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Credible release scenarios for nuclear-powered vessels operating in Nordic waters

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Abstract

The Nordic countries are surrounded by large ocean areas where there is frequent traffic of foreign nuclear-powered vessels, both naval and civilian. Increased activity of these vessels in the High North, new emerging technologies and designs, and experience from events have given a need for updating existing information, exchange views and discuss credible release scenarios for nuclear-powered vessels operating in Nordic waters. In that regard, the NKS-B CRESCENT project facilitated two workshops held with NKS funding – one in Asker, Norway, 5-6 October 2021 and one in Reykjavik, Iceland, 8-9 June 2022.

Key words

credible, scenarios, nuclear-powered, Nordic countries

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Credible release scenarios for nuclear-powered vessels operating in Nordic waters

Final Report from the NKS-B CRESCENT activity

(Contract: AFT/B(20)7)

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Disclaimer

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1. Introduction

The Nordic countries are surrounded by large ocean areas where there is frequent traffic of foreign nuclear-powered vessels, both naval and civilian. All Nordic countries have such vessels operating in their economic zones, and some countries in their territorial waters. In addition, Norway receives visits from NATO naval nuclear-powered vessels in sheltered waters or to harbour on a regular basis. New emerging technologies and designs such as floating nuclear power plants, vessels with small modular reactors etc., are of increasing concern. Having a good understanding of the risk and hazard represented by these vessels, is an important fundament for both regulation and emergency preparedness and response.

A number of previous NKS projects have been fully or partly related to understanding the hazard represented by these vessels. Some examples are NKS RAK-2 (1994-1997), NKS SBA-1 (1998-2001) and the follow-up NKS Knowledgebase (2002-2003), NKS NUCVESS (2004-2005), NKS NordThreat (2008), NKS MareNuc (2010-2011), NKS NORCOP-COAST (2015), and NKS COASTEX (2016-2017). There has been a need for complementing these projects with a project that updates the existing information on relevant nuclear-powered vessels from both Russia, China and NATO countries, and related reactor designs and fuel specifications based on open sources. In the CRESCENT project, we have reviewed past minor and major incidents and accidents, and defined credible release scenarios for radioactive material from the reactor during possible incidents or accidents. The project is meant as a foundation for a possible future project on source term estimations for nuclear-powered vessels and floating nuclear power plants in operation today.

The CRESCENT project featured two workshops during 2021 and 2022. The workshops were originally planned for 2020, but had to be postponed due to the covid-19 pandemic. Due to the pandemic, it was possible to attend the workshops by video conference.

The first workshop, 5th-6th of October 2021 in Asker outside Oslo, Norway, was related to information gathering on vessels, reactor designs, fuel specifications, past incidents and accidents, and a review of available literature. The second workshop, 8th-9th of June 2022 in Reykjavik, Iceland, was related to discussions on credible release scenarios. Findings from these workshops are summarized in this report.

The CRESCENT project was carried out in collaboration with Vysus Group (former Lloyd's Register). In addition, the project was further strengthened by the ongoing collaboration between DSA and the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) in this field.

Uncertainties will play an important role in any severe accident analysis. Due to the fact that many of the nuclear-powered vessels are naval, for which relevant information can be expected to be classified, the typical uncertainty in these cases may be even larger. Decision support models based on Bayesian Belief Networks (BBNs) represent an established method for dealing with situations with large uncertainties thanks to the possibility to formulate outcomes in terms of complex conditional probabilities depending on current observations. Also, BBNs typically do not have a minimum set of information needed to provide an estimate. For this reason, the BBN based RASTEP (Rapid Source TErm Prediction) methodology, developed by Vysus Group with support from SSM and the Horizon 2020 project FASTNET (Fast Nuclear Emergency Tools), was assessed during the project. Specifically, an outline of how the RASTEP methodology can be extended or modified to

cope with accidents in unknown systems in a marine environment was a topic at the second workshop, as part of Vysus Group's contribution to the project.

The NKS-B CRESCENT project has been funded by Nordic Nuclear Safety Research (NKS). The presentations held at the workshops have been made available to the workshop participants.

2. Project partners

The NKS-B CRESCENT seminar was organised by the Norwegian Radiation and Nuclear Safety Authority (DSA), the Icelandic Radiation Safety Authority (IRSA), the Danish Emergency Management Agency (DEMA), and the Swedish Radiation Safety Authority (SSM).

Project participants from the different organisations were:

- From DSA: Øyvind Gjølme Selnæs and Inger Margrethe Eikelmann
- From IRSA: Gísli Jónsson
- From DEMA: Agnieszka Ewa Hac-Heimburg
- From SSM: Anna Maria Blixt Buhr

3. The first workshop on 5th-6th of October 2021, Asker outside Oslo, Norway

3.1 Workshop program

The first NKS-B CRESCENT workshop was held at Holmen fjord hotel in Asker outside Oslo, Norway, on 5th and 6th of October 2021.

