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A Nordic Approach to Impact Assessment of Accidents with Nuclear-Propelled Vessels

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Abstract

The MareNuc project has identified the parameters in a graded approach to impact assessment for marine nuclear reactors. The graded approach is founded on the following elements:

- More detailed understanding of previous accidents in nuclear-propelled vessels (initiating events, accident developments, release fractions), including release mechanisms (radionuclide retention in vessel construction);
- Bench-marking of release scenarios using modelling tools applied in the Nordic countries, in addition to demonstration of generally accessible and free software developed by the IAEA;
- Other systematic approaches to safety assessments of vessel port calls, and to the design and maintenance of emergency preparedness systems;

More specifically, increased emphasis compared to earlier analysis after the Kursk accident is given to the engineered vessel barriers. Relevant standards from impact assessments for commercial nuclear power plants have been identified, such as from the NUREG series.

The Nordic approaches to safety evaluation, impact assessments and emergency preparedness organisation was also reported as part of the project. The Canadian approach for international port calls was carefully reported and assessed as part of the project, and commended for its broad and comprehensive approach to reactor and vessel design for the nationalities involved, to the design and maintenance of emergency preparedness systems, and the well-structured and broad cooperation between civilian and military institutions. This approach goes beyond the current approach in the Nordic countries, also in the case of Norway, which experience regular port calls from allied nuclear navies. The overall result is a broader understanding in the Nordic countries for the importance of the various parameters for impact assessment of releases from marine reactors, and to the design and maintenance of an emergency preparedness organisation without detailed knowledge of the installation in question.

Key words

nuclear-propelled vessels, nuclear submarine, nuclear icebreaker, naval reactors, impact assessment, source term, nuclear accident

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A NORDIC APPROACH TO IMPACT ASSESSMENT OF ACCIDENTS WITH NUCLEAR-PROPELLED VESSELS

Final Report from the NKS-B MareNuc activity

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Summary

The MareNuc project has identified the parameters in a graded approach to impact assessment for marine nuclear reactors. The graded approach is founded on the following elements:

- More detailed understanding of previous accidents in nuclear-propelled vessels (initiating events, accident developments, release fractions), including release mechanisms (radionuclide retention in vessel construction);
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1. Introduction

This report summarizes the overall results of the workshops held on Iceland October 4-5, 2010 and August 25-26 2011 under the NKS-B MareNuc activity. The objective was to establish a coordinated Nordic approach to impact assessments of accidents with marine reactors.

The first NKS MareNuc workshop, held in Reykjavik October 4-5, 2010, was titled *Impact assessment of accidents with nuclear-propelled vessels: Release scaling factors in design and accident scenarios for various military and civilian vessels and the application of relevant modeling tools* and addressed design and safety issues, and state-of-the-art tools applied in the Nordic countries for impact assessments of radiological releases.

The second MareNuc workshop was held at Keflavik on August 25-26 2011 under the heading *Marine Reactors in Arctic waters: New challenges in construction, designs and applications, and sailing*. The objective of the workshop was to present and discuss all recent developments in relation to construction and intended use of nuclear-propelled vessels and FNPPs, assess their possible consequences on Nordic countries, and revisit the graded approach in light of new challenges identified.

2. Background

Even if nuclear-propelled vessels for decades have been present in the international high seas, there is no well–defined system for classification of accidents and assessment of possible consequences associated with naval reactors as there is for civilian power plants. The main methodological problems are – in addition to the general uncertainty when considering accidental releases – the lack of relevant information on nuclear vessels' design operation, safety performance, and fuel materials, and subsequently, on radionuclide behavior in fuel matrixes under extreme conditions (high temperature, saltwater intrusion etc.) deciding the fuel release fraction. Accidents involving nuclear vessels have resulted in considerable releases of radionuclides to the environment. The largest accidental release from an operating naval reactor was the criticality accident in Chahzma Bay (1985), which involved the release to air of 200 x 10^{15} Bq,[1] with a high fraction of short-lived isotopes.[2] For first-generation reactor units with fuel dumped in the Kara Sea, possible release rates averages between 100-1000 x 10^{9} Bq/ year for the various objects, with a peak release of 2700 x 10^{9} Bq/ year by the year 2040 as the total.[3] The main release mechanism has been assessed to be pitting and bulk corrosion. For a decommissioned vessel, the maximum release rate to seawater has been assessed to 2000 x 10^{12} Bq/ year, falling to 60 x 10^{12} Bq/ year – however, with no significant doses, as the scenario was placed in a sparsely populated

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[1] Y. V. Sivintsev *Number of fissions in the 1985 accident on the nuclear powered submarine in Bukhta Chazhma*. Atomic Energy 2000; 89(3): 775–776.

[2] V. N. Soyfer et al. *Analysis of the severe accident on the K-431 nuclear submarine*. Kurchatov Institute, IAE-5879/4. Moscow 1995.

[3] IAEA. Predicted radionuclide release from marine reactors dumped in the Kara Sea: Report of the Source Term Working Group of the International Arctic Seas Assessment Project (IASAP). IAEA TecDoc-938. Vienna: International Atomic Energy Agency, 1997.

fjord close to Norway.[4] With respect to submarines in operation, for the *Komsomolets*, sunk due to fire and reactor shut-down, the main potentially significant release mechanisms identified were fuel corrosion resulting in a maximum release of Cs-137 of 500 x 10^9 Bq/ year.[5] The release rate of other radionuclides was assessed to be one order of magnitude lower. For a strictly hypothetical incident, in a response to the *Kursk* accident, the potential consequences in the Sea of Japan was assessed, using leaching rates from 7.8 x 10^{15} Bq/ year vs. 6.6 x 10^9 Bq/ year, respectively 30 days and one year after the accident, with a result of 25,000 manSv as the collective effective dose commitment (CEDC).[6] the *Kursk* inventory was assessed to be 5 x 10^{15} Bq (Sr-90, Cs-137 each) after 24 000 MWd of operation, released after one year with the total collective dose from all nuclides estimated to 97 manSv.[7]

Various possibilities for migration of releases from the submarine hull to seawater have been described, including ventilation system and open access hatches. All these assessments – with respect to real-life accidents or hypothetical incidents –provides, however, the foundation for establishing a more to-the-point methodology for using representative inventory assessments, more flexible tools for impact assessments. For civilian facilities of similar size, the reference accident used as a basis for further analysis varies between a Design Basis Accident describing complete and partial meltdown followed by water/ aluminum interaction and loss of mitigating systems. Considering the fact that neighboring countries may soon embark upon construction of a new generation of naval reactors, there is a need to systemize the approach for assessing possible consequences of accidents in relation to these installations. Floating power reactors also involve new safety challenges that need to be discussed.

3. Design and operation of naval reactors

Design information for all types of Russian military and civilian nuclear-propelled vessels, together with some information on nuclear-propelled vessels from other countries, was assessed initially.[8]

The operation of Russian submarine reactors was discussed and an overview presented.[9] An overview of operational Soviet/Russian submarine reactors in the period 1959 – 2020 is given in Figure 1, the VM-A reactor model corresponds to the first generation Russian submarines (two reactors per vessel), the VM-4 (also two reactors per vessel) to second generation and the OK-650 to third generation Russian submarines. Similarly, as described in Figure 2, the surface vessel reactor models were discussed, again focusing reactor models (OK-150 representing first generation icebreaker reactors, OK-900/ 900 A representing

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[4] NATO CCMS Pilot Study *Cross-border environmental problems emanating from defence-related installations and activities: Final report, volume 4: Environmental risk assessment for two defence-related problems. Phase II: 1995–1998*. NATO report 227. Oslo 1998.

