern was transiently at or even above the surface, with the bow on/in the seabed, given the depth of water (108m) and the vessel's length (155m). This is discussed below and in Appendix 5.2.

Thus in addition to the tribulations already visited on the "survivors" and the reactors, that of an extreme angle, possibly about 45 degrees, may have been added. As compartments gradually flooded, the stern would drop to the seabed. The "survivors" notes of 2 hours after the explosion make no

reference to extreme angles and the fact that they could gather at all suggests that such a condition was short lived.

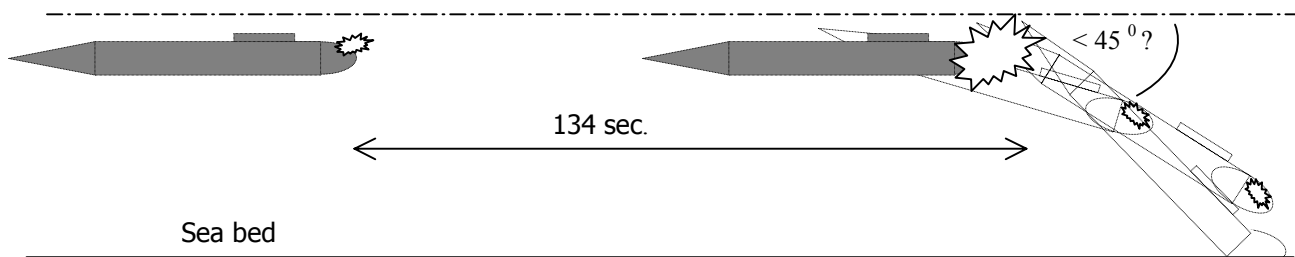


Figure 1. Submarine motion in active scenario before and after second explosion

Passive scenario

In the passive scenario the submarine would have arrived at the seabed before the second explosion took place. In case the reactors were already shutdown, triggered by the effects of the explosion or the (limited) flooding causing the loss of electricity, the explosion had no further relevance to the capability of the reactor control systems to function. The second explosion would now have ripped apart the first compartment intensifying the flooding. Had the reactors not yet been shut down the conditions for a scram are the same as for the active scenario.

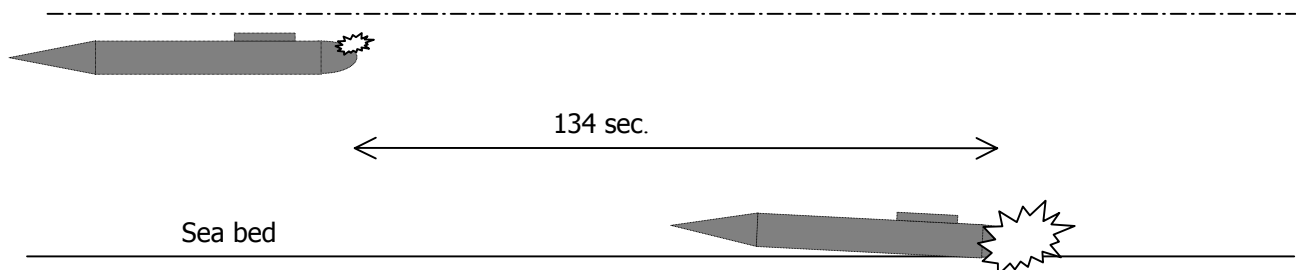


Figure 2. Submarine motion in passive scenario between explosions

The fact that the bow section containing the forward ballast tanks were found to be broken off and not crushed and the damaged first compartment structure not folded, as could be expected in a steep

dive into the seabed, supports the passive scenario. (Fig. 2) This scenario is in contradiction with the reports of recorded tank blowing noises and increasing propeller revolutions. These arguments support the case for the active scenario.

The reactor compartment having maintained its integrity would not flood as quick as the forward compartments. It is estimated by the Russian authorities that this compartment flooded through small gauge measuring lines and that it took 150 hours to flood the upper parts of the compartment and another 70 hours for the spaces immediately above the reactor tank and below it to fill up. There would be an air pocket in the top of the compartment.

3.5 Possibility of unexploded munitions

It can be presumed that there are still unexploded torpedoes or parts thereof in and around the submarine, although many of the torpedoes are destroyed in the second explosion. Also the cruise missiles are still in place in their silo's, which have the same design requirements as the pressure hull.

This issue is outside the scope of this analysis, but it is understood the operating safety envelope of the consortium's plan includes the following elements:

- The Consortium accepts that the occurrence of an outside explosion taking place is a possibility.
- The effects of such an explosion of munitions, not accounted for, on the reactors has been analysed and it has been established that such shock loads are within the design limits of the reactors and will not create an environmental threat.
- To protect the divers procedures have been set up with hold points and ROV inspections before and after all actions. Divers will not be in the area when the silt is jet washed from Compartment I prior to cutting. The cutting will be done by remote control.
- To protect salvaging equipment stand off distances will be observed.
- Monitoring (radiation) of the reactors throughout all phases of the work with documented hold points will be maintained.
- The sensitivity of the cruise missiles to external effects including inadvertent explosions of munitions has been examined. The protective storage and inherent protection systems of the missiles have been found to preclude a (sympathetic) detonation under the lifting and transportation conditions.
- The lifting plan excludes the smallest likelihood of 'dropping' the submarine when lifting or during transportation. The impact of dropping the submarine is not creating shock loads to the reactor systems that would bring them back to criticality.

4 NUCLEAR HAZARDS

4.1 Overview

There has been no evidence of any change in background radiation levels in the surrounding sea, which is continuously monitored. This is confirmed by the Norwegian Radiation Protection Authority in their report published this year. (Ref. 6)

What is known or may reasonably be surmised is that high shock levels allied with unknown power demands were imposed on the reactors in their last moments.

In these circumstances, it would seem prudent to take the absence of increased radiation rather as good fortune for the present but the question presents itself whether this situation will continue when the vessel is disturbed and lifted.

It is therefore necessary, in what follows, to examine the possible conditions in which the reactors may now be, how these could change and the hazards, which could arise.

The time needed to move from the (presumed) low power state to the emergency-driven full power is thought to be longer than the interval between explosions; it is therefore unlikely that the reactors could have been at full power at the second explosion - some increase over the 20-25 % power level reported by the Russian authorities for the period just before the first event.

The coldness of the water at the wreck site would act to encourage reactivity; that there has been no trace of measurements above background, including high-energy gamma's, in the 11 months since the disaster implies strongly that the reactors are shut down. The means by which this may have occurred are discussed below.