Tuesday 5th of October 2021

12:00 – 12:30	Welcome, practical issues (Øyvind Gjølme Selnæs, DSA) Presentation of participants

Part 1: Introduction – National EPR arrangements and approaches to NPVs

12:30 – 12:50	Overview of NPVs operating in Nordic waters and background for the NKS-B CRESCENT project (Øyvind Gjølme Selnæs, DSA)
12:50 – 13:20	Establishment of a new Norwegian harbour for receiving NPV visits and the Norwegian Guidance for application for licence for NPV visits to Norway (Inger Margrethe Eikelmann, DSA)
13:20 – 13:40	Information on NPV visits to Australia and Australian EPR arrangements (Blake Orr, Arpansa)
13:40 – 14:00	Sweden's EPR arrangements in case of an emergency at a NPV (Anna Maria Blixt Buhr and Elisabeth Tengborn, SSM)
14:00 – 14:30	Coffee break
14:30 – 14:50	DEMA's prognosis on NPVs and the visit of Charles de Gaulle in 2020 (Agnieszka Hac-Heimburg, DEMA)
14:50 – 15:10	Presentation of Iceland's EPR arrangements (Gísli Jónsson, IRSA)
15:10 – 15:30	EPR arrangements for NPVs in Finland (Aleksi Mattilä, STUK)
15:30 – 16:00	Discussions
19:00	Workshop dinner

Wednesday 6th of October 2021

Part 2: Past incidents and accidents

09:00 – 09:10	Some notable incidents with Russian NPVs in the High North (Øyvind Gjølme Selnæs, DSA)
09:10 – 09:30	The 1995 NATO/NACC Analysis of the Komomolets Accident (Steinar Høibråten, FFI)

09:30-10:00	Some notable incidents with NATO NPVs (Ingrid Dypvik Landmark, DSA)
10:00 – 10:30	Coffee break

Part 3: Reactor designs, fuel specifications and review of available literature

10:30 – 10:50	Nuclear-powered vessels: Interesting aspects related to design and fuel (Ole Reistad, IFE)
10:50 – 11:10	Russian nuclear-powered icebreakers and the floating nuclear power plant (Naeem Ul Syed, DSA)
11:10 – 11:30	Summary from past NKS projects (Øyvind Gjølme Selnæs, DSA)
11:30 – 12:00	The Australian Reference Accident Scenario from 2000 (Blake Orr, ARPANSA)
12:00 – 12:45	Submarine reactors, fuels and scenarios (Anders Riber Marklund and Sergey Galushin, Vysus Group)
12:45 – 13:00	Source term estimations (Naeem Ul Syed, DSA)
13:00 – 14:00	Lunch
14:00 – 14:15	International cooperation on maritime EPR in the Arctic (Øyvind Aas-Hansen, DSA)
14:15 – 14:30	Arctic Council EPPR RAD EG project with NPV accident modelling (Mikko Voutilainen, STUK)
14:30 – 14:45	SMR EPZ zoning size studies and proposal for a future NKS-B project (Mikko Ilvonen, VTT)
14:45 – 15:00	Closing remarks (Øyvind Gjølme Selnæs, DSA)

It was possible to participate at the workshop through video conference (Microsoft Teams).

3.2 Workshop participants

There were 21 participants to the workshop. 12 of these were physically present at Holmen fjord hotel in Asker, the rest participated through video conference.

List of participating organizations:

Norway:
- Institute for Energy Technology, Norway (IFE)
- Norwegian Defence Research Establishment (FFI)

- Norwegian Radiation and Nuclear Safety Authority (DSA)

Finland:
- Radiation and Nuclear Safety Authority of Finland (STUK)
- VTT

Iceland:
- Government of Iceland/University of Iceland
- Icelandic Radiation Safety Authority (IRSA)

Denmark:
- Danish Emergency Management Agency (DEMA)

Sweden:
- Swedish Radiation Safety Authority (SSM)

Others:
- Australian Radiation Protection and Nuclear Safety Agency (ARPANSA)
- Vysus Group

3.3 Summary of presentations

Part 1: Introduction – National EPR arrangements and approaches to NPVs

Overview of NPVs operating in Nordic waters and background for the NKS-B CRESCENT project (Øyvind Gjølme Selnæs, DSA)
The Nordic countries are surrounded by large ocean areas where there is frequent traffic of foreign nuclear-powered vessels, both naval and civilian. All Nordic countries have such vessels operating in their economic zones, and some countries in their territorial waters. In addition, Norway receives visits from NATO naval nuclear-powered vessels in sheltered waters or to harbour on a regular basis.

A number of previous NKS projects have been fully or partly related to understanding the hazard represented by these vessels. This is once again raised as a topic due to the increased activity of these vessels in the High North. New emerging technologies and designs are not necessary covered in the previous projects, and knowledge and experience withers as time passes. Having a good understanding of the risk and hazard represented by these vessels, is an important fundament for both regulation and emergency preparedness and response.

Norwegian assessments of nuclear and radiological hazards states that there has been an increase in the activities of naval nuclear-powered vessels in the High North, with an increased probability of Norway being affected by events related to such vessels close to Norway or in Norwegian waters. In addition, there has been an increase in traffic of civil nuclear-powered vessels and vessels carrying radioactive waste along the Norwegian coastline. A warmer Arctic has led to the potential use of northern sea routes, and Norwegian authorities expect that traffic between Europe and Asia through the Northeast Passage will increase in the future. This may in turn lead to an increase in the traffic of nuclear-powered vessels and vessels with radioactive cargo along the Norwegian coastline. The towing of the floating nuclear power plant Academician Lomonosov from St. Petersburg to Murmansk in

April/May 2018, and further to Pevek on the Chukotka peninsula in 2019, is an example of such new activity (NRPA 2018).