[5] S. Høibråten et al., *The environmental impact of the sunken submarine Komsomolets*, FFI 2003.

[6] T. Kobayashi et al. *Estimates of collective doses from a hypothetical accident of a nuclear submarine*. Journal of Nuclear Science and Technology. 38 (8), p. 658, 2001.

[7] I. Amundsen et al. *The Accidental Sinking of the Nuclear Submarine, the Kursk: Monitoring of Radioactivity and the Preliminary Assessment of the Potential Impact of Radioactive Releases*, Marine Pollution Bulletin vol. 44, no. 6, pp. 459-468.

[8] V. Larin, *Russian Nuclear Powered Civil Fleet – 2010*, presentation at NKS MareNuc Workshop, Iceland, October 4, 2010.

[9] O. Reistad, *Operational experiences and design – nuclear-propelled vessels,* presentation at NKS MareNuc Workshop, Iceland, October 4, 2009.

second generation icebreaker and military surface vessels, KLT-40 representing the modern icebreaker reactor, and KN-3 Russian aircraft carriers.)

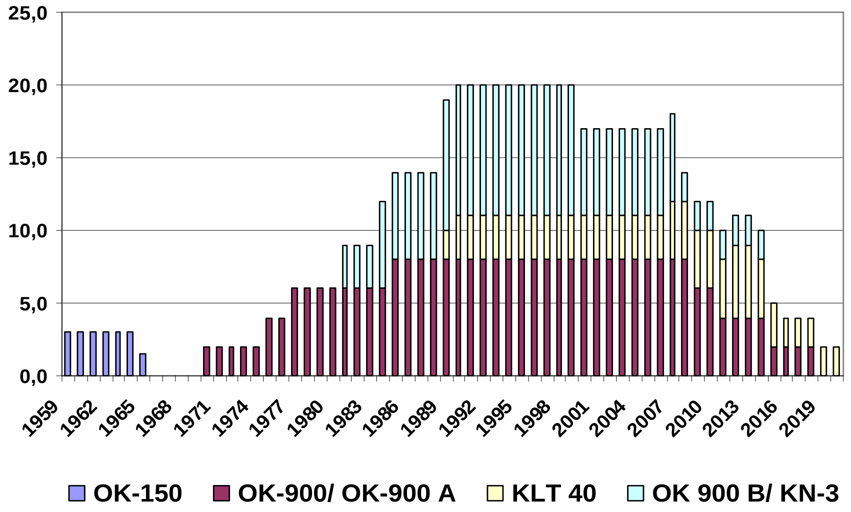

Figure 1: Submarine reactors in operation (1959 – 2020)

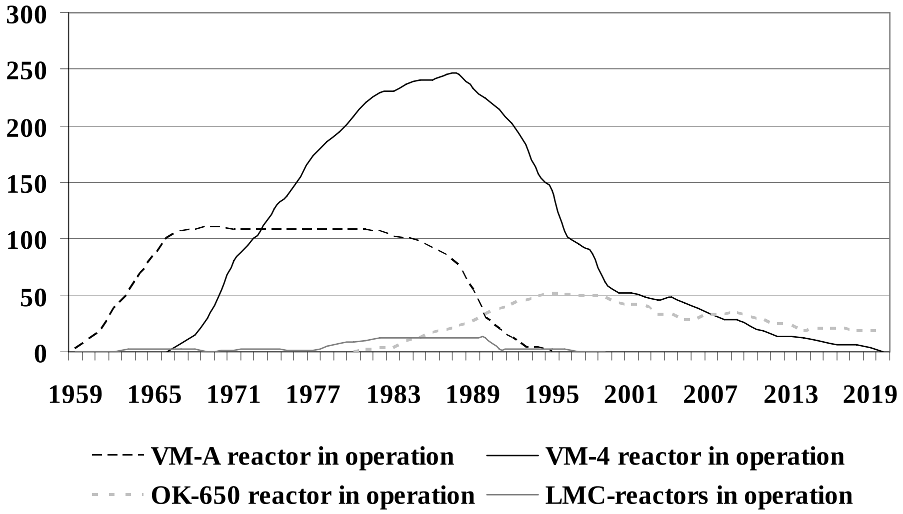

Figure 2: Surface vessels reactors in operation (1959 – 2020)

The initial conclusions for the Russian naval reactors are that the overall design is known to a certain extent, while the knowledge of the reactor models, fuel design and operational experience is scarce, in particular when it comes to modern vessels forming the main part of the Russian military fleet. To some extent even less information is available on allied naval reactors.

4. Accidents and incidents

In a survey of accidents and incidents for Russian vessels, 165 safety-related events involving Russian nuclear submarines from 1959 to 2007 are surveyed with respect to vessel generation, reactor type, various types of initiating event (loss-of-coolant accident, transients, and common cause initiators), safety significance and the release of radioactivity.[10] The survey shows that the accumulated number of reactor operating years accumulated by the Russian navy from 1959 to 2007 is 9335. With respect to the survey of safety-related events, out of the 165 events registered, there have been identified 17 accidents, 134 incidents and 15 deviations. As to event characteristics, 14 LOCA and 7 criticality events have been identified. The accident rates for each of the vessel generations exhibit the usual characteristics of a technological system under development, gradually going from a high accident rate to a stable lower level.

The overall results show that a) Many external events (fires, collisions, etc.) have potential serious consequences for the submarine (such as sinking), but not necessarily radiological consequences, b) many of the more radiological serious accidents have happened during construction/maintenance of the vessel (criticality accidents), and c) first generation Russian vessels had several accidents with release of radioactivity inside the vessels (mainly caused by primary circuit and fuel integrity issues), but apparently small releases outside the vessel. The safety of Russian submarines has improved substantially between vessel generations. Another conclusion was that the International Nuclear Event Scale INES could be a useful tool for classifying accidents with nuclear-propelled vessels. Probably due to the strong hull of submarines, few accidents have radiological consequences outside the vessel.

The Russian civilian nuclear ships have experienced a number of incidents resulting from malfunctions in the reactor and steam supply system’s components, malfunctions in the ship’s systems unrelated to the nuclear systems, and from human error of the crew (the most common of which include navigational errors, disregard for safety measures, regulations and instructions, alcohol consumption and the uncontrolled actions that follow, physical and psychological overload).[11] Little public information is available on incidents in allied vessels.

An initial conclusion on accidents was that due to large-scale dismantlement of early generation vessels in Russia, all of the nuclear-propelled vessels presently operating in the Nordic and Arctic waters probably have similar properties with respect to the risk for releases. This is due to the fact that there have been major changes in the design of Russian submarine reactors. While the first generation reactors were a dispersed design with lot of piping, and often with poor quality on materials and welds, current third and fourth generation reactors utilize an integrated design where LOCA accidents are very unlikely due to the elimination of coolant piping.

