THE SINKING OF THE SOVIET MIKE CLASS NUCLEAR POWERED SUBMARINE

A preliminary technical assessment of the potential radioactive inventory release into the marine environment associated with the Soviet Mike class nuclear powered attack submarine accident, Norwegian Sea, 7th April 1989.

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SINKING OF THE USSR MIKE CLASS SUBMARINE BOAT

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SUMMARY

At about 0940 hours on 7 April, 1989 a nuclear powered submarine boat of the USSR Northern Fleet surfaced about 150 miles SSW of Bear Island - the boat was obviously in some difficulty and with a fire raging on board. Shortly thereafter members of the submarine crew were sighted in the water and a few hours later, at approximately 1515 hours, the boat sank to the ocean floor, about 1800m deep.

Soviet statements have confirmed that the boat surfaced because of a fire on board. Attendant ships of the USSR fleet were unable to reach the boat before the sinking so the nuclear weapons acknowledged to be on board were not removed, although the Soviets have stated that both of the twin propulsion reactors were completely shut down. Thus the submarine sank with all of its radioactive materials on board. These radioactive materials include the highly radioactive fuel cores of the reactors, the activated and radioactive materials of the reactor structures, and the fissile material components of at least two nuclear weapons acknowledged to be on board by the Soviets.

The purpose of this preliminary study is to assess the quantities of the longer-lived or persistent radioactive materials, or source terms, that have been lost at sea with the sinking of the Soviet submarine. The report arrives at an assessment of the amount of radioactivity and compares this to the quantities of radioactive materials dumped by the UK from 1953 to 1982 at which time sea dumping of radioactive wastes was suspended by international resolve. This comparison can be used to assess the relative significance of the sinking of this submarine.

The study does not extrapolate the estimated radioactive source terms to an environmental or radiological significance of the sinking, although it is concluded that unless the submarine is recovered intact from the ocean floor, the by far greater part of the radioactive materials on board will disperse to the marine environment at some future time, if they are not doing so already.

SINKING OF THE USSR MIKE CLASS SUBMARINE BOAT

1 INTRODUCTION

This is intended as a preliminary study for a technical report on the radioactive hazard deriving from the accident and sinking of the Soviet MIKE class submarine off Bear Island on 7 April, 1989.

In this study we have identified the likely magnitude of the radioactive source terms on board the submarine at the time of the sinking, although we have not commented upon the radiological significance of the dispersion of these to the marine environment.

2 MIKE CLASS SUBMARINE BOAT

This vessel was the first of its type, a recently introduced class of Soviet nuclear powered submarine. In addition to this prototype, another boat of this class may be in or nearing commission.

The NATO identification of the Class is MIKE.

2.1 Commissioning and Service Role

This submarine was launched in or around 1983, underwent sea trials for about one to two years and finally entered service in 1984-1985. The service role of this submarine is as a 'hunter-killer' for anti-submarine warfare with conventional torpedoes and 4 to 6 short range nuclear missiles (torpedo tube fired), although the armament capability is likely to include 4 to 6 nuclear armed cruise missiles, which may be torpedo tube or deck tube launched. The class may include a nuclear sea mine or depth-bomb laying capability.

It is likely that the MIKE is a development class of submarine boat, as opposed to a potential production model such as the VICTOR class, and thus is primarily for the proving of prototype propulsion systems (including the reactor) and quiet-running (stealth) technology. If so, the general class is not likely to enter serial production. It is not unusual to have development classes of submarines and the Soviets also operate two SIERRA class submarines, which seem to fulfil the role as test vehicles for weapons.

The single known MIKE submarine was attached to the Soviet Northern Fleet and therefore operated from the Kola peninsula, most likely the Northern Fleet home port of Severomorsk or Severodvinsk.

2.2 Displacement, Size and Crew

The MIKE class submarine displaces approximately 9,700 tonnes (dived), and has a length and beam of about 120m and 12m+ respectively.

A notable feature of the MIKE class boat is the wide beam which at 12m+ is considerably larger than the 10.1m beam of the Royal Navy SSBN (Polaris) submarines, although the MIKE class is shorter than the 130m RN boats.