The visits of naval nuclear-powered vessels to Norway have increased significantly the last few years. From 10-15 visits per year earlier, there is now on average 30-40 visits per year.

Both naval and civilian nuclear-powered vessels operate in the area.

Notable naval nuclear-powered vessels:
The United States of America:

- Los Angeles class SSN submarines
- Seawolf class SSN submarines
- Virginia class SSN submarines
- Nimitz class CVN super-carrier

United Kingdom:

- Astute class SSN submarines
- Trafalgar class SSN submarines

France

- Rubis Améthyste class SSN submarines

Russia

- Borei class SSBN submarines
- Delta-IV class SSBN/SSAN submarines
- Delta-III class SSAN submarine
- Typhoon class SSBN submarine
- Kirov class CGKMN battle cruiser
- Severodvinsk class SSN submarines
- Sierra-II class SSN submarines
- Oscar-II class SSN submarines
- Akula class SSN submarines
- Small auxiliary SSAN submarines

In addition, Russian nuclear-powered icebreakers and the nuclear-powered transport ship Sevmorput operates in the area. The floating nuclear power plant Academician Lomonosov and other future floating nuclear power plants may be present in the area in the future.

The aim of the NKS CRESCENT project is to update existing information about these vessels and provide an opportunity to exchange knowledge and views related to credible release scenarios from them.

Establishment of a new Norwegian harbour for receiving NPV visits and the Norwegian Guidance for application for licence for NPV visits to Norway (Inger Margrethe Eikelmann, DSA)
In Norway, visits of foreign nuclear-powered vessels require both a diplomatic clearance and a licence according to the Nuclear Energy Activity Act, except for emergency situations. The Norwegian Radiation and Nuclear Safety Authority (DSA) is the highest national authority on issues related to nuclear safety and security according to the Nuclear Energy Act, and is

responsible for giving recommendations on licencing and advice in relation to the visits. In addition, DSA is responsible for national nuclear emergency preparedness and heads the national nuclear emergency preparedness organisation (NRPA 2013). The Norwegian Defence represents the licensee, hosts the visits, makes practical arrangements, ensures safety/security and emergency preparedness during the visits, issues diplomatic clearances in agreement with the Norwegian Ministry of Foreign Affairs and continuously work on emergency preparedness, safety/security, competence building etc. between visits.

DSA has recently published guidance for applications for licence under the Nuclear Energy Activities Act for visits from naval nuclear-powered vessels to Norwegian ports and territorial waters (DSA 2021b). The guidance describes requirements to

- responsibilities and management, resources and quality insurance
- documentation and storage
- competence and exercises
- area control
- risk and vulnerability analysis and design basis threats
- visit plans and safety/security
- emergency preparedness and response plans
- environmental monitoring
- information on the visiting vessel, purpose, time and place for the visit etc.
- escort and presence during the visit
- threat assessment
- particular requirements for harbours
- requirements to the vessel, incl. documentation from the visiting nation
- information to civilian authorities

In addition to the requirements to the licensee, civilian authorities make EPR preparations. Good cooperation between the Norwegian Defence as host for the visits and local and regional civilian authorities responsible for emergency preparedness and response are a requisite.

A new harbour at Tønsnes outside Tromsø in Northern Norway was opened for visits of naval nuclear-powered vessels in May 2021. The county governors are responsible for coordinating regional emergency plans in Norway, and in preparation to opening the harbour for this kind of visit, there was a close cooperation between the country governor of Troms and Finnmark, the local police, the civil defence, the municipalities, the regional hospital, the armed forces and DSA. The focus for the cooperation was notification between the authorities and emergency plans, and information to the public.

Information on NPV visits to Australia and Australian EPR arrangements (Blake Orr, ARPANSA)

Visits by allied Nuclear Powered Vessels (NPV) to Australian ports require special government planning and arrangements. An inter-departmental committee named the Visiting Ships Panel (Nuclear) (VSP(N)) was established to oversee these visits. Conditions of entry, responsibilities and procedures are detailed in a Defence operation manual OPSMAN 1 (Australian Government 2016). Since the 1970s, Australia has had approx. 240 visits from NPVs, with the vast majority of visits occurring in Western Australian and Queensland.

To assist with EPR planning and the establishment of emergency planning zones (EPZ), a Reference Accident scenario is applied for the two types of vessel visits, namely Submarines and Aircraft carriers (ARPANSA 2000). The scenario is a Contained Loss of Coolant accident (LOCA) and is used in planning to establish EPZ for precautionary and urgent response actions during a radiological emergency on a visiting NPV.

Sweden's EPR arrangements in case of an emergency at a NPV (Anna Maria Blixt Buhr and Elisabeth Tengborn, SSM)
Sweden does not have any nuclear-powered vessels (NPVs) and do not harbour NPVs. However, NPVs can drift into Swedish territorial waters and be in need of an emergency port. Thus, NPV emergencies in Sweden belong to emergency preparedness category (EPC) IV since the location is unforeseen. In SSM report 2020:15 planning documentation for protective actions for the public and emergency workers as well as scenarios (SSM 2020). The report builds on common positions in the Nordic flag book.

The reference level for the public in a nuclear or radiological emergency belonging to EPC IV is 20 mSv effective dose during the first year. Thus, in order to keep the residual doses below the reference level, dose criteria and intervention levels are given in the Report to optimise the emergency planning and response.

