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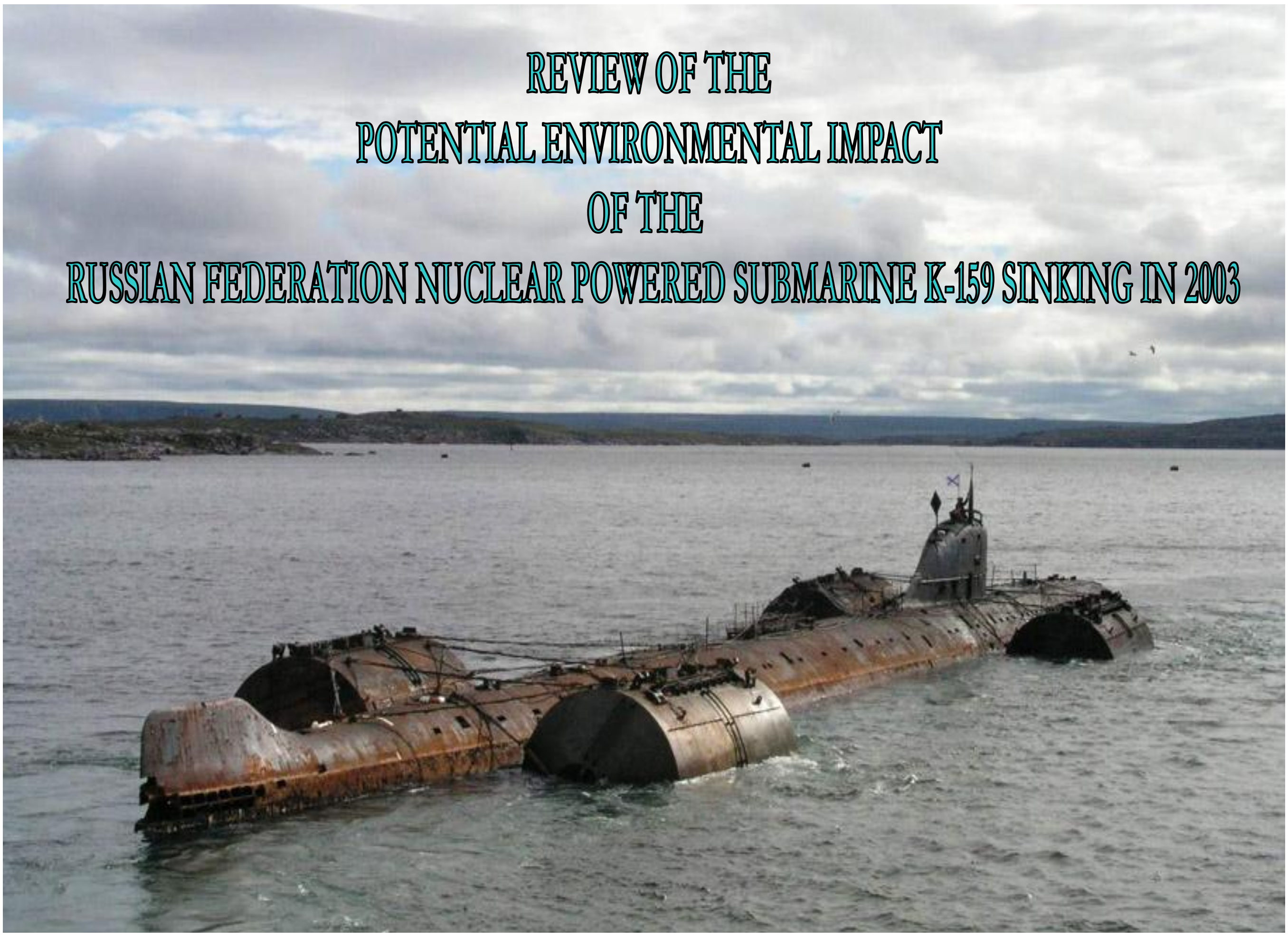

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REVIEW OF THE POTENTIAL ENVIRONMENTAL IMPACT OF THE RUSSIAN FEDERATION NUCLEAR SUBMARINE K-159 SINKING IN 2003

SUMMARY:

This paper reviews the potential radiological impact to the marine environment arising from the sinking of the Russian Federation Northern Fleet nuclear powered submarine K-159 in late August of 2003.