The lifting process may:

- shake and possibly tilt the Reactor Compartment as it is lifted out of the silt on the bottom
- probably cause water leakage from the compartment, due to reducing ambient pressure
- increase temperature in the compartment, due to increasing water temperature

None of these and associated events are likely to provide any incentive by themselves for the reactor state to change from a shutdown state; increasing water temperature will act to decrease the likelihood of change in the reactor status. Furthermore the salvaging company has stated that the lifting will be done without any substantial dynamic loading.

There is however the potential that the originally inflicted damage could be exacerbated by the lifting process. But the more likely hazard from the originally inflicted damage lies not in any likely change of state during lifting but the hastening deterioration of the containment barriers if the boat is left on the bottom of the sea.

The monitoring of the state of the boat before and during the lifting shall be an integral part of the lifting plan, as should the taking of water samples and measuring of temperatures and radiation levels at least close to if not inside the Reactor Compartment by remote means.

The discussion of the subsystems is based on the assumption that the Kursk reactor systems are functionally similar to those of Russian icebreakers and the discussions with the Russian Authorities.

4.2 Condition of Relevant subsystems

The conditions of a number of subsystems determine the potential hazards. The systems under consideration are:

Emergency Protection System

Reactivity Control System

[A Liquid Poisoning System is available on icebreakers but not on the Kursk]

Decay Heat Cooling System

Pressuriser system

Containment barrier 1: the fuel element

Containment barrier 2: the Primary Loop system

Containment barrier 3: the Shield enclosure System

Containment barrier 4: the Reactor Compartment

As a result of the explosions and subsequent movements of the submarine these subsystems may or may not have incurred enough damage to prevent their proper functioning or breach their integrity.

There may also be an interaction between the conditions of the subsystems that have a bearing on the ultimate potential hazard. The failure of one subsystem may have an influence on the condition or (future) integrity of an other subsystem. This is evaluated in Section 4.3. First, each subsystem is discussed.

4.2.1 Emergency Protection System (EPS)

There are a number of absorber structures, which are withdrawn from the core before start-up. To shut down the reactor rapidly they are driven back into the core by scram springs. (mechanical- or gas springs).

The absorber structure is withdrawn by a geared induction motor, driving a gear rack mechanism. There is an electromechanical latching mechanism between the spring-loaded absorber elements and the withdrawal mechanism. This latch is secure against unintentional scrams even when subjected to shock loading. The scram is achieved by de-energising the latching mechanism.

When driven in the EPS is locked in place to prevent it from inadvertent extraction from the core, like falling out if the submarine would roll over.

The first explosion will most likely not have caused a scram, because the shock was light enough not to release the latch inadvertently and the crew had no desire to lose propulsion. However the EPS may have been activated after the first or the second explosion for a number of reasons.

- The crew manually initiated the scram
- The shock may have broken the latching mechanism
- The loss of all electricity - caused by opening of circuit breakers and/or the destruction of all switchboards and the battery in the forward departments - may have automatically released the latch
- Sudden loss of pressure - if that could have happened so fast - may have triggered an automatic release

There are also a number of possibilities to consider that may have prevented a scram with the EPS. Apart from the causes for automatic shutdown, cited above, possible reasons for this not having happened are:

- There were no crew members available, either because they were stunned or killed by the explosion or not at a location where they could activate a scram.

- The absorber elements may have jammed when driven into the core, due to deformations from shock and vibration.
- The shock may have bent or broken the guides or destroyed the spring mechanism.
- The attitude of the boat (either in combination with damage or by its effect alone) immediately after the shock may have increased the friction in the absorber element guides causing jamming. Also the effect of gravity would be less if the boat's forward pitch became severe.

If the EPS release mechanism has operated, but the absorber material has only partly entered the core there is the question of the reactivity worth of the EPS effective in the core. The same question may be asked about the EPS reactivity worth in comparison to the eventual drop in temperature from operating temperature to the surrounding water temperatures for the given fuel burn-up of the reactors. The initial shut down of the reactors could have been negated by the temperature drop and a state of criticality could have been reinstated, though at low power. The Russian Authorities have calculated that the temperature of the primary system, now almost a year after the incident, would be 7 to 8 °C given the heat transfer mechanism of the flooded compartment and the present decay heat production of about 1 kW. This low value corresponds with a reported 5-year history of limited burn-up. (Corresponding with an average annual power level of only a few percent of nominal, see also Ref. 6) At these low temperatures the amount of reactivity worth of the EPS and other absorbing materials is much more than only partly inserted EPS elements could provide. If the reactors were still critical the reactor low power in equilibrium with the low temperatures and existing heat transfer properties in the shield tank and flooded compartment would not be negligible probably in the order of 200 kW. Such a reactor output would certainly register on the monitoring sensors, which indicate only background levels.

Assuming the EPS - or other systems - have shut-down the reactors the possibility of the present status to change depends on the reactivity worth re-introduced into the reactors and the certainty of (all) the absorber material remaining in the reactors. This change could result from:

- A slow return to criticality as the water cools down from operating temperature creating excess reactivity in respect to the worth of the absorber material.
- A sudden inrush of cold water, when the boat is shifted during lifting and assuming the temperature in the core is relatively elevated due to the absence of any appreciable cooling, bringing the reactor in a critical state again.

The long time that has elapsed since the accident and the radiation measurements make either of the above possibilities extremely remote.

4.2.2 Reactivity Control System (RCS)

This control system, consisting of a number of absorber control elements that are driven in and out of the reactor by a screw mechanism and a geared stepping motor, has two functions. During normal operations it provides the reactivity control for start-up, shut-down and compensation for changes in core reactivity during operation. In an emergency the RCS can be used for a scram trip by de-energising the motors of the drive motors. The control absorbers then fall into the core under gravity, its speed dependent on the friction of the screw mechanism. It is also possible a passive latch is incorporated in the mechanism. The activation of the RCS may have happened for the following reasons:

- The crew manually initiated the scram.
- The destruction of the electrical equipment resulting in a loss of electricity de-energised the motors and made the absorber elements to drop into the core.
- A de-energised latch.

Arguments against the activation of the RCS during the accident are:

- As for the EPS it is not likely that the crew were capable to set the RCS in operation in scram mode: shut down by this means is probably very unlikely.
- The same damage considerations prevail as for the EPS.
- The free fall of the absorber elements is more dependent on friction than for the EPS. An extreme bow-down angle and/or damage may have hindered such operation.

The probability that the RCS has functioned in the emergency mode is much less than for the EPS, although it is not to be excluded.

Assuming the reactors were indeed shut-down the reactivity worth introduced in the reactors by the EPS and/or the RCS is important. The excess reactivity worth of the absorber material relative to the temperature differences is important in reassuring continued shutdown even if some absorber material would inadvertently be withdrawn from the reactor.