In SSM report 2020:15 one of the scenarios is an accident on an NPV derived from ARPANSA: The 2000 reference accident used to assess the suitability of Australian ports for visits by nuclear powered warships. The protective action evacuation is unlikely to be necessary in this scenario. However, the dose criterion for sheltering can be exceeded locally in the direction downwind (few km) from the NPV. Thus, the public announcement from the incident commander would be to encourage people present in the downwind area to shelter.

SSM has the role to support authorities responsible for public protective actions in a nuclear or radiological emergency. SSM therefore welcomes a more detailed knowledge regarding both source terms and radiological consequences in connection with nuclear emergencies involving NPVs.

DEMA's prognosis on NPVs and the visit of Charles de Gaulle in 2020 (Agnieszka Hac-Heimburg, DEMA)
Nuclear propelled vessels pass Danish waters frequently, including last year visit of the aircraft carrier Charles the Galle in the Danish harbour, therefore DEMA is increasing nuclear preparedness and response for these occasions. This includes back-up for nuclear duty officer which is available 24/7 and setting up autoprognoses with our decision support system ARGOS for nuclear propelled vessels, which are running every hour at 10 different positions in Danish waters, 24/7. These prognoses relay, among others, on precise source terms, therefore DEMA is highly interested in getting more insights on these aspects in the CRESCENT project.

In addition, DEMA is cooperating with other authorities like police and Maritime Assistance Service (MAS) regarding positional tracking of the vessel. Because of the increased public interest - mostly for submarines - communication department is also activated and prepared to post respectively messages.

Presentation of Iceland's EPR arrangements (Gísli Jónsson, IRSA)
The talk is about the EPR situation in Iceland. The size of Iceland's Exclusive Economic Zone and Search and Rescue Region in the middle of the Atlantic Ocean give rise to challenges regarding EPR arrangement for nuclear disasters. The nearest nuclear power plant is Scotland, so the worst-case scenario is a Nuclear accident on a NPV near the Icelandic coast.

EPR arrangements for NPVs in Finland (Aleksi Mattilä, STUK)
In recent years Gulf of Finland has seen visits by several nuclear powered vessels including the cargo ship Sevmorput, icebreakers and different military vessels. Construction work of nuclear powered icebreakers takes place in St. Petersburg and vessels run initial sea tests in the nearby waters. Also, the floating nuclear power plant Akademik Lomonosov was constructed in St. Petersburg towed for fuel loading to Murmansk. Gulf of Finland is also busy with ships carrying cargo, passengers and oil products moving in crossing shipping lanes sometimes in challenging winter conditions. Finland is prepared to handle maritime accidents with the Border Guard being the authority responsible for SAR capabilities. In case of a nuclear powered vessel accident, maritime SAR would be undertaken considering prevailing radiation conditions with multiple authorities supporting the first responders and estimating the safety significance and potential development of the situation. Nuclear powered vessels are considered in STUK's emergency plans. Current CRESCENT NKS project is being followed in STUK with the aim of improving existing nuclear powered vessel related dispersion modelling tools with well estimated source terms.

Part 2: Past incidents and accidents

Some notable incidents with Russian NPVs in the High North (Øyvind Gjølme Selnæs, DSA)
There have been several incidents with Russian naval nuclear-powered vessels in the High North. A short summary of some of them was given. Several of the incidents are related to fires on the hull of the vessel during maintenance work while the vessel is at dock. Other incidents are fire on board while the vessel is in open waters, or loss of ship due to bad weather or other reasons. There are also examples of reactor-related incidents.

The 1995 NATO/NACC Analysis of the Komsomolets Accident (Steinar Høibråten, FFI)
Dr. Steinar Høibråten from the Norwegian Defence Research Establishment presented *"The 1995 NATO/NACC Analysis of the Komsomolets Accident."* This study was based on a commissioned report from the Kurchatov Institute in Russia and provided detailed information about the state of the sunken submarine, measurements made at the site, inventory of radionuclides, corrosion estimates and current (as of 1995) and future releases of radionuclides. Estimates of ocean transport and uptake of these radionuclides in the food chain led to the conclusion that *"the sunken nuclear submarine Komsomolets represents no significant hazard to man, today or in the future."*

Some notable incidents with NATO NPVs (Ingrid Dypvik Landmark, DSA)
A short presentation of known incidents and accidents with NATO NPVs comprising vessels from France, UK and the US and mainly attack submarines. As noted in several of the presentations, when it comes to incidents involving military vessels, we know very little besides what has been reported by the media. As far as we know there has been no known

release of radioactive material from these incidents. But the overview still shows that accidents happen and are caused by both human errors and technical failures.

Part 3: Reactor designs, fuel specifications and review of literature

Nuclear-powered vessels: Interesting aspects related to design and fuel (Ole Reistad, IFE)

A presentation on aspects related to reactor design and fuel for Russian nuclear-powered vessels was given, with reference to work in earlier NKS projects and Reistad's doctoral thesis on Russian naval nuclear safety and security (Reistad 2008).