The main group of vessels is submarines, potentially equally divided between Russian and US submarines due to the continued high presence of the US Navy together with reduced sailing time in the Russian Navy. The main group of vessels not part of this assessment is Russian nuclear-propelled surface vessels. Due to low availability and

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[10] S. Hustveit, *Review of previous identified release scenarios for marine reactors,* presentation at NKS MareNuc Workshop, Iceland, October 4, 2009, based on O. Reistad, S. Hustveit and S. Roudak: *Operational and accident survey of Russian nuclear submarines for risk assessments using statistical models for reliability growth,* Annals of Nuclear Energy Volume 35, Issue 11, November 2008, Pages 2126-2135.

[11] V. Larin, *Russian Nuclear Powered Civil Fleet – 2010*, presentation at NKS MareNuc Workshop, Iceland, October 4, 2010.

extremely little sailing time, there is not enough data to make any assessment of their safety level. However, compared to Russian vessels with reactor systems of similar design, some concern is relevant for the overall safety level for these vessels.

In addition to Russia and the US, UK, France and China are also operating nuclear submarines. Nuclear surface ships are mainly operated by the US (as aircraft carriers) and Russia (as icebreakers).

While the aim of the workshops was to discuss impact assessments from reactor accidents, it should be noted that strategic submarines also contain significant quantities of plutonium in their nuclear warheads which could be dispersed as a fine aerosol in the case of an uncontrolled fire in the submarine, even though the likelihood of this happening is very low.

5. Methodological approaches for impact assessment

A maximum credible inventory has been developed on the basis of a conservative approach to the average annual burn-up for third-generation reactors, and increased reactor power before the accident to maximize the release, within reasonable limits. Most accident scenarios include a period where the reactor has been shut down or is operating on minimal power and subsequently a lower inventory of short-lived isotopes, before the release starts. There is no well-defined system for classification of accidents associated with naval vessels in general as for civilian power plants with Design Basis Accident (DBA), Reference Accident or Maximum Credible Accident (MCA). The main methodological problem here is the lack of relevant information on fuel materials, and, subsequently, on radionuclide behaviour in fuel matrixes under extreme conditions (high temperature, saltwater intrusion etc.) that will determine the fuel release fraction.

The methodological considerations were introduced with considerations of impact assessments similarities between nuclear power plants and marine reactor accidents.[12] An impact assessment is divided into three parts: a) the development of the radionuclide source term: scenario and the chain of events resulting in a release; released radionuclides, their amounts and characteristics; time behaviour of the release; release height (physical & effective); other source-point phenomena (e.g. initial dimensions of the plume due to building or other effects), b) dispersion: transport, atmospheric diffusion and deposition of radioactive substances (dry and wet deposition) between the source site and target site, and application of a relevant dispersion model, and c) assessing the exposure to humans and biota: external exposure from the release cloud and deposited activity; internal exposure due to inhalation and ingestion (or drinking) of contaminated foodstuff; possibly also other exposure paths.

The approach to event analysis can either be probabilistic[13] or deterministic[14]. Radionuclides can be divided into groups according to their physicochemical properties with respect to the probability of them being released from the core. There are several groupings

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[12] J. Lahtinen, *Similarities between NPP and Marine Reactor Accident Consequence Analyses*, presentation at NKS MareNuc Workshop, Iceland, October 4, 2010.

[13] Probabilities of possible events resulting in releases are estimated, as well as often also the probability of the occurrence of different environmental conditions, and the consequences are expressed as probabilities or frequencies (i.e., the total number of certain consequences or the probability of the occurrence of certain consequences per unit time).

[14] Source term and prevailing environmental conditions are (more or less) accurately defined; e.g. the so-called "worst cases" and other "reference scenarios", like design basis accidents in connexion with NPPs.

that can basically be used regardless of the technical details of the reactor. [15] The source term consists of an inventory of radionuclides, released as a function of time and a release point. The core inventory has primarily two components: the fuel matrix itself and the fuel burn-up. While the fuel matrix itself has only indirect influence on the amount of fission products, the amount of transuranic and release rates will depend directly on the type of matrix. The main methodological problem with respect to the release fractions is the lack of relevant information on fuel materials, subsequently, on radionuclide behavior in fuel matrixes under extreme conditions (high temperature, saltwater intrusion etc.). The second component of the release fraction is fuel degradation and corrosion. The release point is also of fundamental importance due to the importance of the release transport time and distance for subsequent consequences. A potential major difference between NPP and e.g. submarine reactor inventories is that the latter contain in proportion less amounts of transuranium elements (because of higher fuel enrichment).

6. Preliminary assessments on sample source terms

For the first workshop a suitable source term for a submarine accident with releases to air was identified in the open literature as a basis for dispersion modeling.[16] This source term was based on previous Canadian assessments, where the reference was made to NUREG-1062[17] as a basis for choosing release fractions based on similarity in releases categories. Updates on the Canadian approach to source terms and impact assessments were also introduced at the workshops. [18]

The sample source term for the workshop was based on a 200 MW_{th} PWR reactor with 97% enriched uranium and zirconium alloy fuel in Zircalloy-2 cladding with roughly 26 wt% uranium in the U-Zr alloy and a total mass of uranium in the core of 400kg at the beginning of its life. This is meant to approximate the reactor in a US *Los Angeles* class submarine. The power history of the core was set as 12 years at an average of 25% of full power, 100 hours at full power and finally two hours at 50% power (for transit into the harbor). At this point in time the reactor experienced a large-break LOCA. An escape hatch is assumed to be left open to make a pathway for the release into the atmosphere. An important element of the source term is the effect of the barriers between the reactor and air releases. Several dispersion models were presented at the workshop using ARGOS[19] as well as other tools.[20] An example of an earlier Finnish approach was also presented.[21] A recent study completed

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[15] WASH-1400 (1975): Noble gases, iodines, Cs-Rb, Te-Sb, Ba-Sr, Ru group, La group. NUREG-1150 (1991): Inert gases, iodine, caesium, tellurium, strontium, ruthenium, lanthanum, cerium, barium. NUREG Regulatory Guide 1.183 (2000): Noble gases, halogens, alkali metals, tellurium metals, Ba+Sr, noble metals, cerium group, lanthanides.

[16] B.J. Lewis and J.J.M.R. Hugron, *Source Term Analysis for a Nuclear Submarine Accident*, Proc. 6th Intern. Conf. on CANDU Fuel, Canadian Nuclear Society, Toronto ON, 1999

[17] T.S. Margulies, J.A. Martin Jr., *NUREG-1062 Dose calculations for severe LWR accident scenarios,* Nuclear Regulatory Commission 1 May 1984

[18] F. Lemay, *Allied Military Vessels Safety in Port Calls*, at NKS MareNuc Workshop, Iceland, August 25, 2011

[19] S. Hoe, *Applying ARGOS on sample source term*, presentation at NKS MareNuc Workshop, Iceland, October 4, 2010

[20] S.E. Pálsson, *Assessing dispersion, the solution used in Iceland*, presentation at NKS MareNuc Workshop, Iceland, October 4, 2010

[21] In 1993 STUK carried out a threat study that included deterministic analyses on the consequences of severe accidents at near-by NPPs and on a nuclear submarine. The inventory (100 MW_{th} reactor, full-power operation for 600 days) and total release fractions used in the submarine study were based mainly on the

of NRPA in order to assess the radioecological consequences after a hypothetical accident for a Russian nuclear submarine has been based on modeling of potential releases of radionuclides, radionuclide transport and uptake in the marine environment[22]. Modeling work has been done using a revised box model developed at the NRPA.[23] IAEAs capabilities for assisting member states with modeling tools were also presented based on the sample source term.[24]

7. Naval reactor operations in the Arctic – future prospects

As can be seen in Figure 1 there has been a dramatic decrease in the number of reactors operated by the Russian Navy during the last 20 years. This has been mostly due to decommissioning of older 1st and 2nd generation submarines. Today the situation is that several of the 'new' 3rd generation vessels are also approaching the end of their life span.