4.2.3 Decay Heat Cooling System (DHC)

The cooling of the reactor core after shutdown is ensured by a Decay Heat Cooling System. The heat is removed by natural circulation between the reactor and a heat exchanger, which transfers the heat to the outside sea water. (It is assumed there is no forced circulation that depends on the availability of electric power.) The DHC keeps the core temperature down to protect the integrity of the fuel elements in the core.

The shield tank is filled with 25 m³ of water, surrounding the reactor vessel. This provides a heat sink of substantial capacity to which the effect of a flooded compartment may be added. The 220 hours that it may have taken to flood the compartment however may have impaired the initial cooling of the fuel elements producing decay heat. The extent of the (initial) proper functioning may also have been determined by the amount of damage the system sustained during the explosion by blast or shock.

If a Decay Heat Exchanger is positioned inside the reactor shield enclosure the shock may have been dampened enough for the system to survive.

If the reactor core is not sub-critical or may become critical at a later period (see above) the heat output could be larger than that of the decay heat, increasing the risk of cracking of the fuel elements and future release of fission products.

4.2.4 Pressurizer System

The reactor is pressurised by gas. The gas, argon or nitrogen, is stored in large quantities of reserve gas. The cooling down of the primary system would not automatically reduce the pressure in the Primary Loop supposing the integrity of the Primary Loop is not broken. (Reasons for gradual pressure loss would be sustained damage as for instance indicated above for the DHC)

In case of a leak in the Primary Loop the shield enclosure system may have been pressurised to its 18 bar maximum. Having reached this maximum the pressure in the Reactor Compartment, depending on its integrity, may have risen. Supposing such a damage condition it is more likely all pressure has leaked away over time. This would be an indication of loss of integrity of the Primary Loop, the shield enclosure and the Reactor Compartment. If the gas storage pressure of the submarine could be measured an indication of this condition would be obtained, as an indicator for future contamination risks.

If the pressure in the reactor system has remained since the sinking there is a (non-nuclear) mechanical risk of having a high pressure gas system aboard the boat during lifting. It may be possible to release the gas pressure before the operation, unless it is deemed to be radioactive.

4.2.5 Containment barrier 1: the fuel element

The first containment barrier is formed by the fuel element itself. The fuel may be in the form of oxide pellets or an alloy foil inside metal rods (cans or cladding) or, like in some research reactors, dispersed in a metal (e.g. aluminium) matrix. The cladding and/or the matrix material forms the protection against loss of fission products. The fuel is protected from shock by the heavy structure of the reactor vessel and shield enclosure. The possible damage condition of the fuel can range through:

- No damage at all, the primary barrier is intact
- The cladding or matrix material is cracked, with no immediate release of fission products but the gaseous elements.
- The cladding or matrix is broken so that fission products could be released.
- Pieces of the fuel elements have broken off and have fallen to the bottom of the reactor vessel.

The last two events have most probably not happened. Early release of fission products would have been detected immediately. And any broken pieces have not aggregated to a critical mass, since such an occurrence would also have been detected by the radiation monitoring done to date.

The detection of fission products in the Primary Loop is more difficult to measure and such a possibility can not yet be ruled out as cannot the occurrence of cracks. Hairline cracks would not diminish the structural integrity so much that they would pose a nuclear hazards for the lifting operation, but they could enhance corrosion attack and hasten the future contamination, were the Kursk left on the sea bottom.

4.2.6 Containment barrier 2: the Primary Loop system

The reactor vessel and equipment directly connected to it form the Primary Loop system. The main items are:

- The reactor vessels
- The piping for the in- and outlet of the cooling water
- The pressurising system
- The circulation pumps
- The steam generators
- Various auxiliary and support systems with connections to the Primary Loop

These pieces of equipment are mostly sturdy and heavy walled items calculated to sustain severe shocks. The primary system is mounted in the Shield Tank. More delicate equipment mounted on the main equipment is protected by the mass of the main equipment and may furthermore be spring mounted against shock. The second explosion of the Kursk was extreme and it is not known if the construction was designed to withstand such levels. As discussed the evidence of the temporary survivors points to a shock below credible design limits, but the extent of the potential damage can only be analysed with extensive shock calculations. Apart from the considerations given to damage to the control systems, the fuel and the pressurising system it is not to be expected that damage to the Primary Loop constitutes a hazard during lifting.

If cracks in the Primary Loop components have occurred, whilst not deteriorating the structural integrity essentially, corrosion may be hastened increasing the risk of future contamination if the submarine is not lifted. Broken lines of auxiliary systems (e.g. ion-exchange equipment) could spill radio

active fluids or particles. This contamination would be contained in the shield enclosure and/or the reactor compartment.

4.2.7 Containment barrier 3: the Shield Enclosure System

The shielding system around the reactor is integrated in a pressure tight enclosure around the Primary Loop system. The Shield Tank is placed on resilient shock mounts in the submarine structure. The sealing pressure is 18 bar. The likelihood of damage is probably less than to the Primary Loop system, because of the nature of the heavy construction and large mass with no or few moving parts. It is conceivable that the shield itself may have suffered local damage in the form of cracks. These cracks based on the nature of the construction may not be completely through the shield.

The seals where piping passes through the shield are more likely to have been breached by the shock waves from the explosion. In consequence, if gas from the pressurisation system was released inside the shield enclosure it would probably not have been able to build up pressure inside the shield.

The damage to the shield will most likely not have impaired the shielding function in general. There may have developed a few places where radiation could stream out if there is a source of radiation from the reactor. The damage if any will not present a hazard to the lifting operation. The resilient mounts most likely still capable to absorb shock loads, which if coming from the lifting operation will be much lower than the explosion effects.

The risk of contamination in the future is dependent on the level of damage and the size of the openings made in the shield.

4.2.8 Containment barrier 4: the Reactor Compartment

The Reactor Compartment constitutes the last barrier between the NSSS and the outside world. The second explosion would have set the hull in into a bending mode vibration in the vertical plane. Furthermore waves of radial distortion and concertina-mode axial compression have propagated along the hull.

From observations it is obvious that not only the first but also the second compartment has been completely destroyed. The likelihood that more compartments forward of the Reactor Compartment are destroyed is high. The diver observations have indicated that the pressure hull aft of Compartment II is intact. It has also been established that all (most?) of the compartments are flooded, indicating that at least internal damage has occurred.

The Reactor Compartments structural integrity may have been preserved, as seems to be the observation of divers visiting the submarine. That does not mean that there is no internal damage or that the pressure tightness has not been lost. The overall situation can only be begun to be established by internal viewing. As said above a blast and shock calculation could indicate what is most likely to be expected, but give limited certainty because of the complexity of such an analysis.