It is noted that before the longer term environmental impact can be assessed, further information is required from the Russian Federation authorities, particularly the Northern Fleet, to determine the condition and quantity of any fuel remaining on board, the means and measures deployed to isolate the nuclear plant when the K-159 was withdrawn from service in 1989-1993, together with knowledge of other local-specific factors relating to the wreck undersea area and, particularly, the robustness of the immediate containments of the fuel (cladding, primary circuit, submarine hull reactor compartment) and the extent to which these might have been damaged by the sinking.

It is concluded that it is a certainty that at some time in the future the nuclear plant of the K-159 could have a not insignificant impact on the marine environment – if there is irradiated fuel on board, because the short- and interim-lived fission products have mostly decayed since the reactor plants were closed down and with the natural radioactive decay now dominated by long-lived radioisotopes, there is little benefit to be gained in delaying any salvage or entombment options to mitigate the radiological impact. Finally, although this review has not considered the public perception of the risks of the wreck of a nuclear submarine abandoned at the bottom of the fish-rich Barents Sea, the fish exporting industries of Norway and Russia could suffer dearly should the public become aware of any radioactively contaminated fish catches from the Barents Sea.

K-159 NUCLEAR POWERED ATTACK SUBMARINE

The K-159 is a November class SSN Attack class submarine originally constructed at the Severodvinsk shipyard being commissioned in 1963 and laid up in 1992 or earlier in 1989.

The first of the Class, *Leninskiy Komsomolets*, was commissioned in 1958 being the first Soviet operational nuclear powered submarine. Fifteen submarines of this class were constructed of which one sank in the Atlantic 300 miles off Spain in 1970, two other boats were discarded due to reactor problems (possibly mishaps), a further boat was unsuccessfully converted with a liquid metal reactor, and the remainder of the Class was withdrawn from active service between 1989 to 1993, all being laid up in the bays of the Kola since that time.

1 K-159 in Operation at Sea

Construction comprises carbon steel, externally ribbed pressure hull entirely enclosed with a casing (flood hull), 5,300 tonnes displaced and of 110m length and 8-9m beam. The K-159 was powered by two VMA 70MWt pressurised water nuclear reactors located in N° 5 compartment, generating a total of 30,000shp through two shafted propellers. The nuclear reactors of the K-159 would have remained permanently shut down[1] since withdrawal from active service (1989-93), although because of the spent fuel storage limitations on the Kola both reactors are likely to have contained full cores of spent nuclear fuel at the time of foundering.

SINKING OF THE K-159

During the early morning of 30 August, 2003 the K-159, whilst under tow and strapped to floatation pontoons, encountered a strong sea state causing it to founder and sink in the Barents Sea some 5km northwest of Kildrin Island. Nine members of the ten skeleton towing crew were lost with the submarine.

The position of the wrecked submarine has been fixed at about 200m depth of seawater, although the orientation to the sea bed and structural state of the hull is unknown.

2 K-159 under tow with floatation pontoons

1 Russian practice when laying up the nuclear propulsion plant, when the plant has reached 'thermal rollover', about one year following reactor shut down, is to replace the primary circuit water coolant with a boronated fluid (probably ethyl based) charged at atmospheric pressure, lock down the control rod assemblies and to physically sever power cables to the control rod drives – it is not known if this process had been completed on the nuclear plant of the K-159.