It is believed that this class of Soviet submarine is extremely quiet running and difficult to detect. One feature to assist noise suppression and non-detection would include the double hull cavity incorporated within the larger than usual overall hull cross section.

In fact, Jane's[1] reports a beam of 12m and a displacement of 6,400 tonnes, although these figures contradict the generally upheld opinion (eg, US Dept of Defence) that the MIKE submarine is the largest of the fleet with a displacement of about 10,000 tonnes.[2,3]

As with the submarine size, there is some doubt about the normal crew complement, which is variously stated to be 69 and 95 submariners.

2.3 Armaments

The MIKE submarine can probably accommodate SS-N-15 rocket-propelled nuclear depth bombs, SS-N-16 ASW (anti-submarine warfare) missiles and conventional (peroxide) and nuclear tipped torpedoes. The submarine might also be capable of carrying the longer range SS-N-21 SLCM (sea-launched cruise missile).

2.4 Operating Performance

The MIKE class is capable of remaining submerged at sea for extended periods, as can all nuclear powered submarines, with full oxygen and desalination recovery equipment.

The submarine is believed capable of operating at a maximum depth of 300-350m with a cruising speed of 38 knots.

2.5 Propulsion

The MIKE class submarine is powered by twin nuclear reactors, raising steam to drive turbo-alternators which, in turn, power the main propulsion motors.

As noted earlier, it is believed that this class of Soviet submarine is quiet running and difficult to detect. Other features to assist non-detection would include the inner hull cavity (steam cycle) condensers and, perhaps, water jet propulsion rather than a contra-rotating propeller.

2.6 Reactors

Reactor details are very scant. However, it is believed that the MIKE class is fitted with two liquid metal cooled reactors.

It is only possible to speculate on the type of nuclear reactor. It is unlikely that these would be fast reactors, which operate without significant neutron moderation, because of the large volume that would be taken up by radiation shielding materials within the confined machinery spaces of the submarine.

The United States Navy has also developed a liquid metal (sodium) cooled reactor known as the S7G which was to be installed in the SSN Seawolf class. The US experienced development difficulties with this reactor but recent development work (reported briefly in the 1987 Nuclear Propulsion Programme, Committee on Armed Services, House of Representatives[4]) indicates that this type of reactor may be under further consideration for service within submarine boats.

Liquid metal cooled reactors provide for a compact design suited to the confined hull space of a submarine. There is also a significant thermodynamic advantage in that, unlike a water cooled reactor, it is not necessary to highly pressurise the reactor primary containment to inhibit boiling of the coolant. The primary coolant pumps may be electromagnetic in operation, with no moving parts to generate noise.

In fact, the reactor design may include a composite of an inner water-cooled, compact fuel core operating at high pressure within a small jacket, all of which is encased in a liquid sodium or lead-cadium-bismuth (essentially, a solder alloy) bath. Moderation may be introduced via graphite wedges acting between the plate fuel elements.

If so this design provides two liquid-metal/water interfaces. One disadvantage of this design is that liquid metals, particularly sodium, are violently exothermically reactive with water. A steam generator tube leak could result in a serious outbreak of explosion and fire on board the submarine.

However, this should not be taken to imply that the source of the fire on board the MIKE submarine was with a malfunctioning reactor. Naval ships are always at high risk of fire and, particularly, the conventional weapons (and nuclear weapon tampers), if based on peroxide, are acknowledged to be unstable and at high risk of fire. Electrical malfunctions, batteries and short-circuits are also likely sources of possible fires on board submarines, and one of these is thought to have been the cause of the fire on the submarine.

3 RADIOACTIVE INVENTORY

The total radioactive inventory on board the submarine at the time of sinking would have comprised the reactor components and fuel cores, together with the fissile material content of any nuclear weaponry aboard.

3.1 Reactors

The total radioactive materials inventory of the reactors comprise the fission products yielded by the irradiation of the fuel and, quite separately, the activated materials of the reactor core and primary coolant circuit.