4.3 Hazard Analysis

4.3.1 Combinations tree

To analyse the effects of the multitude of combinations presented by the interaction of the conditions of the subsystems a tree structure is used. The subsystems are arranged in 4 groups. Each group forms a level in the structure.

Although not a submarine system by itself, the condition of flooding of the Reactor Compartment is also included in the tree structure.

In the structure a subsystem is either functioning or not (the system has failed). Or as the case may be a system integrity is breached or the system is still intact. The arrangement is given below in Table 1.

TABLE 1							
Subsystem combination tree structure							
	LEVEL 1		LEVEL 10		LEVEL 100		LEVEL 1000
	Reactor Control		Primary System		Containment Barriers		Reactor Compartment Integrity
	EPS activated = + RCS activated = +		Decay Heat Cooling sufficient = + System Pressurised = +		Fuel Elements intact = + Primary Sys. intact = + Shield Sys. intact = +		Reactor Comp. intact = + Reactor Comp. flooded = +
1	EPS +, RCS +	X1	DHC +, SP +	XX1	FE +, PS +, SS +	XXX1	RC +, RCF +
2	EPS +, RCS -	X2	DHC +, SP -	XX2	FE +, PS +, SS -	XXX2	RC +, RCF -
3	EPS -, RCS +	X3	DHC -, SP +	XX3	FE +, PS -, SS +	XXX3	RC -, RCF +
4	EPS -, RCS -	X4	DHC -, SP -	XX4	FE +, PS -, SS -	XXX4	non-existent
				XX5	FE -, PS +, SS +		
				XX6	FE -, PS +, SS -		
				XX7	FE -, PS -, SS +		
				XX8	FE -, PS -, SS -		

4.3.2 Possible states

In very general terms the boundaries of possible conditions of the NSSS are as follows if it is assumed that the compartments, and the Reactor Compartment in particular, are presently flooded through leaking bulkhead penetrations or broken piping:

1) Physical state

- *Most benign case:* that pressure hull, shielding, reactor vessels and Primary Loops are intact
- *Worst case:* that pressure hull is intact but shielding, reactors and Primary Loops are all damaged and open to the flood water in the compartment. (assuming that a Primary Loop exists outside the reactor vessels)

2) Operating condition when flooded.

- *Most benign case:* that the reactors were properly shut down before flooding occurred.
- *Worst case:* that the reactors were at elevated power and maintained their criticality, be it at low power.

3) Effect of an extreme transient angle

- *Most benign case:* that this was within the design limits and had no effect, or did not occur.
- *Worst case:* that it did occur and interfered with reactor or Primary Loop functions.

The following sections address the subsystems in more detail to assess the consequences for the overall condition of the NSSS for the effects on the lifting/transfer operations and potential future contamination hazards.

4.3.3 Coincident conditions

The foregoing discussion is about the subsystems having functioned/remained intact as designed or not. In section 4.3.1 the subsystem condition after the explosion is given a plus or a minus sign to indicate: functioning or failed. Each combination of subsystem conditions, named "coincidence case" for the purpose of this analysis, is represented by a four digit number in the tree structure, as can be read from Table 1.

Some coincidence cases are more hazardous than others. Families of cases, which can be considered to involve the same type (and level) of risk, are grouped and graded as follows:

Group 1 - No criticality implications

These cases pose no "criticality risk" during the lifting of the Kursk, because the reactors have been shut-down by one of the two possible means corresponding to the first three conditions of level 1, reactor control. The groups of cases are summarised in Table 2.

TABLE 2.				
No criticality Risk, Protection from radiation, future contamination risk				
Coincidence group	Reactor safety	Contamination	Protection	
1111 - 1223	Reactor in safe condition	Potential future contamination	Protection by 3 to 4 barriers, X1XX: gas pressure risk	X13X,X14X,X17X, X18X non-existent
1223 - 1283	Reactor in safe condition	Potential future contamination	Protection by 0 to 3 barriers	
1311 - 1483	Reactor in safe condition	Potential future contamination	Protection by 0 to 4 barriers, weakened fuel elements , X35X,X36X: gas pressure risk	X33X,X34X,X37X, X38X non-existent
2111 - 2223	Reactor in safe condition	Potential future contamination	Protection by 3 to 4 barriers, X1XX: gas pressure risk	X13X,X14X,X17X, X18X non-existent
2223 - 2283	Reactor in safe condition	Potential future contamination	Protection by 0 to 3 barriers	
2311 - 2483	Reactor in safe condition	Potential future contamination	Protection by 0 to 4 barriers, weakened fuel elements, X35X,X36X: gas pressure risk	X33X,X34X,X37X, X38X non-existent
3111 - 3223	Reactor in safe condition	Potential future contamination	Protection by 3 to 4 barriers, X1XX: gas pressure risk	X13X,X14X,X17X, X18X non-existent
3223 - 3283	Reactor in safe condition	Potential future contamination	Protection by 0 to 3 barriers	
3311 - 3483	Reactor in safe condition	Potential future contamination	Protection by 0 to 4 barriers, weakened fuel elements, X35X,X36X: gas pressure risk	X33X,X34X,X37X, X38X non-existent

Although the risk of the reactors being or becoming critical is excluded in these coincidence cases the risk of future contamination is not absent. There are 3 groups that have the highest risk in this respect. They are the groups:

1311 to 1483, 2311 to 2483, 3311 to 3483

The common hazard of this set is the *failure of adequate Decay Heat Cooling*. In combination with some or all of the barriers broken the future contamination hazard is greatest. The worst case is presented by:

- X483 , the fuel elements may be damaged by overheating and the shock has damaged all the barriers.

The failure to remove the decay heat in these cases is also predominantly caused by the mechanical damage to the system. The *risk of remaining high pressure gas* stored in the system or in the storage vessels is by the same token not present for the X483 cases.

Group 2 - Potentially critical reactor

The remaining coincidence cases all consider the risk of continued criticality of the reactor(s). Table 3 below shows these groups of coincidence cases. The difference among these case groups is the potential risk for future contamination and the added gas pressure hazard in some distinct cases.