Russian nuclear-powered icebreakers and the floating nuclear power plant (Naeem Ul Syed, DSA)

Russian nuclear ice breaker fleet is used for escorting caravans in open and shallow waters of the Northern sea route corridor. For this purpose, the Rosatomflot uses a fleet of six icebreakers and light aboard ships:

- Arktika – 8.15k hp using 2x175 MW_{th} reactors of RITM-200 type
- Yamal – 75k hp, using 2x 171 MW_{th} reactors of OK-900A type
- 50 Let Pobedy 75k hp, using 2x 171 MW_{th} reactors of OK-900A type
- Taymyr – 50k hp, using 1x 171 MW_{th} reactors of KLT-40M type
- Vaygach 50k hp, using 1x 171 MW_{th} reactors of KLT-40M type
- Sevmorput – 40k, using 1x 135 MW_{th} reactors of KLT-40 type

From the above list one can notice that three reactor types are used in the operational nuclear icebreakers and light board ship: OK-900A, KLT-40 and RITM-200.

The reactor types OK-900 A and KLT-40(M) are second generation reactors, having a modular layout of reactor pressure vessel, recirculation coolant pumps, steam generators and pressurizer. The main difference is that KLT-40 reactor is employed in limited draft icebreakers and light board ships for their mobility in shallow waters, while OK-900 A is used in heavy draft icebreakers for their use in open deep sea.

RITM-200 is a 3rd generation reactor, employing an integrated steam generator inside reactor pressure vessel. It has both passive and active safety systems and has a longer lifetime of 40 years as compared to 20-25 years lifetime of OK-900A and KLT-40 reactors. The RITM-200 reactor is used in double draft, multipurpose icebreaker for its usage both in the open and shallow sea.

Russia launched its first floating nuclear power plant (FNPP) Akademik Lomonosov using 2x135 MW_{th} reactors of KLT-40S type. The plant is operational in Pevek, Chukotka region since December 2019. For the future optimized floating power units OFPUs, an evolutionary design RITM-200M reactor may be used.

With this overview, it is concluded that it is of common interest of Nordic countries to get a better understanding of new evolving and modernized Russian technology in nuclear powered icebreakers and floating power plants. It will also be beneficial to estimate source term(s) for one or more accident scenarios in these reactor types.

Summary from past NKS projects (Øyvind Gjølme Selnæs, DSA)

A summary of past NKS projects on nuclear-powered vessels was given. These projects were:

- NKS RAK-2 (1994-1997): Accidents in Nuclear Ships, where the project gave a discussion on types of nuclear vessels accidents, in particular accidents which involve the nuclear propulsion systems, and available information on 61 reported nuclear ships events, comparison between reported Soviet accidents and information available on dumped and damaged Soviet naval reactors, and an analysis of the accidents and estimate of accident probabilities.
- NKS SBA-1 (1998-2001): The Potential Risks from Russian Nuclear Ships, with a review of information available on Russian nuclear-powered ships, information on decommissioned vessels, their storage sites and the procedures planned for further decommissioning work, handling of spent fuel, consideration on various types of accidents which might occur with examples, and measures taken by Russia to avoid such accidents.
- NKS Knowledgebase (2002-2003): Nuclear Threats in the Vicinity of the Nordic Countries – Supplementary Report, with an online database with information on possible nuclear threats in the vicinity of the Nordic countries, including nuclear installations such as nuclear power plants, ship reactors and storage, and handling of used fuel and radioactive waste.
- NKS NUCVESS (2004-2005): Inventory and Source Term Evaluation of Russian Nuclear Power Plants for Marine Applications, with a discussion og inventory and source term properties in regard to operation and possible releases due to accidents, discussion on relevant accidents, and on most important factors for the source term, reactor operational characteristics and radionuclide inventory.
- NKS NordThreat (2008): Nordic Threat Assessments, a seminar on revised threat assessments in the Nordic countries due to changes in the international security environment with several topics related to nuclear-powered vessels, such as overview of possible scenarios, spent nuclear fuel at Andreev Bay, Russian Nuclear Submarine Accident Survey 1959-2007, and public perception of radionuclear threats.
- NKS MareNuc (2010-2011): A Nordic Approach to Impact Assessment of Accidents with Nuclear-Propelled Vessels, with identified parameters in a graded approach to impact assessment for marine nuclear reactors, reports on Nordic approaches to safety evaluation, impact assessments and EPR organization, and a report on the Canadian approach for international port calls.
- NKS NORCOP-COAST (2015): Workshop on icebreaker traffic and transport of radioactive material along the Nordic coastline, where existing EPR systems, possible scenarios and capabilities in each country, notification procedures and interaction between countries were topics discussed.
- NKS COASTEX (2016-2017): Scenarios and table top exercise concept on events related to traffic of nuclear-powered vessels and transportation of spent nuclear fuel along the Nordic coastline, which resulted in a report on nine maritime accident scenarios and an exercise guide.

The Australian Reference Accident Scenario from 2000 (Blake Orr, ARPANSA)

The Reference Accident scenario is a planning tool for EPR arrangements during NPV visits. The chosen scenario of a contained LOCA, is used to represent the upper bound risk to the surrounding population. The scenario was first established in 1976, and later supported through a parliamentary committee in 1989. At the request of the VSP(N), an update was undertaken and published in 2000, while still maintain the overall contained LOCA scenario. Two vessel types are considered for the Reference Accident, Los Angeles class submarines and Nimitz class Aircraft carrier.