The Russian Northern Fleet currently operates 16 attack submarines of the Victor III, Sierra II, Akula II and Oscar II classes and 11 strategic submarines of the Delta III, Delta IV, Typhoon and Borey class as well as some smaller nuclear research vessels. The Northern Fleet also operates the only nuclear powered military surface vessel in Russia, the *Pyotr Velikiy* (*Peter the Great*). The Pacific Fleet operates 13 attack submarines (Akula II and Oscar II) and 4 strategic submarines (Delta III). [25]

Very limited production of new vessels since the collapse of the Soviet Union means that the number of Russian submarines probably will decrease from the current level before the production of new vessels can catch up with the decommissioning rate. Russia is currently constructing a class of new strategic submarines, *Project 955 Borey*, where two of a planned eight vessels have been completed. The pacific fleet currently operates the oldest strategic vessels, the Delta-III submarines, and these are probably the first to be replaced with *Borey* subs as they enter into service, even though the first-of-class *Yury Dolgoruky*, will be stationed with the Northern Fleet.[26] There are also plans to build ten new attack submarines of the *Project 855 Yasen* class of which currently one has been completed. While the Soviet Union and Russia historically, and still today, have built several different classes of attack and strategic submarines in each generation they seem to currently be simplifying to one

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following two references; a) Eriksen V.O. *Sunken nuclear submarines*. Norway; 1990, and U.S. Atomic Energy Commission. *NS 'Savannah' Safety Assessment, Vol. III.* U.S.A.E.C; 1961. It was assumed that half of the total release takes place (immediately after the reactor shutdown) during the first hour and the latter half – depending on the nuclide group – in the following 5, 11 or 23 hours. The release was " a close-to-the-sea-level release".

[22] M. Iosjpe, O. Reistad, A. Liland, *Radioecological consequences after a hypothetical accident with release into the marine environment involving a Russian nuclear submarine in the Barents Sea* StrålevernRapport 2011:3. Østerås: Statens strålevern, 2011.

[23] M. Iosjpe M., J. Brown, P. Strand. *Modified approach for box modeling of radiological consequences from releases into marine environment,* Journal of Environmental Radioactivity 2002, 60, 91–103.

M. Iosjpe, *Environmental modeling: Modified approach for compartmental models*, In: Povinec P.P., Sanchez-Cabeza J.A., eds. Radionuclides in the environment: International conference on isotopes in environmental studies, Monaco 2004. Radioactivity in the Environment, vol.8. Amsterdam: Elsevier, 2006: 463–476.

[24] G. Winters, IAEA, Presentation at MareNuc Workshop October 5, 2010

[25] P. Podvig, *Russian nuclear ships*, NKS MareNuc Workshop, Iceland, August 26, 2011

[26] *Yury Dolgoruky to join Northern Fleet in 2012*, http://rusnavy.com/news/navy/index.php?ELEMENT_ID=14610, 19.03.2012

class each of strategic and attack submarines for the fourth generation (the already mentioned *Borey* and *Yasen*) like the allied navies.

The Russian civilian nuclear fleet today consists of 6 icebreakers in operation, 3 of which were fairly recently refueled, and is operated by the Russian organization Atomflot. On March 20, 2008, the president of the Russian Federation signed Order № 239 called *Measures for Creating State Atomic Energy Corporation Rosatom.* Consequently, FGUP *Atomflot*, which services ships with nuclear power units for commercial use, became part of the State Atomic Energy Corporation *Rosatom*, and was no longer a structural subdivision of OAO Murmansk Shipping Company. On August 28, 2008, nuclear-powered vessels, nuclear mechanical support ships, and an onshore facility in the Murmansk port were transferred to *Atomflot*. The enterprise currently owns the only icebreaker production facility of the Russian commercial nuclear fleet, which is part of OAO *Atomenergoprom*; *Atomflot's* responsibilities in 2010 included:

- escorting by icebreakers cargo ships through the Northern Sea Route and frozen Russian ports
- conducting scientific research expeditions on the study of hydrometeorological sea patterns and raw mineral resources in the Arctic shelf located along Russia's northern coast (currently four of 6 icebreakers in operation are capable of conducting this work);
- conducting emergency rescue missions in the ice along the Northern Sea Route and frozen seas beyond the borders of the Arctic region (currently 4 of 6 icebreakers in operation are capable of conducting this work);
- servicing tourist's cruises in Russian sector of Arctic (currently 4 icebreakers in operation are capable of conducting this work);
- servicing and minor repairs, both general and specialized, for the nuclear fleet (there are currently 3 technical support ships (service ships);
- handling of nuclear materials and radioactive waste

The future to the Russian civilian icebreaker fleet is not clear. On one side, there are plans to extend the use of marine reactors to floating power stations, of which the first unit is under construction, and to underwater operations.[27] There are also plans to use nuclear powered icebreakers to increase cargo transport through the Northern Sea Route from Europe to Asia.[28] On the other side, application of nuclear icebreakers is not economically profitable. Nuclear powered ships are presently used primarily in relation to the operations of the Norilsk industrial conglomerate, and the owners of Norilsk Nickel metallurgic plant have ordered a few new conventional cargo icebreakers at Singapore shipyard as nuclear power is not required for their requirements. Because almost all of the currently operating icebreakers are ageing, it is hardly possible to build new vessels fast enough to avoid an icebreaker pause starting in 2015-20 when the current icebreakers are scheduled for retirement.

Levels of allied nuclear vessel seems to have stabilized, with the US operating 50-60 attack submarines, 14 strategic submarines and 10 aircraft carriers at any one time, the UK and France each have 4 strategic submarines and 8 and 6 attack submarines respectively.[29] There does not seem to be any indication of impending changes in these structures. The presence of Chinese Nuclear submarines in the arctic is unclear.

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[27] O. Reistad, *Floating power reactors* at NKS MareNuc Workshop, Iceland, August 26, 2011

[28] A. Moe, *New Sailing Routes in Arctic Waters* at NKS MareNuc Workshop, Iceland, August 25, 2011

[29] Jane's Fighting Ships of the World 2011-2012

A new issue regarding reactor operations in the Arctic is the possibility of future floating nuclear power plants (FNPP) in the region. The keel of the first FNPP, *Academician Lomonosov*, was laid at Sevmash on 15 April 2007. While the plan is to deploy this FNPP at Kamchatka in the Far East, there are also plans to deploy similar power plants on the Kola Peninsula.[30] There is great uncertainty of the economics of these power plants, and as such unclear at present if any more will be built and if so where they will be located.