Without a certain knowledge of the reactor type, liquid-metal cooled or not, and whether sodium, lead-bismuth or some other variety, it is not possible to determine accurately the total reactor radioactive inventory. However, the by far greater part of the radioactivity contained within a nuclear reactor (land or ship based) is within the irradiated fuel. Since the irradiation of the fuel, and hence the gross radioactivity, is related to the power output of the reactors, the (radio)activity inventory of the coolant is of secondary importance in this respect.

3.1.1 Fuel Fission Products

Typically, US and UK nuclear submarines are refuelled during the major docking refits only,[5] because of access difficulties to the reactor cores. These refits occur about every six to seven years of service operation. The reactor internals are only accessible through the hull plating which has to be cut away and removed for the refuelling operation. It is likely that the Soviets follow a similar practice. **FIGURE 1** shows the reactor and machinery section of a Royal Navy nuclear submarine, which is illustrative of the cramped machinery space of all nuclear submarines.

Thus nuclear fuel for submarine reactors has to remain in the reactor core for long periods of service. As the fuel is irradiated or burnt-up the reactivity worth of the fuel decreases. To compensate for this decrease in excess reactivity the fuel is either highly enriched (as in the US and UK submarine reactors) or, if low-enriched fuel is used a greater mass of fuel is charged into the reactor core.

Typically, reactor fuel is usually in the form of metal plate uranium alloy or dioxide, and clad in zirconium or stainless steel. Other variants of fuel include ceramic coated dioxide pellets, but such detail of the fuel type is not particularly important for our analysis.

US submarine plate fuel is highly enriched in the fissile ^{235}uranium content with 97.3% enrichment. This compares, on one hand, to weapons grade uranium which is typically of a slightly lower enrichment of 95% and, on the other hand, to commercial reactor fuels which may be enriched up to 4%.

Fuel within the reactor is progressively irradiated during operation so the 'burn-up' or accumulation of radioactive fission products increases with service life. Essentially, the fission product content of the fuel relates to the total power output produced by the fuel charge within the reactor - the greater the service of the fuel core then the greater the radioactivity.

Thus the first step in assessing the radioactive source term of the reactors is to determine an estimate of the service activity of the reactors, via their power rating.

3.1.2 Power Rating of the Reactors

The power rating for each of the MIKE submarine reactors is not available at this time, although the total power requirements might be reasonably assessed from the propulsion requirements with some allowance for secondary functions.

Jane's[1] suggests a tentative figure of 60,000 shaft horsepower so, on this basis, the reactor output would be calculated as follows (and working backward from the shaft power to the reactor output):

shaft horsepower 60,000 shp = 45.0MW

this figure must be increased to allow for losses in the reduction gearing and steam raising system:

say mechanical efficiency @ 90% => 49.8MW
say Rankine steam cycle @ 30% => 166.2MW$_t$
(loss of power to waste heat)

reactor services @ 15% => 191.1MW$_t$
(some power drawn to
reactor cooling etc)

boat services, say 15MW$_t$ => 206.1MW$_t$

split between two reactors. Thus we have a power rating of, say, 103MW$_t$ for each of the two reactors on board. For comparison, this is about 1/40th the thermal output of the landside Sizewell B PWR nuclear power station.

The power of the submarine reactors might be roughly cross-checked by working through the propulsive effort required to propel the boat at 38 knots. For a fully submerged, bluff body (bullet shape) cruising at 38 knots the propulsive effort required principally derives from the drag coefficients for the areas of the main hull and conning tower presented to the water; these have form ratios of 1:9 and 1:7 respectively. Thus we can calculate the force required (in newtons), and from that the power output:

main hull 1.74 10^6N
conning tower 0.15 10^6N
37.7MW_s

propulsive efficiency @ 90% => 41.9MW
mechanical efficiency @ 90% => 46.6MW
Rankine steam cycle @ 30% => 155.2MW_t

reactor services @ 15% => 178.5MW_t
boat services, say 15MW_t => 193.5MW_t

or, say, 97MW_t for each of the two reactors on board.

Reasonably therefore, each reactor of the MIKE submarine might be assumed to produce about 100MW_t. For comparison the Royal Navy Trafalgar class submarines (which are smaller and slower than the MIKE) are powered by a single PWR reactor believed to be of approximately 60MW_t rating.