To estimate the core inventory, the simplified Bateman equation approach is applied. This equation estimates the nuclide activity in the inventory based on the reactor power, load factor of the reactor, fission yields, and number of fissions produced per Megawatt of thermal power. In the Reference accident approach, during the LOCA, fission products are instantly removed from the core into containment based on their relative volatility. Release to the environment is via slow leaks in containment, with a primary (reactor containment) and secondary (vessel hull) reducing atmospheric emissions.

In 2020, ARPANSA in collaboration with DSA, commissioned Lloyd's register (now Vysus group) to undertake a review of the Reference Accident methodology. Based on the findings of the review, it was ARPANSA's assessment that a revision to Reference Accident is required within the next 3 years. A program is currently being setup to undertake this work. Collaborations through projects such as NKS-CRESCENT offer valuable assistance to the update of Reference Accident.

Submarine reactors, fuels and scenarios (Anders Riber Marklund and Sergey Galushin, Vysus Group)

The word *"credible"* of the CRESCENT project title raises the question of what exactly a *"credible"* scenario is. In traditional safety & licensing of nuclear power systems, notions such as design basis and beyond design basis accidents are common, together with quantitative measures such as core damage frequency, acceptable and unacceptable release frequencies. As a large fraction of the nuclear-powered vessels operating in Nordic waters are naval vessels, where information on the safety design is (and will remain) classified, assessment of risks becomes a challenge for the typical regulatory framework which is driven by quality assurance of processes and data as well as verification and validation of codes and systems.

A possible interpretation of a *"credible scenario"* therefore partly has to come from other considerations, for example a scenario or set of scenarios that does not seem incredible, but at the same time ensures that all potential emergency response measures will be exercised to a reasonable level.

Even with the above definition, some level of safety assessment of unknown systems will have to be made. This needs to be based partly on open (but uncertain) information and partly on engineering judgement. Valuating the impact of the uncertain information and finding a good balance between too much and too little guessing thereby become two key questions for emergency preparedness and response in this field.

Typical emergency preparedness and response relies on the notion of emergency planning distances. To create such distances using dose predictions, source terms must be estimated and propagated through an atmospheric dispersion model and thereafter a dose calculation model. State-of-the-art source term assessment of an unknown system can roughly be outlined by the following scheme:

1. Create a core inventory estimate
2. Assume an accident sequence. A classical choice would be an unmitigated LOCA with intact containment. Based on this:
    a. Define fuel release fractions based on publicly available information, such as NUREG-5747 (US NRC 1993) and NUREG-1465 (US NRC 1995).

b. Use simplified approaches to model retention in reactor compartment (containment) and vessel hull, based on experimental evidence or simplified models, e.g. NUREG-6189 (US NRC 1996).
c. Assume environmental release rates from the containment based on the accident sequence.

The scheme can be repeated e.g. to create a database of various core inventories and accident types.

Core inventories correlate, although not one-to-one, with the absolute burnup level, i.e. the number of split heavy atoms in the reactor. This quantity van be estimated based on nominal core power, time since refueling, average capacity and load factors, and can thereby be used 1) to compare risk levels of different vessels by estimating a less complex quantity than the core inventory and 2) to assess for which burnup levels core inventory simulations and sensitivity studies could be made. For example, NKS-139 contains a few core inventories calculated based on assumptions on detailed reactor designs (NKS 2006). A hypothesis based on preliminary investigations made during the CRESCENT project is that these NKS-139 inventories are somewhat on the low side for the older and larger US naval reactors, relevant for UK naval reactors and too large for French naval reactors.

Concerning accident sequences, the example of unmitigated LOCA with intact containment stems from the historically used maximum credible accident scenario, traditionally used as design basis for reactor containments. However, accident sequences with bypass of the containment or various physical phenomena failing the containment integrity are, a priori, fully possible. Their frequency is probably relatively low compared to the core damage frequency. For commercial nuclear power, an often-used target is that the large release frequency (which more or less can be directly translated as the frequency of accidents including bypass or failure of the containment) should be about 1 % of the core damage frequency. It is difficult to state to which extent these numbers would translate to naval reactors. For example, on one hand, their containments probably have a higher design pressure than commercial plants, but on the other hand, their containments volumes are much smaller. Regarding bypass scenarios for submarine reactors, it has been noted that they may very well be equipped with a shutdown residual heat removal system, e.g. for use in port, cooling the primary system directly with seawater, thereby creating a potential release path directly to the marine environment in case of heat exchanger failure in this system.

The selection of relevant accident sequences might also be informed by statistics of known events. Here, a comprehensive compilation of accident statistics for a long period of time up until today is lacking although some preliminary compilation has been made within the CRESCENT project. The conclusion of this is that the absolute number of incidents has decreased, it is not entirely clear to what extent this is due to lower naval activity overall after the cold war and to what extent it is due to real safety improvement. There seem to be no reports on naval system LOCAs or criticality accidents since the end of the cold war.

Some remarks on interpretation and wording in texts on this topic:

- Contamination of crew does not imply core damage (due to neutron induced activation).
- Significant release can occur with gap (fission gas) release only (no core melt).
- Any leakage from the primary system is, by definition, a LOCA. If the LOCA is followed by failure of safety injection systems or failure of residual heat removal, it is

called an unmitigated LOCA, which will lead to core damage if safety functions are not restored in time. If the reactor compartment (containment) is not intact or bypassed during a LOCA scenario, it is called an uncontained LOCA. The notions of unmitigated/uncontained LOCA are sometimes mixed up.