8. Recommendations from MareNuc

As a conclusion on naval reactor operations in the Arctic, it is clear that while the number of reactors has decreased since the days of the Cold War and improvements in design has made todays vessels safer than those in earlier decades there will be a continued operation of nuclear propelled vessels in the area in the foreseeable future. As such impact assessments of potential nuclear accidents will be of continued interest to countries bordering the Arctic seas.

8.1 Source-term analysis and impact assessment

Regarding concentrations of radionuclides for some marine organisms used as foodstuffs, one study from NRPA, involving release from a third-generation Russian submarine, exceeded international guideline levels for a period of time after the accidental releases of radioactivity. This is related to the immediate aftermath after the accident (up to one month). The results are hampered by the continued lack of a system for accident evaluation with associated source terms based on general vessel design and operational parameters. This effort led to additional consideration of the various elements being parts of the impact assessment.

Regarding the source term, consisting of a radionuclide inventory released as a function of time and a release point, the participants agreed that 2–3 parameter sets may represent the most relevant release scenarios. The most relevant scenarios which should be further assessed is the source terms developed as part of the emergency preparedness efforts in relation to aircraft carrier and submarine port calls.[31] The shared criteria for each set would be maximum credible burn-up, conservative figures for years of reactor operation, and a high operating power fraction the last operational phase before the time of incident. As described earlier a relevant source term for a modern nuclear submarine was put forward at the first workshop. The participants agreed that these scenarios may be assessed in relation to the INES-scale as the obligations for notification as spelled out in the international convention are also relevant for military vessels. The importance of considering beyond design basis accidents (BDBA) was also discussed, as DBA is of less importance outside the hull itself. While fewer accidents have been registered for civilian nuclear-propelled vessels, emphasis was put on the fact that incidents has occurred and should not be under-estimated. While detailed reactor and fuel properties may be relevant for the assessment of long-term releases to sea, this information is of less importance with respect to releases to

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[30] O. Reistad, *Floating power reactors* at NKS MareNuc Workshop, Iceland, August 26, 2011

[31] F. Lemay, *Allied Military Vessels-Safety in Port Calls* at NKS MareNuc Workshop, Iceland, August 25, 2011

air and associated impacts assessments. Detailed analysis of design information for the identification of accidents and equipment failure sequence was discussed, but assessed as being of less relevance as this type of information in case will not be disclosed for the public authorities in the Nordic countries managing the emergency preparedness systems. The importance of close monitoring and measurement strategy was emphasized, in particular monitoring of hullshine for nuclear propelled vessels in port calls. Increase in this property would probably be an early, and in some instances the only, indicator for vessel anomaly due to ability of the hull to act as release containment.

8.2 Proposal for international cooperation

The technical specifications of marine reactors and nuclear fuel have long been considered sensitive information. If, for example, one knows the exact reactor core configuration in a nuclear reactor (the physical arrangement of fuel and other materials), then it is possible to calculate the heat-generation in the fuel elements, and, subsequently, the upper limits of operational capacity. From this, much sensitive information related to operational schemes and capabilities may be derived. Information on speed, noise, diving depth etc., are also kept strictly confidential, in order to make it harder to track and detect the vessels. For the civilian vessels there has always been a link to the military realm. However, knowing the core configuration and burn-up levels – as well as fuel composition and current status with respect to fuel storage – is also relevant for assessing the consequences of the continued operation of these vessels, not least the probability and consequences of a release of radioactivity to the environment, or the need for remedial action.

This set-up has not encouraged the international community, in particular the international civilian nuclear authority, the International Atomic Energy Agency, to engage in these issues. Their presence at both the workshops is, however, a strong signal of their interest in these issues. During the project implementation, it has been clear that IAEA is ready to engage, at request, to facilitate an international cooperation between interested states for addressing emergency preparedness issues for marine reactors. Even in the case of military vessels, the Agency is capable of taking part as long as they are engaged in assistance to protect civilian interests as defined by the country in question. The Canadian experience has provided much previously unknown knowledge to this initiative, and it is well-known that Australia also has a close eye on the safety of port calls from allied nuclear ships in Australian waters. A strong recommendation after the completion of MareNuc is therefore for the Nordic countries to approach IAEA collectively to sort out a way to address these issue further internationally.

Acknowledgement

A range of organizations and individuals should be acknowledged for their contributions to this project. The cooperation between the radiation protection and nuclear safety authorities in Denmark, Iceland and Norway was instrumental to set up the project. Dr. Sigurður Emil Pálsson has restlessly worked on the documentation and organization of the project, particularly when the project manager relocated to a new position at the Institute for Energy Technology, Norway. Dr. Francois Lemay has to be thanked for his instrumental

contributions in describing how a non-nuclear country has been managing the in-flux of a large nuclear fleet, using the best principles from international emergency preparedness systems – inspiring to us all.

Enclosures

1. Program – workshop 1
2. Program – workshop 2

Annex I. Radionuclide Inventory – Russian Third Generation Submarine[i]

42000 MWd (94594 MWd/ t HM) – Selected Decay Periods

Burn-up:	42000 MWd/ 94594 MWd/ t HM				
Decay (days)	0,1	1	10	100	1 000
	# Bq	# Bq	# Bq	# Bq	# Bq
H3	2,21E+13	2,21E+13	2,21E+13	2,18E+13	1,90E+13
C14	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
CL36	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
FE55	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
NI59	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
CO60	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
NI63	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
SE79	3,15E+10	3,15E+10	3,15E+10	3,15E+10	3,15E+10
KR85	4,12E+14	4,11E+14	4,11E+14	4,04E+14	3,45E+14
SR89	3,04E+16	3,00E+16	2,65E+16	7,73E+15	3,37E+10
Y90	4,15E+15	4,15E+15	4,15E+15	4,13E+15	3,89E+15
SR90	4,15E+15	4,15E+15	4,15E+15	4,13E+15	3,88E+15
Y91	3,41E+16	3,37E+16	3,03E+16	1,04E+16	2,45E+11
NB93M	1,18E+06	1,18E+07	1,18E+08	1,18E+09	1,12E+10
ZR93	1,01E+11	1,01E+11	1,01E+11	1,01E+11	1,01E+11
ZR95	3,63E+16	3,60E+16	3,26E+16	1,23E+16	7,22E+11
NB95	1,59E+16	1,63E+16	1,92E+16	1,83E+16	1,59E+12
NB95M	4,03E+14	4,03E+14	3,80E+14	1,45E+14	8,49E+09
ZR97	8,24E+16	3,40E+16	4,83E+12	1,71E-26	0,00E+00
NB97	8,36E+16	3,47E+16	4,93E+12	0,00E+00	0,00E+00
NB97M	7,82E+16	3,22E+16	4,58E+12	0,00E+00	0,00E+00
MO99	7,86E+16	6,26E+16	6,46E+15	8,90E+05	0,00E+00
TC99	6,88E+11	6,89E+11	6,91E+11	6,91E+11	6,91E+11
TC99M	1,69E+16	5,57E+16	6,26E+15	8,62E+05	0,00E+00
RU103	2,47E+16	2,43E+16	2,07E+16	4,23E+15	5,32E+08
RH103M	2,46E+16	2,43E+16	2,07E+16	4,23E+15	5,31E+08
RU105	1,04E+16	3,58E+14	8,12E-01	0,00E+00	0,00E+00
RH105	1,48E+16	1,06E+16	1,55E+14	6,34E-05	0,00E+00
RU106	1,48E+15	1,48E+15	1,46E+15	1,23E+15	2,30E+14