3.1.3 Reactor Core Fuel Loads

Published data on other marine propulsion reactors is sparse, although details are available[6] for the early nuclear powered merchant ship NS Savannah, whose reactor was essentially derived from the US naval reactor programme.

This ship, commissioned in 1962, was powered by a pressurised water reactor utilising slightly enriched (4.4%) uranium fuel. The single reactor rating was 76MW_t producing 20,000 shaft horsepower with an additional 2.2MW_e electricity generating capacity. With this relatively low level of fuel enrichment, the NS Savannah reactor core required a total uranium fuel load of 7,111 kg (7 tonnes) which was replaced every sixth year of operation following a burn-up of 7,300 (average) to 22,000 (maximum) MW-day/tonne (MWd/t).

On this basis, the fuel cores for each of the 100MW_t MIKE submarine reactors might include, say, 10 tonnes of moderately enriched uranium.

A reliable assessment of the radioactive inventory of the fission product yield for the fuel of the MIKE submarine is not really possible in the absence of further data.

However, a rudimentary assessment of the fuel load and radioactive inventory can be completed if a number of key assumptions are made. The MIKE submarine was commissioned in about 1985, although up to two years of previous sea trials may have been undertaken before final commissioning into full operational service. If the Soviet Navy has adopted the six year refuelling cycle then the fuel within the reactor cores would have reached a moderately high level of burn-up by the time of the sinking. It might then be reasoned that the higher enrichment used in military naval reactors, the need for economy of space versus the civil reactor need for fuel economy, and the decreased requirement for fuel economy in the military as argued by US Admiral Rickover, would result in a higher burn-up than is used in nuclear powered naval ships such as the NS Savannah. Thus if it is assumed that the maximum fuel burn-up rating for these submarine reactors with highly enriched fuel is <u>at least</u> as high as a modern PWR with only slightly enriched fuel at 34,000MWd/t, then the <u>minimum</u> radioactive inventory of the fuel will be about the same as a modern PWR irradiated fuel.

However, if the reactor fuel load is properly assumed to be highly enriched (at 97% or thereabouts[4]), then the average burn-up equivalent might be similar to fast reactor fuel at 80,000-100,000MWd/t.

To determine the core fuel tonnage (amount of uranium in the reactor core), we may assume that this class of Soviet submarine is designed to refuel at six year intervals, that it spends about two-thirds of the time at sea (the rest undergoing minor refits in dock) and at 50% power (ie, it does not travel full-speed all the time). The total energy generated throughout this period is therefore:

2 reactors x 100 million watts x 50% power x
365 days x 6 years x 66% time at sea

= 144,540 MWd

so, for an average fuel burn-up of 100,000MWd/t, the minimum fuel core will be:

144,540/100,000 = 1450 kg U

or about 725kg of enriched uranium fuel per reactor core. However, at high fuel burn-up, reactor poisons accumulate and decrease power output per unit mass of fuel, so that extra fuel mass would probably be included in the core. Reasonably, the reactors might be expected to be fuelled to about twice the nominal amount, for about 1.5 tonnes of uranium in each core.

On this basis, it would be expected that the Soviets utilised highly enriched fuel at a high burn-up. Hence the reactor cores are each likely to contain the lower mass of fuel yielded by the foregoing analyses, that is about 1.5 tonnes of highly enriched uranium in each reactor core.

If after 4 years service operation, an average fuel burn-up of 30,000 to 50,000 MWd/t had been achieved, the total radioactive fission product and actinide inventory for the fuel on board the MIKE submarine at the time of the sinking would be approximately 4 to 6 $\times 10^{17}$ Bq (11 to 16 million Ci), excluding tritium and the shorter lived radio-isotopes such as ^{131}Iodine.

3.2 Reactor Activated Materials

Activated materials within the submarine are those directly associated with neutron bombardment from the nuclear processes within the reactors.

means that as the metal cools the constituent parts separate (precipitate out), forming grain boundaries and micro-fissuring when in the solid state. Essentially, the different constituent elements in the alloy undergo liquid/solid phase changes at different temperatures, and varying 'regions' of a given minority constituent may be solid or liquid within a mainly liquid majority constituent (or vice versa).