TABLE 3.				
Criticality Risk, future contamination risk				
Coincidence group	Reactor safety	Contamination	Protection	
4111 - 4223	Reactor in temporarily stable condition, criticality risk.	Potential future contamination	Protection by 3 to 4 barriers, X11X, X12X: gas pressure risk	X13X,X14X,X17X, X18X non-existent
4131 - 4283	Reactor in temporarily stable condition, criticality risk.	Potential future contamination	Protection by 0 to 3 barriers, X35X,X36X: gas pressure risk	
4311 - 4323	Reactor in temporarily stable condition, criticality risk.	Potential future contamination	Protection by 0 to 3 barriers, weakened fuel elements, X31X, X32X: gas pressure risk	X33X,X34X,X37X, X38X non-existent
4331 - 4483	Reactor in temporarily stable condition, criticality risk.	Potential future contamination	Protection by 0 to 3 barriers, weakened fuel elements, X35X,X36X: gas pressure risk	

4.3.4 Commentary

It is considered most probable that, given the absence of outside radioactivity, the reactors are shut down, although it is conceivable that the explosion's shock loads and transient motions could have prevented full shut down so that a state of close to zero power criticality could still exist, while showing no increased radiation outside the pressure hull. Could more definite proof of non-criticality be obtained inside the Reactor Compartment all cases 4XXX would not exist.

The cases 4283 and 4483 (*primary system not pressurised, all barriers breached*) can be taken to be not possible. In this case the leaks would have caused quick contamination and a rise in radioactivity would have occurred and been detected.

There are also the borderline cases where the absorber material, from one or all of the control mechanisms may not have provided for enough reactivity worth compared with the reactivity feedback of the core temperature cooling to surrounding sea water temperatures. The resulting present and temporary sub-critical state could then return to critical later. This presupposes that the core at present is still at an elevated temperature. A break down of the (decay) heat removal system would also have to be assumed with the Primary Loop still in tact and pressure tight. Although not formally belonging to the group 4XXX the borderline cases are considered as part of them. The coincidence cases most likely to support (temporary) criticality are:

- 4111, 4121, 4151 and 4161: *functioning Decay Heat Cooling, Primary system intact and pressurised, Reactor Compartment basically intact and flooded.* This condition would probably sustain zero power criticality best. It would also indicate minimal damage and therefore the proper functioning of the EPS, i.e. shutting down the reactor under loss of electricity.
- 4311, 4321, 4351 and 4361: *no proper Decay Heat Cooling, Primary system intact and pressurised, Reactor Compartment basically intact and flooded.* If it can be established that the pressurisation gas pressure is equal to ambient pressure, these cases do not exist. If a connection with the Pressurisation System could be made the pressure tightness could be checked and or a sample could be taken to verify contamination. There could be *gas pockets* in the Reactor Compartment.
- 4312, 4322, 4351 and 4352: *same as above but now the Reactor Compartment Is not flooded.* This case has probably already been excluded during earlier examinations by the divers concluded that all compartments are flooded. If not it can be easily checked.
- 423X, 424X, 427X, 428X, 443X, 444X, 447X and 448X: *Primary system breached, ambient pressure.* The probability of maintaining an elevated temperature in the core is smaller then for the intact system. If the Primary Loop damage is very limited but enough to depressurise, this status can only be proven with certainty by measurements inside the shield structure. If the Primary Loop breach is large enough samples from the Reactor Compartment could be indicative. A connection with the Pressurisation system could provide a means of sampling.

In weighing the probability that the reactor state is that of low power criticality or may return to that state the previously mentioned low (7 to 8 0C) temperature in the primary system, as calculated by the Russian authorities, must be taken into account. Such low temperature represents maximal reactivity worth for the core, compared to that at normal operating temperature. Assuming that the reactor is not critical now, all required absorber material must be in the core. Introducing outside cold water into the core, e.g. when shifting the boat during lifting, is extremely unlikely to return the reactor to criticality. Were the core critical at very low power (10- 200 kW) at present, than that would most probably be detected by the monitoring of high energy gamma's.

5 APPENDICES

5.1 CREW DISPOSITION

Ref. 1 (Russian origin) gives the official crew disposition and, as Ref. 2 (US origin), gives a description of the compartmentalisation of the vessel. The two disagree on compartment nomenclature and function; the following Table 5.1-1. illustrates the differences.

Ref.2 also gives a "notional" layout that is at odds with Ref.4, the latter being derived from information provided by the class designer.

From all these, the Table (column 4) derives a layout which is taken as the reference basis for this paper, primarily using a combination of the official crew dispositions and the Russian-based weight distribution of Ref. 4.

Western terminology is used.

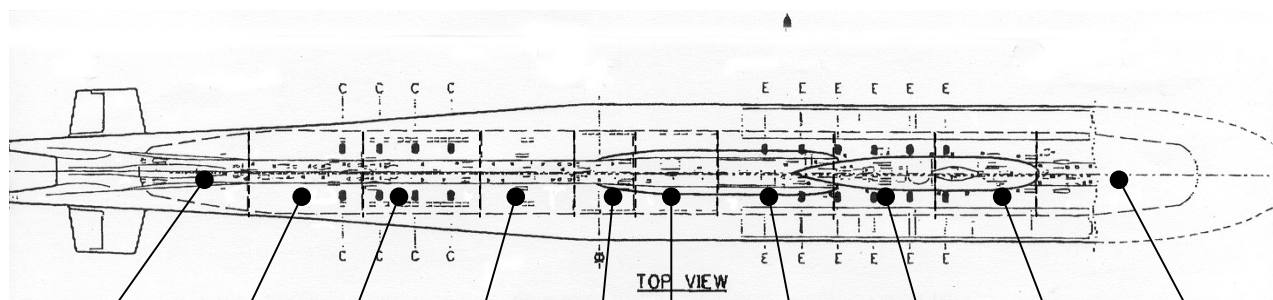
Table 5.1-1				
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5
Compt.	Ref. 1 Definition	Ref. 2 Definition	Principal Function based on Official Crew Disposition (Ref. 1/App. 1) and Ref4	Manning *)
I	Torpedo	Torpedo room	Weapon Compartment.	5- no officers plus 2 riders
II	Control room	Control room	Control room and MCC	31-19 officers incl. CO plus 5 officer riders
III	Electric panels	Combat stations /radio room	Sonar/Comms/EW spaces	24-10 officers incl. Deputy CO
IV	Quarters	Living quarters	Accommodation and Forward Escape Compt.	12-2 officers (1-Doctor)
V	Different stations	Reactor	Primary reactor, propulsion and auxy plant control.	11-6 officers incl. Ch. Eng
V-bis	Different stations	Reactor	Diesel-generator Compt.	4-1 officer
VI	Reactor	Propulsion eng.	Reactor Compt/local control.	5-2 officers
VII	Turbines	Main propn turbines	Engine room	9-1 officer
VIII	Turbines	Main propn turbines	Engine room	7-1 officer
IX	Electric motors	Electric motors	Motor room and Aft Escape Compt.	3-1 officer

*) A Senior-Lieutenant is taken as an "officer" in the Manning column.

The compartment arrangement of column 2, also shown in the general arrangement in Appendix 1 is the reference for the paper.