RH106	1,48E+15	1,48E+15	1,46E+15	1,23E+15	2,30E+14
AG110M	1,83E+12	1,82E+12	1,78E+12	1,39E+12	1,14E+11
AG111	3,89E+14	3,58E+14	1,55E+14	3,58E+10	1,53E-26
SB125	9,26E+13	9,25E+13	9,20E+13	8,64E+13	4,62E+13
TE125M	2,13E+13	2,13E+13	2,13E+13	2,07E+13	1,13E+13
SN126	2,28E+10	2,28E+10	2,28E+10	2,28E+10	2,28E+10
SB126	1,78E+07	1,74E+08	1,37E+09	3,18E+09	3,19E+09
SB126M	2,27E+10	2,28E+10	2,28E+10	2,28E+10	2,28E+10
SB127	2,24E+15	1,90E+15	3,76E+14	3,45E+07	0,00E+00
TE127	2,22E+15	1,86E+15	4,54E+14	6,27E+13	2,05E+11
TE127M	1,06E+14	1,08E+14	1,11E+14	6,39E+13	2,09E+11
TE129	5,67E+14	5,57E+14	4,63E+14	7,23E+13	6,25E+05
TE129M	8,84E+14	8,68E+14	7,21E+14	1,13E+14	9,73E+05
I129	8,72E+08	8,72E+08	8,73E+08	8,77E+08	8,78E+08
I131	3,77E+16	3,49E+16	1,61E+16	6,86E+12	1,38E-21
TE132	5,59E+16	4,61E+16	6,80E+15	3,29E+07	0,00E+00
I132	5,67E+16	4,75E+16	7,01E+15	3,39E+07	0,00E+00
I133	1,88E+17	9,16E+16	6,86E+13	3,76E-18	0,00E+00
XE133	8,96E+16	9,45E+16	3,43E+16	2,33E+11	0,00E+00
CS134	8,90E+14	8,89E+14	8,82E+14	8,12E+14	3,54E+14
I135	8,56E+16	8,77E+15	1,11E+06	0,00E+00	0,00E+00
XE135	6,47E+16	3,27E+16	4,24E+09	0,00E+00	0,00E+00
CS135	3,89E+10	3,89E+10	3,89E+10	3,89E+10	3,89E+10
CS136	7,73E+14	7,37E+14	4,59E+14	4,01E+12	1,04E-08
CS137	4,29E+15	4,29E+15	4,29E+15	4,26E+15	4,03E+15
BA137M	4,05E+15	4,05E+15	4,05E+15	4,02E+15	3,80E+15
BA140	7,57E+16	7,20E+16	4,42E+16	3,32E+14	1,88E-07
LA140	7,58E+16	7,52E+16	5,07E+16	3,82E+14	2,17E-07
CE141	5,02E+16	4,92E+16	4,07E+16	5,96E+15	2,75E+07
CE143	7,39E+16	4,69E+16	5,03E+14	9,94E-06	0,00E+00
PR143	7,09E+16	7,04E+16	4,77E+16	4,81E+14	5,21E-06
PR144	1,55E+16	1,55E+16	1,52E+16	1,22E+16	1,36E+15
PR144M	2,18E+14	2,17E+14	2,12E+14	1,71E+14	1,91E+13
CE144	1,55E+16	1,55E+16	1,52E+16	1,22E+16	1,36E+15
ND147	2,80E+16	2,64E+16	1,50E+16	5,11E+13	1,08E-11
PM147	4,72E+15	4,73E+15	4,84E+15	4,69E+15	2,45E+15
SM147	3,40E+05	3,40E+05	3,41E+05	3,49E+05	4,04E+05
ND148	1,30E+04	1,30E+04	1,30E+04	1,30E+04	1,30E+04
PM148	1,16E+15	1,03E+15	3,35E+14	3,87E+12	1,06E+06
PM148M	3,91E+14	3,85E+14	3,31E+14	7,30E+13	2,01E+07
PM149	1,46E+16	1,10E+16	6,57E+14	3,69E+02	0,00E+00
SM151	3,15E+13	3,16E+13	3,17E+13	3,16E+13	3,10E+13
PM151	5,40E+15	3,19E+15	1,64E+13	2,08E-10	0,00E+00
SM153	5,68E+15	4,11E+15	1,62E+14	1,43E+00	0,00E+00
EU154	5,80E+13	5,80E+13	5,79E+13	5,67E+13	4,65E+13
EU155	3,66E+13	3,65E+13	3,64E+13	3,51E+13	2,44E+13
EU156	8,16E+14	7,83E+14	5,19E+14	8,55E+12	1,25E-05
TB160	7,17E+11	7,10E+11	6,52E+11	2,75E+11	4,92E+07

TL208	2,86E+06	2,87E+06	2,95E+06	3,84E+06	1,28E+07
PB210	6,60E-06	4,48E-03	4,48E-01	4,48E+01	4,48E+03
BI210	6,60E-06	4,48E-03	4,48E-01	4,48E+01	4,48E+03
PO210	6,60E-06	4,48E-03	4,48E-01	4,48E+01	4,48E+03
BI214	6,60E-06	4,48E-03	4,48E-01	4,48E+01	4,48E+03
PB214	6,60E-06	4,48E-03	4,48E-01	4,48E+01	4,48E+03
PO214	6,60E-06	4,48E-03	4,48E-01	4,48E+01	4,48E+03
PO218	6,60E-06	4,48E-03	4,48E-01	4,48E+01	4,48E+03
RN222	6,60E-06	4,48E-03	4,48E-01	4,48E+01	4,48E+03
RA226	6,60E-06	4,48E-03	4,48E-01	4,48E+01	4,48E+03
TH228	7,94E+06	7,97E+06	8,21E+06	1,07E+07	3,56E+07
TH230	7,56E+02	7,56E+03	7,56E+04	7,56E+05	7,56E+06
U232	3,51E+07	3,51E+07	3,54E+07	3,86E+07	6,13E+07
PA233	5,71E+09	5,71E+09	5,70E+09	5,72E+09	5,73E+09
U233	6,80E+00	6,80E+01	6,79E+02	6,80E+03	6,82E+04
PA234	8,41E+05	3,54E+06	3,87E+06	3,87E+06	3,87E+06
PA234M	2,97E+09	2,97E+09	2,97E+09	2,97E+09	2,97E+09
TH234	3,03E+09	3,02E+09	3,01E+09	2,98E+09	2,97E+09
U234	3,00E+11	3,00E+11	3,00E+11	3,00E+11	3,00E+11
U235	1,18E+10	1,18E+10	1,18E+10	1,18E+10	1,18E+10
U236	2,27E+10	2,27E+10	2,27E+10	2,27E+10	2,27E+10
PU236	1,38E+09	1,38E+09	1,37E+09	1,30E+09	7,19E+08
U237	1,29E+16	1,18E+16	4,67E+15	4,62E+11	8,56E+09
NP237	5,61E+09	5,62E+09	5,68E+09	5,72E+09	5,73E+09
PU238	1,11E+13	1,11E+13	1,12E+13	1,13E+13	1,13E+13
NP238	1,49E+15	1,11E+15	5,81E+13	3,96E+08	3,91E+08
U238	2,97E+09	2,97E+09	2,97E+09	2,97E+09	2,97E+09
PU239	4,69E+12	4,70E+12	4,72E+12	4,72E+12	4,72E+12
U239	2,10E+15	5,00E-02	0,00E+00	0,00E+00	0,00E+00
NP239	1,00E+17	7,68E+16	5,43E+15	3,19E+09	3,19E+09
NP240	1,15E+13	5,75E+06	0,00E+00	0,00E+00	0,00E+00
PU240	2,53E+12	2,53E+12	2,53E+12	2,53E+12	2,53E+12
PU241	4,06E+14	4,06E+14	4,06E+14	4,01E+14	3,56E+14
AM241	2,37E+12	2,37E+12	2,39E+12	2,55E+12	4,02E+12
PU242	1,21E+09	1,21E+09	1,21E+09	1,21E+09	1,21E+09
CM242	7,14E+13	7,20E+13	6,99E+13	4,77E+13	1,11E+12
AM242M	8,81E+10	8,81E+10	8,81E+10	8,80E+10	8,70E+10
AM242	4,51E+14	1,77E+14	1,03E+11	8,76E+10	8,66E+10
PU243	5,56E+13	2,71E+12	2,06E-01	0,00E+00	0,00E+00
AM243	3,19E+09	3,19E+09	3,19E+09	3,19E+09	3,19E+09
CM243	4,76E+09	4,76E+09	4,76E+09	4,72E+09	4,45E+09
AM244	5,17E+12	1,18E+12	4,29E+05	0,00E+00	0,00E+00
CM244	7,24E+10	7,26E+10	7,26E+10	7,19E+10	6,54E+10
CM245	2,16E+06	2,16E+06	2,16E+06	2,16E+06	2,16E+06
CM246	7,05E+04	7,05E+04	7,05E+04	7,05E+04	7,05E+04
CM248	2,58E-02	2,58E-02	2,58E-02	2,58E-02	2,58E-02
CF252	7,67E+00	7,66E+00	7,61E+00	7,14E+00	3,74E+00