Potential Environmental Impact of the K-159

Radioactive Source Term

Putting aside the conventional toxins[2] contained within the hull of the K-159, the potential (radio)active source term options are as follows:

Table 1 – Potential Source Terms of K-159

	Condition of the Reactor Cores	Radioactive Source Term[3] TBq	Likelihood - Comments
i)	Defuelled at some following lay-up	6.10^3	**Unlikely** - fuelling storage crisis on the Kola quite desperate[4] - source term based on activation of reactor pressure vessel and lifetime build up of operational CRUD[5] deposits throughout primary circuits of both reactors for a Royal Navy generic submarine reactor.
ii)	Both reactor cores fuelled with fuel last operated and irradiated prior to lay up in 1989-93 – each reactor core contains about 800kgU of irradiated fuel, originally zoned between 20 to 40% HEU enrichment	$0.5.10^5 + 6.10^3$ for 20 to 40% enriched fuel total plutonium content would comprise ~0.75g per MWday – say, 4.5kg per reactor	**Most Likely** - fuel remaining in reactor cores since 1989-93 without adequate water chemistry on primary circuit with significant cladding and fuel bundle corrosion – source term assumes each reactor 70MW nuclear plant that has operated at full power for an equivalent of 600 days, with a 10 years shut down decay, mostly Sr-90, Cs-137 and beta-gamma emitters.
iii)	As for ii) but with additional unbottled irradiated fuel assemblies loaded into each reactor compartment[6]	$0.5.10^5 + 6.10^3$+ additional fuel	**Possible** – as a result of the irradiated fuel crisis and it is possible that the K-159 was being moved from Gremika to Andreeva Bay or Polyarny.
iv)	As for ii) or ii) but with additional irradiated fuel loaded into the floatation pontoons	$0.5.10^5 + 6.10^3$+ additional fuel	**Possibility but Unlikely** - again because of the mounting irradiated fuel crisis the transfer and/or interim storage of fuel sometimes by the most ad hoc of means should not be discounted.[7]

Environmental Factors

Putting aside local factors in order to determine a gross effect, for the assumed case of the K-159 submarine twin reactors being fully fuelled – case ii) – the release of the entire inventory from the submarine being uniformly dispersed over a sea area of, say, 200 by 200km at an average depth of 200m,[8] would result in a mean concentration of fission products of 50kBq per m^3 seawater which compares with the present background levels of below $1kBq/m^3$.[9] Similarly, such a full release scenario suggests the Cs-137 uptake and reconcentration in fish would be of the order 80 to 100 Bq/kg.

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2 Conventional toxins bound into the construction and equipment of the submarine include gels used in the hydraulic systems, diesel fuel, battery components, crocidolite, chrysotile and amosite asbestos based materials used extensively in earlier boats, anti-fouling paints, PCBs and dioxins, etc..

3 Published source terms for Russian Federation submarine (single) reactors vary considerably (eg 2.76E+15 to 0.25E+17 bq) and, accordingly, some caution should be applied to the figures cited here

4 17th Contact Meeting of the Contact Expert Group, IAEA of November 2003 at which the Head of the Russian Ministry of Atomic Energy's Department of Ecology and Nuclear Installation Decommissioning stated at that time about 130 reactor cores remained in laid up submarines with first priority being given to clearing the 118 or more cores in store on onshore bases and in nuclear service ships. Although reports vary, as of May 2000 the Northern Fleet had approximately 28 operational nuclear-powered submarines and two nuclear-powered cruisers. A total of 117 Northern Fleet nuclear-powered submarines had been withdrawn from active service by May 2001. Of this total, 43 submarines have not been defuelled and just fourteen submarines had been dismantled as of December 2000.

5 CRUD – Chalk River Unidentified Deposits – US jargon for deposits of minerals etc on the linings of pipework etc, in this case radioactive magnetite layers rich with Co^{60}.

6 This is the condition of a number of sealed submarine reactor compartments that were dumped in the bays of the nuclear weapons test island Navaya Zemlya.

7 Although the floatation pontoons appear to be remarkably similar in size and shape to a submarine reactor compartments (after the compartment had been isolated by topping and tailing the submarine hull), there is no evidence of the external ribbing that characterises Soviet/Russian submarine pressure hull fabrication.

8 A water column of $8.10^{12}m^3$, although the eventual long term dispersion volume would be much larger, say the entire North Atlantic Basin of about $10^{16}m^3$.