Crew disposition (Analysis of Official crew dispositions from Ref.1)

Compt	Captains			Snr-Lt	CPO	PO	Snr Mid	Mid	Sea men	Riders	Crew Disciplines
	Rank 1	Ranks 2-3	Capt-Lt								
I							1	1	3	1-Snr Lt. 1-civil	Torpedo, sonar, water systems
II	1 C.O.	6	4	8		1	2	7	2	5-Capts Ranks 1-3 from HQ	Command, nav, missiles, ship control, water and electric systems
III		2 inc Deputy C.O.	8			1	5	5	3		Comms, sonar, EW, missiles, water systems
IV		1 (Doctor)		1	1		2	1	6		Medical, Damage Control, water systems
V		3 Ch.Eng	3		1		1	2	1		Propulsion control, electrics, water systems.
V bis				1			2	1 Hd of Water systems			Diesel, water systems
VI			1	1	1			1	1		Propulsion, turbine control
VII			1			3	1	1	3		Propulsion, turbine control, electrics
VIII			1		1		2		3		Propulsion, turbine control
IX				1				2			Propulsion(electric?), water systems



9	8	7	6	5 bis	5	4	3	2	1
Gears, thrust block	turbines	turbines	Reactor compartment	Controls Emergency diesel	Control & monitoring	Accommodation?	Sonar, missile control	Central control room	Torpedo room
3	7	9	5	4	11	12	24	36, incl. C O	5+2

5.2 Estimate of forward pitch after second explosion

The explosive force

The pressure of an explosion taking place in a restricted space, like the Weapons Compartment, can be estimated by the following approximation of the "equivalent static pressure":

$$p_1 = 2.25 \left(\frac{W}{V} \right)^{0.72} \quad [MPa] \quad (1)$$

With:

W : mass of TNT in kg

V : volume of space in m^3

p_1 : equivalent pressure

Taking the volume of the Weapons Compartment as 80% of the displacement volume of Compartment I the value of V is about $1100 m^3$. With $W=5000$ kg the pressure p_1 is given by (1) as 6.7 MPa.

The pressure hull was abruptly broken open by the explosion. If it is assumed that p_1 is the pressure at which this happened, the combustion products of the detonation - upon breaking free - formed a gas bubble in the water. At the same time the escaping gas exerted a reaction force against the submarine's bow, pushing it down.

The downward force could be approximated as the gas pressure in the gas bubble acting on the area of the opening in the pressure hull. The force would exist for the time it takes for the gas to expand to about ambient pressure. If it is assumed the expansion of the gas had taken place in the sea at a depth H [m] below the surface without the presence of the submarine the maximum size of the bubble and the time it takes to expand to this radius can be calculated from:

$$R_{\max} = 3.42 \left(\frac{W}{H + 10} \right)^{\frac{1}{3}} \quad [m] \quad (2)$$

$$T = 1.05 \frac{W^{\frac{1}{3}}}{(H + 10)^{\frac{5}{6}}} \quad [s] \quad (3)$$

Taking H at 22m, periscope depth, the maximum radius becomes 18.4 m. The volume of the bubble then is $26000 m^3$, making the assumption of neglecting the Compartment I volume acceptable. The time to maximum volume is now 1 sec.

The next simplification postulates that the average bubble pressure, i. e. 3.4 MPa times the surface of the opening in the pressure hull is the force pushing the boat down for the duration of 1 sec. Considering the extensive destruction wreaked on the submarine's front end this area is estimated at $10 \times 8 m$. The average force becomes $2.72 \cdot 10^8 N$

The characteristics of the submarine

The parameters necessary to approximate the submarines motions are reflected in Table 5.2-1 below:

TABLE 5.2-1													
MAIN INPUT CHARACTERISTICS													
	Surface displacement [tonnes]		Submerged displacement [tonnes]		Envelope displacement [m ³]		Maximum speed [kn]		Maximum propulsion power [MW]		Cdrag = Power / (Displ ^{2/3} *V ³)		Totals
	14700		19700		24000		33		72		17.6		
compartment	Stern	IX	VIII	VII	VI	V- bis	V	IV	III	II	I	Bow	
Length [m]	17.5	11.7	13.3	14.4	11.4	7.1	9.9	14.5	11.7	12.0	19.1	12.4	155
Compt CoG [m]	8.8	23.4	35.9	49.7	62.6	71.9	80.4	92.6	105.7	117.5	133.1	148.8	
Section weight	560	599	1276	1694	2070	681	886	1335	1496	1458	2219	446	14661
Ballast water [t]	1500			2000 tonnes at CoG (= GoB)								1490	4990
Total weight [t]													19651
Loss of weight[t]											250	90	
CoG in [m] from stern	82.3												

When the submarine suffered the second explosion, not only the explosive force acted on the bow, also the loss of weight and buoyancy had an effect on the motions of the boat. It is very difficult to form an idea of the mass of the structural material and equipment that was blown off. Therefore the calculations have to be based on assumed amounts. For the purpose of making a reference calculation the following assumptions are made:

- The boat sailed at periscope depth at low speeds when the first explosion occurred. The submarine remained in this position and horizontal trim until the second explosion took place, and maybe had blown its tanks and was maybe speeding up.
- The big explosion took away the top of the pressure hull (a piece of 10 x 8 m) plus equipment and the secondary hull and bow structure.
- The forward ballast tanks were lost and with it the buoyancy of Compartment I. Other ballast tanks kept their buoyancy or weight, according to the situation.

The resulting changes to the submarine's characteristics are as presented in the Table 5.2-2:

TABLE 5.2-2					
MIN INPUT CHARACTERISTICS					
	CoG [m]	CoB [m]	Weight force [N]	Buoyancy force [N]	Rotary Inertia [kg.m ²]
Tanks blown	75.70	71.99	1.405 *10 ⁸	1.644 *10 ⁸	1.968 *10 ¹⁰
Tanks not blown	70.38	71.99	1.748 *10 ⁸	1.644 *10 ⁸	3.137 *10 ¹⁰

Simplified ship motions

The forces acting on the submarine will have resulted in a vertical translation of the CoG and a rotation around the CoG. The submarine also has an (unknown) forward speed. The life of the expanding gas bubble was 1 sec. For that first second the forces and moments working on the submarine were:

- $F_b - F_g - F_{expl}$, causing a vertical translation towards the sea floor.

With:

- F_b is the buoyancy force
- F_g is the weight force
- F_{expl} is the explosive force

With the tanks blown the downward force is $2.481 * 10^8$ N, while the force is $2.824 * 10^8$ in case the tanks were not blown.

- A moment relative to the CoG by these forces, causing a rotation around a horizontal axis through the CoG.