Annex II. Radionuclide Inventory – Russian Icebreaker - Sevmorput

78000 MWd (466000 MWd/ t HM)) – SELCETED DECAY PERIODS

Burn-up:	**78000 MWd (466000 MWd/ t HM)**				
Decay (days)	**0,1**	**1**	**10**	**100**	**1 000**
	# Bq	# Bq	# Bq	# Bq	# Bq
H3	4,10E+13	4,10E+13	4,10E+13	4,04E+13	3,52E+13
C14	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
CL36	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
FE55	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
NI59	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
CO60	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
NI63	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
SE79	5,85E+10	5,85E+10	5,85E+10	5,85E+10	5,84E+10
KR85	1,01E+15	1,01E+15	1,01E+15	9,92E+14	8,46E+14
SR89	6,62E+16	6,54E+16	5,78E+16	1,68E+16	7,36E+10
Y90	8,68E+15	8,68E+15	8,68E+15	8,63E+15	8,12E+15
SR90	8,68E+15	8,68E+15	8,68E+15	8,63E+15	8,12E+15
Y91	7,98E+16	7,89E+16	7,10E+16	2,44E+16	5,72E+11
NB93M	2,20E+06	2,20E+07	2,19E+08	2,18E+09	2,07E+10
ZR93	1,87E+11	1,87E+11	1,87E+11	1,87E+11	1,87E+11
ZR95	8,83E+16	8,74E+16	7,93E+16	2,99E+16	1,75E+12
NB95	7,80E+16	7,81E+16	7,90E+16	4,98E+16	3,87E+12
NB95M	9,81E+14	9,80E+14	9,24E+14	3,52E+14	2,06E+10
ZR97	7,41E+16	3,05E+16	4,34E+12	1,45E-26	0,00E+00
NB97	7,52E+16	3,12E+16	4,43E+12	2,26E-26	0,00E+00
NB97M	7,03E+16	2,90E+16	4,12E+12	0,00E+00	0,00E+00
MO99	9,42E+16	7,51E+16	7,75E+15	1,07E+06	0,00E+00
TC99	1,23E+12	1,23E+12	1,23E+12	1,23E+12	1,23E+12
TC99M	2,03E+16	6,68E+16	7,50E+15	1,03E+06	0,00E+00
RU103	4,60E+16	4,53E+16	3,86E+16	7,88E+15	9,91E+08
RH103M	4,59E+16	4,52E+16	3,86E+16	7,87E+15	9,89E+08
RU105	1,15E+16	3,95E+14	8,96E-01	0,00E+00	0,00E+00
RH105	1,60E+16	1,15E+16	1,68E+14	6,87E-05	0,00E+00
RU106	5,41E+15	5,40E+15	5,31E+15	4,49E+15	8,38E+14
RH106	5,41E+15	5,40E+15	5,31E+15	4,49E+15	8,38E+14
AG110M	1,04E+13	1,04E+13	1,02E+13	7,92E+12	6,51E+11
AG111	3,87E+14	3,56E+14	1,54E+14	3,55E+10	1,53E-26
SB125	3,25E+14	3,25E+14	3,23E+14	3,03E+14	1,62E+14
TE125M	7,48E+13	7,48E+13	7,47E+13	7,27E+13	3,96E+13
SN126	4,23E+10	4,23E+10	4,23E+10	4,23E+10	4,23E+10
SB126	3,30E+07	3,22E+08	2,54E+09	5,90E+09	5,92E+09
SB126M	4,21E+10	4,23E+10	4,23E+10	4,23E+10	4,23E+10
SB127	2,55E+15	2,17E+15	4,30E+14	3,94E+07	0,00E+00
TE127	2,56E+15	2,21E+15	6,06E+14	1,21E+14	3,97E+11
TE127M	2,17E+14	2,18E+14	2,16E+14	1,24E+14	4,04E+11