Source term estimations (Naeem Ul Syed, DSA)
In Norway emergency response planning has largely been based on nuclear power plants abroad and the two Norwegian research reactors at Kjeller (2 MW) and Halden (25 MW). Since both these research reactors have now been permanently shut down, the emphasis has been shifted more towards nuclear powered vessels such as submarines, icebreakers and floating NPPs. Since, such sources may lead to serious consequences if a large accident would occur somewhere along the Norwegian coast – or at a port of call.

The method of determining the source term is such that an initial worst-case scenario is set for various reactor types and power plants. In the pre-calculated source terms, seven radionuclides (^{133}Xe, ^{131}I, ^{88}Rb, ^{137}Cs, ^{132}Te, ^{90}Sr, ^{99}Mo) are used for the air dispersion modelling. Standard source terms for the following reactor types have been precalculated:

- Generic Boiling water reactor (BWR)
- Generic Pressurised water reactor (PWR)
- Generic VVER reactor V213
- Nuclear Powered Vessels
- IAEA source term database

For the generic PWR and BWR RApid Source TErm Prognosis (RASTEP) program is used.

During an accident or exercise an initial worst case is used. Later-on getting information on the state and condition of the nuclear power plant, the *"real source"* is estimated and used in the air dispersion modelling.

For nuclear powered vessels an updated source term is under development.

International cooperation on maritime EPR in the Arctic (Øyvind Aas-Hansen, DSA)
The Emergency Prevention, Preparedness and Response (EPPR) Working Group of the Arctic Council works to promote the protection of Arctic inhabitants and livelihoods and the Arctic environment from emergencies, and strives to be the premier international forum for cooperation on emergency prevention, preparedness and response to advance risk mitigation and improve response capacity and capabilities in the Arctic. The EPPR has three expert groups, with the Radiation Expert Group (RAD EG)'s mandate being to facilitate the implementation of the EPPR mandate and strategic plan framework regarding radiological and nuclear emergencies.

The EPPR and its RAD EG has a special focus on cooperation projects between the eight Arctic States to improve prevention, preparedness and response to maritime radiological and nuclear emergencies in the Arctic. This work includes the ARCSAFE-project report (a deliverable to the 2019 Arctic Council Ministerial meeting) (EPPR 2019), and the three project reports RADEX 2019 Tabletop Exercise (EPPR 2021a), the RADSAR Sharing of competence within search and rescue (SAR) operations in a radiological or nuclear event at sea project (EPPR 2021b), and Radiological/nuclear risk assessment in the Arctic (EPPR

2021c) (all deliverables to the 2021 Arctic Council Ministerial Meeting). All reports are available on www.eppr.org and in the Arctic Council archive.

Arctic Council EPPR RAD EG project with NPV accident modelling (Mikko Voutilainen, STUK)

A project plan of new work under preparation was presented. Recently, Radiation Expert Group (RAD EG) in working group Emergency Prevention, Preparedness and Response (EPPR) under Arctic Council have estimated risks related to nuclear and radiological events in Arctic region (Unpublished work). They have identified two risks as moderate risks with increasing trend: 1. Nuclear Powered Vessel (NPV) accident, and 2. Transit of a Floating Nuclear Power Plant (FNPP). Furthermore, similar analyses may be performed for Small Modular Reactor (SMR) accident if enough support from other members of RAD EG will be received. In risk evaluation report, SMR accident was evaluated as small risk with increasing trend. The consequences of atmospheric releases to people, environment and rescue personnel due to the accidents will be evaluated. In NPV and FNPP accidents, a KLT-40 type reactor will be used. The inventories and release fraction available in previous NKS-reports will be used for two different locations (coastal and open sea). In NPV accident, release fractions related to criticality accident are assumed while in FNPP accident release fractions relate to ones of industrial fire (<900 °C). The dispersion modelling and dose assessment will be performed using JRODOS and the tools provided by it. The data is assessed with probabilistic approach with changing weather conditions. The results are compared with the dose criteria for different protective actions given by IAEA GSR part 7 (IAEA 2015), and Radiation safety authorities of Nordic countries in "Nordic Flagbook" (Nordic Flagbook 2014).

SMR EPZ zoning size studies and proposal for a future NKS-B project (Mikko Ilvonen, VTT)

VTT gave a presentation on recent studies on determining the appropriate sizes for emergency planning zones (EPZ) of small modular nuclear power plants (SMR). VTT has developed a preliminary conceptual design of a small district heating and desalination reactor (LDR-50). Offsite dispersion and dose assessments have been performed for LDR and also some commercially available foreign SMR types. Because there is huge uncertainty about the possible accidental atmospheric radioactive source terms, a scheme has been devised for fast dose calculations with varying release fractions of element groups. Dose results can then be expressed as probability distributions, resulting from variations in both weather and source term. Doses have been calculated using ARANO and MACCS codes for various exposure pathways, integration times and distances. By comparing with generic dose criteria (e.g. in IAEA GSR Part 7), distances can be found where protective actions would be needed. VTT also presented a proposal for an NKS-B project about old & new radiological threats near the Nordic countries, using partially the same methodology as for SMR EPZ.

4. The second workshop on 8th-9th of June 2022, Reykjavik, Iceland

4.1 Workshop program

The second NKS-B CRESCENT workshop was held at Center Hotels Plaza in Reykjavik, Iceland, on 8th and 9th of June 2022.