After the first second the force F_{expl} disappeared and the weight and buoyancy forces governed the submarine motion:

- If F_b was larger than the weight forces the vertical translation of the CoG downwards was reversed and the submarine moved to the surface again (tanks blown: $0.239 * 10^8$ N up). In case the weight force won, the CoG kept sinking (tanks not blown: $0.104 * 10^8$ N down).
- The moment exerted by F_b relative to the CoG continued to increase the rotation of the bow towards the bottom in case the CoB moved further aft than the CoG and vice versa.

The rotation of the submarine is governed by the formula:

$$\sum M = I_{\omega} \dot{\omega} \quad (4)$$

Where:

$$\sum M = M_{buoyancy} + M_{explosion} - M_{resistance} \quad (5)$$

and I_{ω} is the rotational inertia and ω is the angular speed.

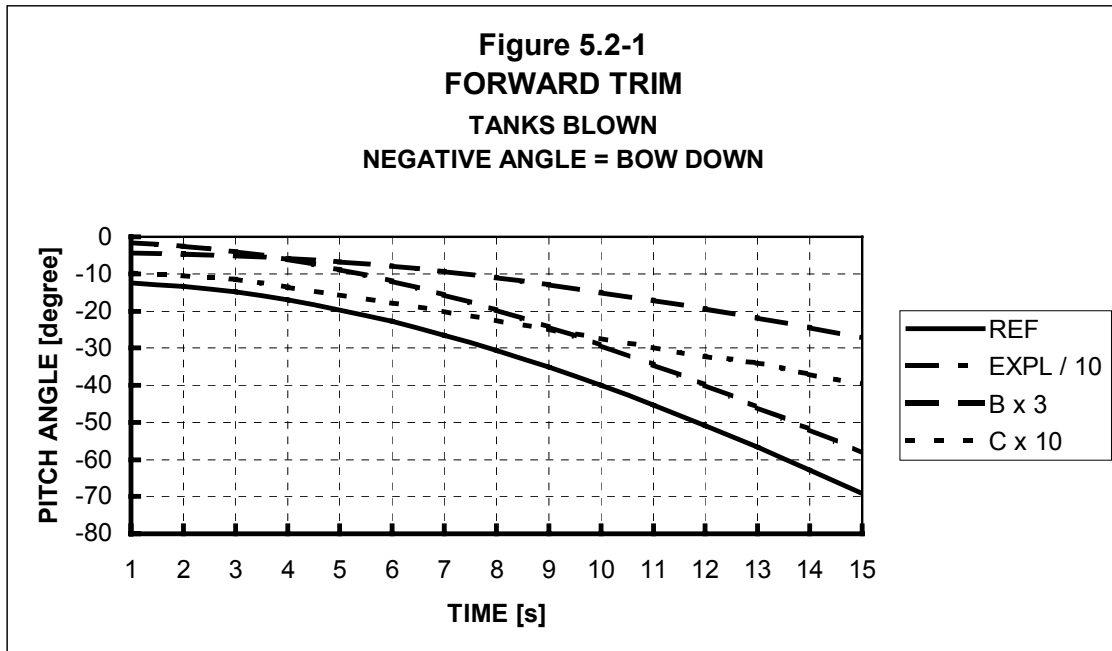
Equation 4 can be integrated over the time interval between t_0 and t to obtain ω . The resulting equation of ω as a function of t - where ω is $d\phi/dt$ - can be integrated numerically to yield ϕ as a function of t . For the reference characteristics of the above tables the result is plotted as the line "REF" in Figures 5.2-1 and 5.2-2 below. The graphs starts at $t=1$, that is to say after the effect of the explosion was extinguished after 1 second.

Figure 5.2-1 illustrates that the buoyancy of the empty aft and side trim tanks reinforces the effect of the lost weight and buoyancy of Compartment I and the forward tanks. The boat dives quickly to the bottom. The opposite of this effect is seen in Figure 5.2-2. The boat initially pitches forward under the explosive force, but then rights itself under the moment exerted by the weight of the ballast water counteracting the weight lost on the bow by its destruction.

The results obtained by this estimation are in line with results of much more elaborate models in use in the "submarine community" in the Netherlands. The input for these more complete models, being so elaborate, takes a long time to prepare. The estimation presented here only covers 10 to 20 seconds of only one motion - the rotation taken as a superposition on the submarine's translations in three dimensions, which are not considered.

The assumptions for three parameters in the estimation need further investigation. These are the actual magnitude and direction of the explosive force, the crossflow resistance to the rotational movement and the magnitude of the virtual mass of the water to be added to the rotational inertia. With reference to Figure 5.2-1 the following comments are made:

- The explosive force was calculated above. The compartment volume involved in the initial blast is taken as 80 % of Compartment I, assuming the decks gave way before the pressure hull broke open. This volume and the size of the breach in the pressure hull can not be

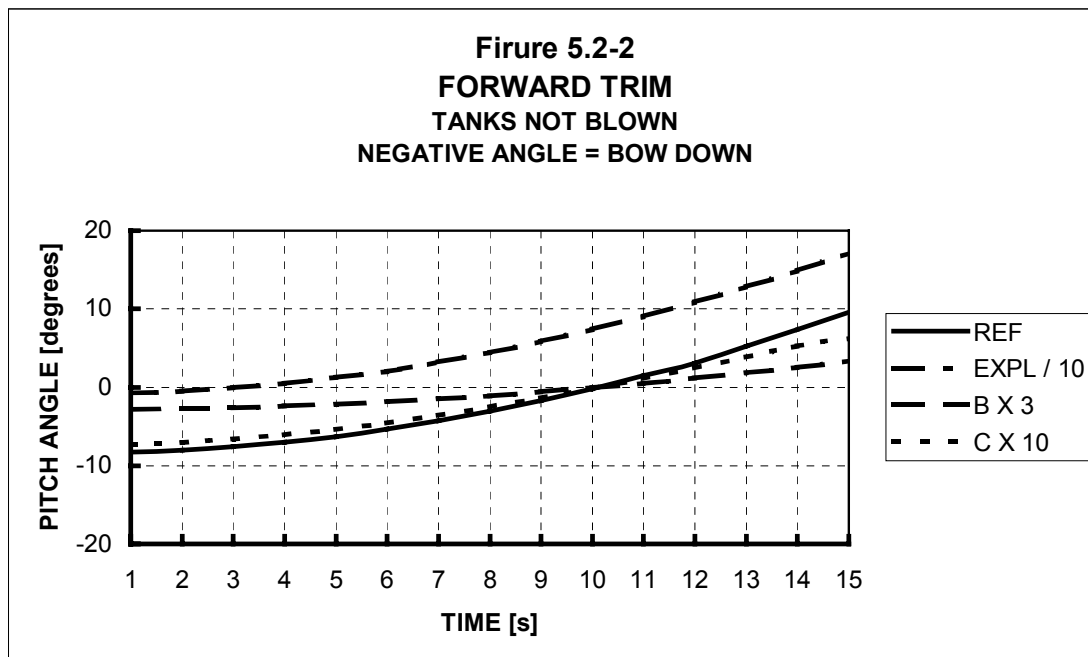


established exactly. If the initial volume was smaller the pressure would have been higher, if the hole were smaller the force would have been smaller. Also the force direction, taken here as perpendicular may actually have had a component in axial direction making the effective force smaller. Therefore the estimation was also run for a ten fold smaller force - "EXPL / 10" in the graph. As can be seen the initial abrupt change in trim of 12 degrees reduces to about two. The end result is the same with only two seconds delay.