The result is that under conditions other than the designed operating condition (ie, if the reactor is shutdown in an emergency, and unexpected temperature changes occur in the coolant), the coolant may become very non-homogeneous, and develop a hardened, fissured structure. Such a non-homogeneous structure would not provide an effective barrier against the migration of the fuel fission products from the reactor core to the marine environment.

apons

e complement and fissile material inventories of
e weapons carried on board the MIKE submarine
e unknown, though they are said to include two
clear warhead-armed torpedoes.

indeed they are on board, such weapons would
clude constituent parts of enriched uranium and
utonium, perhaps with total fissile material
ncluding enriched uranium) content for each
apon of 15 to 25kg.

addition, the weapons would likely include
ryllium reflectors which, although not in an
ctivated or radioactive state, represent a very
ic material.

alone. Under conventional reactor close-down conditions, auxiliary services continue to remove this heat from the reactor core.

In the sinking submarine the auxiliary services would soon cease to function and there would arise an accumulation of the fuel decay heat. This heat would initially dissipate in the reactor liquid coolant and, thereafter, transfer to the marine environment via water in contact with the reactor containment. The surface area of the containment, on the order of 100-200 m^2, might provide for a nett surface heat transfer of $0.1 MW/m^2$ to the surrounding sea water, although it is likely that the submarine's metallic internal structures would provide a greater heat transfer area overall. Thus the heat transfer capability is probably sufficient to prevent heat build-up in the core regardless of auxiliary service failure.

If the containment or any part of the primary liquid metal coolant loop failed during the submarine's descent to the ocean floor, then the abrupt meeting of the molten metal coolant and sea water could have generated a severely damaging steam explosion, resulting in failure of the fuel cladding and further damaging the reactor containments. If the coolant is sodium there there would also occur a violent exothermic chemical reaction between the water and sodium.

If the reactor containments remained relatively undamaged during the descent then, and depending on the efficacy of heat transfer from the reactor cores, the liquid metal coolant is likely to have partially solidified. The volumetric shrinkage of the coolant (which is significant for lead-bismuth alloys) would have provided for further yielding of the outer containment.

Thus containment-failure scenarios of two distinct timescales are possible. The reactor containment could have been severely damaged during the descent, in which case the migration of fission products and radioactive materials from the reactors could proceed relatively unimpeded, perhaps entering the marine environment immediately - that is within a few hours or in timescales of days or weeks. Or, should the reactor containment somehow withstand the high pressures, degradation of the structures will proceed via a number of corrosive, ageing and gas generation processes - these processes, combined, might result in a radioactive release to the marine environment in timescales of months or years.

4.2 Recovery and Salvage Operations

The timescale of containment failure may well be shortened if, as news reports suggest, the Soviets are considering raising the submarine.

A US project (Glomar Challenger, 1974) to raise a previous sunken Soviet Golf class nuclear submarine is known to have broken the back of the vessel - such a violent event would be almost certain to also rupture the reactor containment.

4.3 Nuclear Weapons

We are unable to assess the safety or containment performance of the nuclear weapons that may have been on board the submarine at the time of the sinking.

However, it is probably safe to say that the effect of such high pressures on the nuclear warheads, if present, would not promote a nuclear explosion. In terms of a radioactive release through pressure-related failure of the warhead casing, the radioactive source terms of the weapons would be small compared to the reactor source terms, although account should be taken of the very much higher radiotoxic potential of plutonium compared to other radionuclides.

5 PRELIMINARY FINDINGS

The sinking of the USSR MIKE submarine occurred on 7 April, 1989. Lost with the submarine were a significant quantity of radioactive materials:

5.1 Radioactive Source Terms

Although it is not practicable to determine the quantity of radioactivity that accompanied the sinking to the ocean bed with any great reliability, the total radioactive source term of the MIKE submarine is certainly significant.

Comparisons might be usefully made with the previous consignments of radioactive waste dumped at the North-East Atlantic Dump Site by the United Kingdom between the years 1952 to 1982.[9] During this period the UK dumped materials with a total (radio)activity of 16,883 Ci of alpha-bearing wastes and 930,930 Ci of gamma/beta emitters - the sinking of the MIKE Class represents some 10 to 20 times as much.