TE129	9,74E+14	9,57E+14	7,95E+14	1,24E+14	1,07E+06
TE129M	1,52E+15	1,49E+15	1,24E+15	1,93E+14	1,67E+06
I129	1,55E+09	1,55E+09	1,55E+09	1,56E+09	1,56E+09
I131	4,54E+16	4,20E+16	1,93E+16	8,26E+12	1,66E-21
TE132	6,65E+16	5,50E+16	8,10E+15	3,92E+07	0,00E+00
I132	6,76E+16	5,66E+16	8,34E+15	4,04E+07	0,00E+00
I133	9,02E+16	4,39E+16	3,28E+13	1,80E-18	0,00E+00
XE133	1,05E+17	1,01E+17	3,33E+16	2,27E+11	0,00E+00
CS134	7,16E+15	7,15E+15	7,09E+15	6,53E+15	2,85E+15
I135	7,70E+16	7,88E+15	1,00E+06	0,00E+00	0,00E+00
XE135	3,78E+16	2,55E+16	3,50E+09	0,00E+00	0,00E+00
CS135	5,27E+10	5,27E+10	5,27E+10	5,27E+10	5,27E+10
CS136	2,13E+15	2,03E+15	1,26E+15	1,10E+13	2,86E-08
CS137	8,83E+15	8,83E+15	8,82E+15	8,77E+15	8,29E+15
BA137M	8,34E+15	8,33E+15	8,33E+15	8,28E+15	7,83E+15
BA140	9,72E+16	9,25E+16	5,67E+16	4,26E+14	2,42E-07
LA140	1,00E+17	9,86E+16	6,51E+16	4,90E+14	2,79E-07
CE141	8,79E+16	8,62E+16	7,11E+16	1,04E+16	4,81E+07
CE143	8,91E+16	5,66E+16	6,06E+14	1,20E-05	0,00E+00
PR143	9,33E+16	9,23E+16	6,22E+16	6,28E+14	6,79E-06
PR144	6,55E+16	6,54E+16	6,40E+16	5,14E+16	5,75E+15
PR144M	9,17E+14	9,15E+14	8,96E+14	7,19E+14	8,05E+13
CE144	6,55E+16	6,54E+16	6,40E+16	5,14E+16	5,75E+15
ND147	3,49E+16	3,30E+16	1,87E+16	6,37E+13	1,35E-11
PM147	1,45E+16	1,45E+16	1,46E+16	1,39E+16	7,25E+15
SM147	3,12E+05	3,12E+05	3,14E+05	3,38E+05	5,02E+05
ND148	2,41E+04	2,41E+04	2,41E+04	2,41E+04	2,41E+04
PM148	6,81E+15	6,07E+15	1,94E+15	1,52E+13	4,16E+06
PM148M	1,53E+15	1,51E+15	1,30E+15	2,86E+14	7,86E+07
PM149	2,29E+16	1,73E+16	1,03E+15	5,78E+02	0,00E+00
SM151	1,74E+13	1,75E+13	1,76E+13	1,76E+13	1,73E+13
PM151	6,41E+15	3,79E+15	1,94E+13	2,47E-10	0,00E+00
SM153	1,45E+16	1,05E+16	4,13E+14	3,65E+00	0,00E+00
EU154	2,49E+14	2,49E+14	2,48E+14	2,44E+14	2,00E+14
EU155	1,35E+14	1,35E+14	1,35E+14	1,30E+14	9,01E+13
EU156	5,71E+15	5,48E+15	3,64E+15	5,98E+13	8,73E-05
TB160	3,90E+12	3,87E+12	3,55E+12	1,50E+12	2,68E+08
TL208	2,09E+07	2,10E+07	2,16E+07	2,81E+07	9,36E+07
PB210	1,05E-05	2,72E-03	2,72E-01	2,72E+01	2,73E+03
BI210	1,05E-05	2,72E-03	2,72E-01	2,72E+01	2,73E+03
PO210	1,05E-05	2,72E-03	2,72E-01	2,72E+01	2,73E+03
BI214	1,05E-05	2,72E-03	2,72E-01	2,72E+01	2,73E+03
PB214	1,05E-05	2,72E-03	2,72E-01	2,72E+01	2,73E+03
PO214	1,05E-05	2,72E-03	2,72E-01	2,72E+01	2,73E+03
PO218	1,05E-05	2,72E-03	2,72E-01	2,72E+01	2,73E+03
RN222	1,05E-05	2,72E-03	2,72E-01	2,72E+01	2,73E+03
RA226	1,05E-05	2,72E-03	2,72E-01	2,72E+01	2,73E+03
TH228	5,81E+07	5,82E+07	6,00E+07	7,80E+07	2,60E+08

TH230	4,59E+02	4,59E+03	4,59E+04	4,59E+05	4,60E+06
U232	2,56E+08	2,57E+08	2,59E+08	2,82E+08	4,48E+08
PA233	1,71E+10	1,71E+10	1,71E+10	1,71E+10	1,71E+10
U233	2,04E+01	2,04E+02	2,04E+03	2,04E+04	2,04E+05
PA234	5,03E+04	2,12E+05	2,31E+05	2,31E+05	2,31E+05
PA234M	1,78E+08	1,78E+08	1,78E+08	1,78E+08	1,78E+08
TH234	1,81E+08	1,81E+08	1,80E+08	1,78E+08	1,78E+08
U234	1,82E+11	1,82E+11	1,82E+11	1,82E+11	1,83E+11
U235	4,29E+09	4,29E+09	4,29E+09	4,29E+09	4,29E+09
U236	3,85E+10	3,85E+10	3,85E+10	3,85E+10	3,85E+10
PU236	1,01E+10	1,01E+10	1,00E+10	9,47E+09	5,26E+09
U237	3,15E+16	2,88E+16	1,14E+16	1,11E+12	6,74E+09
NP237	1,68E+10	1,69E+10	1,70E+10	1,71E+10	1,71E+10
PU238	8,09E+13	8,11E+13	8,15E+13	8,16E+13	8,04E+13
NP238	1,01E+16	7,52E+15	3,95E+14	1,23E+08	1,22E+08
U238	1,78E+08	1,78E+08	1,78E+08	1,78E+08	1,78E+08
PU239	7,50E+11	7,52E+11	7,57E+11	7,58E+11	7,58E+11
U239	4,12E+14	9,81E-03	0,00E+00	0,00E+00	0,00E+00
NP239	2,72E+16	2,09E+16	1,48E+15	2,31E+10	2,31E+10
NP240	5,12E+12	2,55E+06	0,00E+00	0,00E+00	0,00E+00
PU240	1,05E+12	1,05E+12	1,05E+12	1,05E+12	1,05E+12
PU241	3,20E+14	3,20E+14	3,19E+14	3,16E+14	2,80E+14
AM241	6,00E+11	6,01E+11	6,14E+11	7,39E+11	1,91E+12
PU242	4,16E+09	4,16E+09	4,16E+09	4,16E+09	4,16E+09
CM242	1,16E+14	1,16E+14	1,12E+14	7,66E+13	1,69E+12
AM242M	2,74E+10	2,74E+10	2,74E+10	2,74E+10	2,70E+10
AM242	2,22E+14	8,71E+13	3,49E+10	2,73E+10	2,69E+10
PU243	2,38E+14	1,16E+13	8,81E-01	0,00E+00	0,00E+00
AM243	2,31E+10	2,31E+10	2,31E+10	2,31E+10	2,31E+10
CM243	2,10E+10	2,10E+10	2,09E+10	2,08E+10	1,96E+10
AM244	5,12E+13	1,16E+13	4,24E+06	0,00E+00	0,00E+00
CM244	1,43E+12	1,43E+12	1,43E+12	1,41E+12	1,29E+12
CM245	6,88E+07	6,88E+07	6,88E+07	6,88E+07	6,88E+07
CM246	1,04E+07	1,04E+07	1,04E+07	1,04E+07	1,04E+07
CM248	2,28E+01	2,28E+01	2,28E+01	2,28E+01	2,28E+01
CF252	7,86E+02	7,85E+02	7,80E+02	7,31E+02	3,83E+02

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[i] Data in Annex I and II provided by Ole Reistad. The included inventories are based on calculations made for Doctoral theses at NTNU, 2008:134: O. Reistad, *Analyzing Russian Naval Nuclear Safety and Security by Measuring and Modeling Reactor and Fuel Inventory and Accidental Releases*.