9 Namjatov, Aleksey (2001). *Modern Level of Radioactivity Contamination and Risk Assessment in the Coastal Waters of the Barents Sea*, Northern Studies Working Paper – see also Lisovsky, I.,Petrov, O, Belikov, A. (1996): *Radioactive contamination of the Arctic by the North fleet of Russia. In: M. Balonov (ed.). Radionuclides in the Russian Arctic. Part 2 of a report to the Arctic Monitoring and Assessment Programme, Oslo.*

This gross analysis provides only a sense of the environmental impact, assuming as it does a single source with uniform dispersion in deep water. However, real sources of radioactivity located in shallow waters of high biological production pose considerably greater threats to the marine environment than a submarine sunk in deep waters,[10] and the impact is more than likely to be inconsistent in account of local-specific factors. Although there are relatively well established models[11] for predicting the impact of the release of a radioactive source in shallow waters, local-specific factors such as sea bed structure, prevailing currents and the relative calmness of the undersea weather situation will determine the rate of onset and ultimate level of radioactive transfer to the environment.

In assessing the hazards of the *Kursk*[12] recovery operations, the environmental and radiological effects of a hypothetical discharge of radionuclides from the *Kursk* during salvage, on the basis of instantaneous release scenario, was undertaken to assess local, medium- and long-scale, regional and long-term effects. The results obtained showed that for the worst case scenario (instantaneous release), the activity concentration in the water column increased significantly only in a relatively small area and for a relatively short time period and that the bottom contamination increased by one or two orders of magnitude from the background level in the salvage area. However, it should be noted that the release fraction assumed was for relatively new fuel of low burn-up (compared to the K-159 old fuel of high burn-up) and that the *Kursk* salvage site was about 100km out in the bay subject to high dispersal currents (compared to the somewhat sheltered location of the K-159 sinking site).

Local-Specific Factors

For the Barents Sea there are a number of sources of radioactive intrusion – these derive from fuel reprocessing plants deep inside Russian, with radioactive wastes and effluent being carried by the Rivers Ob and Yenisey [13] into the Kara Sea; from the United Kingdom Sellafield and Dounreay fuel and reprocessing plants also feeding a complex menu of radionuclides into the area from the North Atlantic; and past scuttling of nuclear submarines around Novaya Zemlya and radioactive waste dumping into the Kara Sea;[14] and, of course, there is the continuing wash out of the atmospheric and shallow underground nuclear testing undertaken in past decades by the Soviets. Locally, there is the radioactive contamination of the area from the poorly managed irradiated fuel and radioactive waste stores across the Northern Fleet military sites of the Kola.[15]

This total 'background' level of radioactivity can serve to mask and confuse the introduction of radioactivity from a new source such as a sunken nuclear powered submarine, so much so, that localised monitoring of the wreck site cannot be entirely relied upon to provide reasonably advanced notice of an impending release.

Also, the staging of any release into the marine environment is ordered by the surety of each of the three levels of containment enclosing the reactor fuel. If, for example, the pressure hull containment of the reactor compartment fails first, then the release might be expected to be progressive, determined in both onset and rate by the nature of failure of the remaining reactor primary circuit and individual fuel sheathing (cladding) containments. In this slow and progressive failure scenario (Scenario a) there might be sufficient time to enable some countermeasure action, such as entombment of the reactor plant, to stem the radioactive release.

If, on the other hand, the outer reactor compartment containment holds whilst the fuel sheathing and primary circuit utterly fail, then upon the inevitable eventual failure of the hull the release could be immediate

10 Six or more fully fuelled submarines are located from accidental sinkings sunken at 2000 to 2000m depth in the Atlantic Ocean and Barents Sea and these are not reckoned to represent a substantive threat because of the relative inactivity of the marine biota at such depths. The largest known potential sources on the seabed of the Barents and Kara Seas are 16 dumped reactors, mostly of military origin, six of which contain spent nuclear fuel and, in addition, a screening assembly with damaged fuel from one ship reactor (nuclear icebreaker *Lenin* - about 60% of the core) has been dumped separately.