5.2 Nature of the Radioactive Materials Lost

A very large proportion of the submarine's activity would be classified as HLW (High Level Waste), including actinides and alpha-emitting wastes.

Again for comparison, this highly active and highly radiotoxic form of radioactive material has never been permitted to be dumped at sea - the UK sea dump was limited to the so-called low- and intermediate-level radioactive wastes. In the UK high-level radioactive wastes are required to be safely stored for at least fifty years and thereafter the disposal has to be completed in a contained manner. At this time, no wastes classified as HLW have been disposed of directly to the environment and the route and means of high-level waste disposal has yet to be determined in the United Kingdom.

5.3 Weapons and other Radioactivity

We are unable to account for the additional radioactive inventories of any weapons carried on board and no quantitative account has been taken of the total activation products of the liquid metal coolant believed to be a feature of the two reactors on board this class of submarine.

5.4 Other Sinkings of Nuclear Powered Submarines

Of the other nuclear submarines that have been lost at sea, the US Navy claims[4] that only trace amounts have been detected in the vicinity of the two sunken US boats, while the Soviets, who are believed now to have lost four nuclear submarines at sea, have published no data whatsoever.

6 CONCLUSION

We conclude that the sinking of the USSR MIKE class submarine on 7 April, 1989 took a significant amount of highly active and toxic radioactive materials to the bottom of the sea. If the submarine is not recovered intact then it is, in our opinion, inevitable that all of this material will disperse to the marine environment.

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REFERENCES

1	JANE'S	Jane's Fighting Ships, 1987-88, Jane's Publishing Co, London, 1988
2	IPS	Neptune Papers N° 2, Nuclear Warships and Naval Nuclear Weapons: A Complete Inventory, J Handler , W Arkin, May 1988, Washington DC
3	NRDC	Nuclear Weapons Data Book, Vols 2-4, National Resources Defense Council /Ballinger Co, 1984, Washington DC
4	HR	Naval Nuclear Propulsion Program 1987, House of Representatives Committee on Armed Services, 99th Congress, February 1986
5	L&A	The Proposal to Construct and Operate a Radioactive Waste Store at HM Royal Navy Devonport Dockyard, Large & Associates, RL1829-1, October, 1988
6	IAEA	Directory of Nuclear Reactors, VII, Power Reactors, International Atomic Energy Agency, 1968, Vienna
7	NAGRA	Inventar und Eigenschaften der Radioktiven Abfaekke in der Schweiz, Tech R NAGRA NTB84-47, NAGRA, Baden, 1984
8	TIMES	The Times newspaper, "'No Nuclear Threat' from Scuttled Sub", 10 April, 1989, London
9	HANSARD	Answer to Parliamentary Question 7746, 18 December 1983,

GLOSSARY

alpha gamma/beta	different types of ionising radiation
burn-up	essentially, the number of fissions that have been completed in uranium fuel stock or the degree to which the energy available in the fuel has been used up, usually expressed in terms of MW day per tonne (MWd/t) of fuel
Ci	Curie, a unit of radioactivity
enriched ^{235}U	uranium fuel stock in which the naturally occurring 0.7% of the fissile ^{235}U atom has been increased or enriched, this is achieved by displacing the other resident ^{238}U atom by, typically, a gaseous diffusion process
fissile	such as the fissile atom of uranium, the ^{235}U atom, which is capable of disintegration when encountering a neutron. The disintegration yields fission products from the parent atom, and a large amount of energy
form ratios	essentially, the shape of a body required to assess the resistance to flow through an incompressible fluid such as water - a sphere as a form ratio of 1 and a whale, for example, a form ratio of about 10 - the higher the form ratio then, generally, the smaller the drag
Glomar Challenger	the unsuccessful venture to raise the USSR submarine by Howard Hughes Corp
MW_t	Mega-Watt or 1 million Watts, a unit of power. The subscript **t** or **e** refers to the unit expressed in thermal (heat) or electrical power respectively