- The cross flow resistance was estimated as being 8 times higher than the resistance in axial direction as derived from the propulsion power and maximum speed (taken as 33 kn) of the submarine. The effect of taking a tenfold higher value is seen in line "C x 10". The submarine trim down starts to lag behind the reference case more and more. In the time span of the graph it has become 5 seconds. This is still not very much while at the same time a ten fold higher resistance is thought to be exaggerated.
- The virtual mass effect on the inertia of the boat is the result of a mass of water that has to be accelerated in the flow around the submarine as it accelerates through the water. For the non-stationary flow around a sphere or cylinder the virtual mass is equal to the displacement of the object. For the reference case the value was taken as 1,5 times the displacement. The effect is taken into account by multiplying the rotary inertia by a factor - B - of 2,5. The influence of a 3 times higher multiplication factor is shown by the line "B x 3". The higher virtual mass has an effect comparable to the lower explosion force but continues to oppose

the submarine's motions, doubling the times to reach the same bow down trim. Again the difference is still less than 10 seconds.

The same parameter variation is presented in Figure 5.2-2. The differences are found to have the



same effect. Because the rotary inertia is larger - tanks not blown - the variations in trim angle are smaller and the parameter variations seem to be less emphasised.

Conclusions

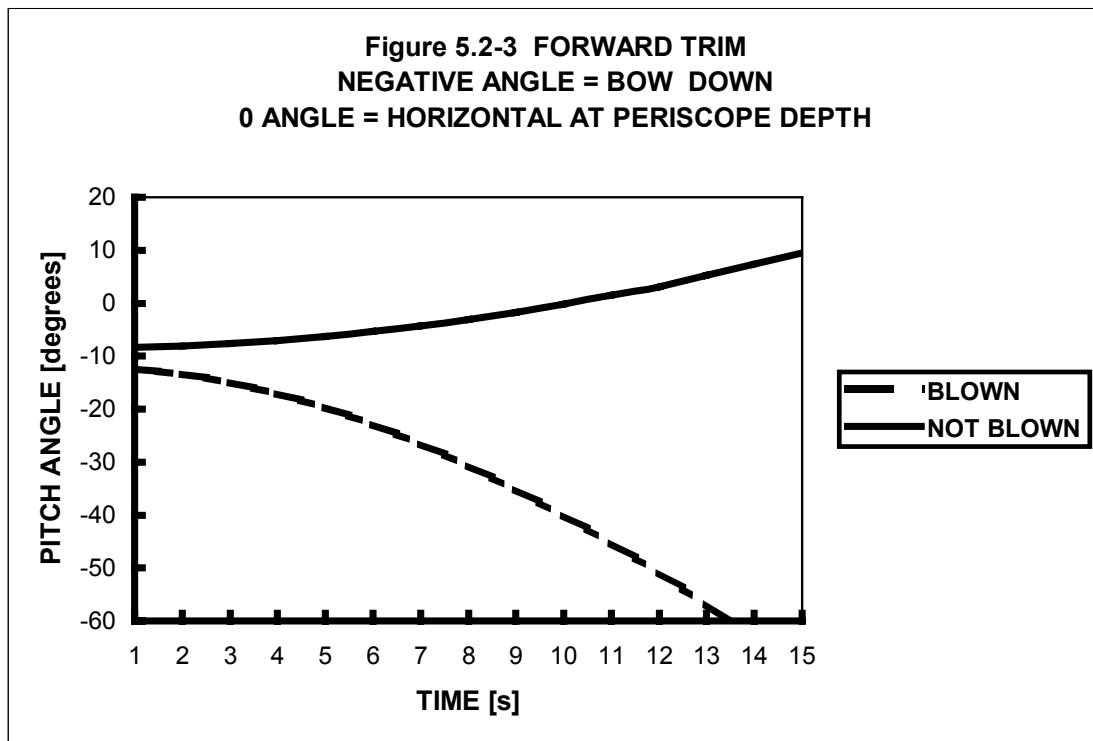
The submarine at or below periscope depth will have undergone transient changes in trim - possibly abrupt and large - from the effects of the explosion. The approximation, limited to this dynamic behaviour - the rotation in the vertical plane - treats two suppositions:

- The ballast tanks were blown after the first explosion in an attempt to surface the boat possibly including an increase of speed.
- The ballast tanks were not blown. (Either because the Command did not conclude that the first event was a disaster or, contrarily, was not capable to act anymore)

The results of the estimation are plotted in Figure 5.2-3. for both suppositions and show the very different outcome for the short period after the explosion has taken place. The trim angles of the boat are plotted as negative for bow down and vice versa for lifting the bow

The maximum up and down trim angles the boat can reach at periscope depth before hitting the bottom or surfacing the bow are indicated in the graph. The time starts at $t=1$, i.e. after downward influence of the explosion has dissipated. Its effect lasts 1 second. The following observations are made:

- The change in trim in the first second is much more abrupt than afterwards, 12 degrees down with tanks blown and 8 degrees with the ballast tanks still filled. The increased rotational inertia of water filled ballast tanks counteracts the result somewhat.
- The action of blowing the tanks has in fact accelerated the dive to the bottom. In the case where action was not taken the submarine may actually have surfaced, certainly if the boat had an appreciable forward speed.



- The submarine would have touched the bottom, after blowing its tanks, in a very short time: 10 to 15 seconds. The transient bow-down trim plus added forward speed must have caused an impact sending a shock wave through the submarine. After that happened the compartments aft of Compartment II would successively have flooded, settling the stern on the bottom.
- With water filled tanks - the other supposition - the boat's trim did not vary substantially from horizontal for 10 to 15 seconds after the first abrupt 8 degree bow-down motion: first the forward trim increased only to decrease again and change direction. As the flooding of the compartments progressed a downward angle would subsequently have developed. The submarine's forward speed, depending on its magnitude, would have created the "bow wave of sand" found on the bottom.

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Any errors that appear in this paper despite their efforts are solely the responsibility of the author.

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