11 For example Poseidon 3.0 – see Lepicard S., Raffestin D., POSEIDON 3.0 – Logiciel *pour l'évaluation des impacts radiologiques en milieu marin*, CEPN-L-99/2, 1999.

12 The Russian Federation nuclear powered submarine *Kursk* that sank in August 2000 which sank in similar sea conditions in the Barents Sea but at 110m depth, and its subsequent successful recovery operation by the Smit-Mammoet consortium – see Large, J H, Davidson, P & Jones H *Assessment of the Nuclear Risks and Hazards in the Recovery of the Sunken Nuclear Powered Submarine Kursk*, Soc of Naval Architects and Marine Engineers, Sans Fransisco, November 2003

13 Releases to the Arctic seas from rivers (most importantly the Rivers Ob and Yenisey) are presently at about 10 TBq of strontium-90 and 1 Tbq of cesium-137 are transported to the Kara Sea annually along the River Ob. The Mayak facility near Chelyabinsk (Russia) is located more than 2000 km upstream of the Ob outlet into the Kara Sea, but is close to the Techa which, ends up as a tributary at the River Ob. In the late 1940s and early 1950s there were substantial releases directly into the River Techa, but these have since decreased significantly. The regular operations of the Mayak facility are not likely to pose a threat to the Kara Sea. A small part of the strontium-90 contamination measured at the Ob outlet into the Kara Sea is due to the earlier releases from this facility, while the major part is probably due to radioactive fall-out in the catchment area.

14 Nielsen, S.P., Iosjpe M. & Strand P. (1995). A preliminary assessment of potential doses to man from radioactive waste dumped in the Arctic Sea. NRPA report 1995:8, ISSN 0804-4910, Øesterås, Norwegian Radiation Protection Authority.

and significant (Scenario b), not providing any margin of time to implement countermeasure actions to control the release to an acceptable level and rate.

ASSESSING AND PREDICTING THE ENVIRONMENTAL IMPACT

The wreck of the K-159 and its environmental impact on the marine environment presents four challenges:

1) First, to establish the type and quantity of radioactive material available for release – have the reactors been defuelled or, if not, does the radioactive inventory comprise just two full cores or is there additional irradiated fuel available for release;

2) Second, when and how will the radioactive release occur – is it occurring now, will it be delayed and progressive, or will it be unannounced and abrupt;

3) Third, how will the release disperse into the marine environment – where in the ocean will the radioactivity go, when and how much will get there, and how confident will be the prediction of the dispersion; and

4) Four, if and how will the environment damage transpire - what will be the damage to the marine environment, the marine species and/or to human receptors ?

These challenges should be addressed as follows:

Type and Quantity of Radioactivity Available: Experience with the Kursk revealed that only the Northern Fleet military are likely to have accurate and reliable records of the quantity, condition and burn-up (inventory) of the fuel on board the K-159 at the time of the sinking. It is unlikely that such detailed information has been passed to the Ministry of Civil Defence, Emergencies and the Elimination of the Consequences of Natural Disasters (EMERCOM).

To determine the radioactive inventory of the fuel discussions will have to be held with Ministry of Defence headquarters personnel at (St Petersburg) and with local Northern Fleet commanders (Severomorsk) – the range of potential source terms (Cases i) to iv) of Table 1) could introduce significant error in any environment impact assessment model. Once that a reliable source term has been established this should be agreed with EMERCOM.

Models of Potential Radioactive Releases: Further information and data is required to model the most probable nature of the release and its onset time.

Here assuming that the two reactors have full cores of irradiated fuel - Case ii) – it would be useful to analyse release scenarios based on an abrupt release - Scenario a) arising from a hull containment failure at some time following fuel sheathing and primary circuit failures and, separately, a slow release – Scenario b) arising from progressive failure of the fuel containments. These failure and radioactive release scenarios could be adapted for 1) deterioration of the submarine whilst left unattended and 2) arising from a damaging incident during a future salvage operation. For both scenarios a probabilistic analysis should be completed to determine a range of frequency of occurrence for cost and impact comparative purposes.

Russian Federation military and EMERCOM personnel need to be consulted on information relating to the condition of the K-159 reactor fuel, primary circuit and hull containments and, for the salvage initiated failure, a practicable scheme of salvage would need to be nominated in advance.

Release Dispersion and Impact: This is a matter of detail of the model chosen for the dispersion and radiological consequence analysis.

The overall objective of the modelling would be to determine the economically weighted environmental choice between:

A) Leaving the K-159 in-situ at the wreck site indefinitely;

B) Leaving the K-159 in-situ but with some entombment work to control the release in future years; and

C) Salvaging the K-159 complete, or the hull section containing reactor compartment, within a determined time period.

Providing a reliable prediction of the longer term radiological impact of the K-159 sinking requires a comprehensive study extending beyond that of a paperwork exercise. A release model for the submarine fuel and its engineered containments will have to be developed and, for this, full co-operation of the Russian Federation authorities is required. This model will also have to be applied to any future salvage or entombment operation if the need to salvage or in situ protect the nuclear plant is to be evaluated so, for this, experienced salvage concerns and/or underwater specialists will need to be consulted.

The foregoing analyses should be undertaken with account of the present radiological situation on the Kola and give regard to the probability of other unrelated nuclear/radiological incidents occurring in future years as these might affect the marine environment.

John H Large

APPENDIX

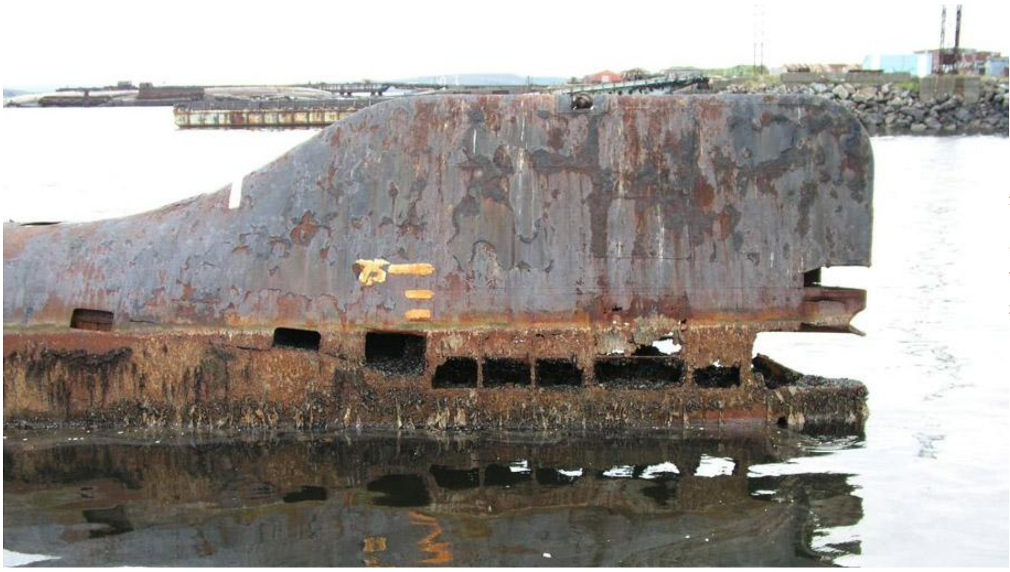
PHOTOGRAPHS OF THE K-159 JUST PRIOR TO ITS SINKING

(photographs courtesy Bellona Foundation - http://www.bellona.no/imaker?id=31503&sub=1&neste=4)

3 Berthed with the floatation pontoons tied alongside

4 Detail of a Floatation Tank and its Hawser Attachment

5/7 Towing Arrangements: Note that the towing yoke is mounted well ahead of the (hidden) prow of the pressure hull, with the yoke apparently picking up on the anchor chains and the deck bollard which is attached to the pressure hull through the deck casing – the towing point is well ahead for the hydrodynamic centre but, even so, there is no stern stabilising tug present (Photo 1).



8 Corroded condition of the stern casing

9 K-159 being tugged out into the open sea