Wednesday 8th of June 2022

09:00 – 09:30	Welcome, practical issues (Øyvind Gjølme Selnæs, DSA) Presentation of participants
09:30 – 10:00	Summary from Workshop 1 at Holmen fjordhotell, 5-6 October 2021 (Øyvind Gjølme Selnæs, DSA)

Part 1: Ship and reactor safety, emergency preparedness

10:00 – 10:20	Source term emergency preparedness ARGOS prognoses (submarines, icebreakers, Charles de Gaulle) (Agnieszka Ewa Hac-Heimburg, DEMA)
10:20 – 10:40	Norwegian emergency preparedness regarding passage of foreign ships with nuclear reactors (Inger Margrethe Eikelmann, DSA)
10:40 – 11:00	Coffee break
11:00 – 11:30	The ARPANSA reference scenario – assumptions and constraints, core inventory sensitivity analysis and current project on scenario update (Blake Orr, ARPANSA)
11:30 – 12:00	How the RASTEP methodology can be extended or modified to cope with accidents in unknown systems in a marine environment (Anders Riber Marklund, Vysus group)
12:00 – 13:00	Lunch
13:00 – 13:45	Ship accidents and potential ship accidents (Stein Haugen, Safetec AS)
13:45 – 14:15	Hazard analysis of sunken Komsomolets (Naeem Ul Syed, DSA)
14:15 – 14:30	New offsite dose calculations for NuScale and VTT's LDR-50 heating reactor, and NKS proposal for 2023 (Mikko Ilvonen, VTT)
14:30 – 14:45	Coffee break
14:45 – 15:00	Consequence assessment for scenarios related to visits from nuclear-powered vessels to Tromsø industrial harbour (Øyvind Gjølme Selnæs, DSA)
15:00 – 15:15	Questions and comments

15:15 – 15:30 Summary of day 1

19:00 Workshop dinner

Thursday 9th of June 2022

Part 2: Work on credible release scenarios

09:00 – 09:15 Introduction to discussions (Øyvind Gjølme Selnæs, DSA)

09:15 – 11:45 Discussions (chair: Inger Margrethe Eikelmann, DSA)
- Choice of scenarios
- Implications of the scenarios on release pathways and source term estimations

11:45 – 12:00 Closing remarks (Øyvind Gjølme Selnæs, DSA)

It was possible to participate at the workshop through video conference (Microsoft Teams).

4.2 Workshop participants

There were 18 participants to the workshop. 13 of these were physically present at Center Hotels Plaza in Reykjavik, the rest participated through video conference.

List of participating organizations:

Norway:
- Norwegian Radiation and Nuclear Safety Authority (DSA)
- Safetec AS

Finland:
- Radiation and Nuclear Safety Authority of Finland (STUK)
- VTT

Iceland:
- Government of Iceland/University of Iceland
- Icelandic Radiation Safety Authority (IRSA)

Denmark:
- Danish Emergency Management Agency (DEMA)

Sweden:
- Swedish Radiation Safety Authority (SSM)

Others:
- Australian Radiation Protection and Nuclear Safety Agency (ARPANSA)
- Vysus Group

4.3 Summary of presentations

Summary from Workshop 1 at Holmen fjordhotell, 5-6 October 2021 (Øyvind Gjølme Selnæs, DSA)
A brief summary of the first workshop was given, with reference to nuclear-powered vessels operating in Nordic waters, previous NKS projects on this topic and the aim of the NKS-B CRESCENT project.

Since the beginning of the project, the Russian invasion of Ukraine 24th of February 2022, the ongoing war and its implications for nuclear safety for nuclear facilities in Ukraine, has led to a renewed focus on nuclear safety and possible release scenarios from the facilities, including the understanding of what is regarded as "credible". International statements and rhetoric have made the use of tactical nuclear weapons in the relation to the war a much more foreseeable scenario. The NATO applications of Sweden and Finland, and their impending membership in the alliance, will have security political implications in the Baltic Sea region. Australia is renewing their submarine fleet, and has opted for reactor-powered submarines. The ongoing covid-19 pandemic has given many opportunities for lessons learned for national emergency preparedness, and several evaluation reports are emerging, with experience and lessons learned relevant also for nuclear emergency preparedness. These are relevant issues also for nuclear-powered vessels, their operations, and our understanding of safety issues, credible scenarios, and emergency preparedness.

Part 1: Ship and reactor safety, emergency preparedness

Source term emergency preparedness ARGOS prognoses (submarines, icebreakers, Charles de Gaulle) (Agnieszka Ewa Hac-Heimburg, DEMA)
A presentation of the Danish nuclear emergency preparedness organization was given. Nuclear-powered icebreakers and submarines pass Danish waters frequently. Danish authorities regularly make dispersion prognoses at ten different locations during their passage, using the RIMPUFF dispersion model in ARGOS. Autoprognoses are made every hour while the vessel is in Danish territory.

There is an increased nuclear preparedness during the passing of a nuclear-powered vessel. There is a back-up for the nuclear duty officer, communication efforts are made (mostly for submarines) due to public interest, autoprognoses are routinely made, and there is a positional tracking of the vessel through the Marine Assistance Service (MAS). DEMA cooperates with other Danish authorities such as MAS and the police.

During March 2020, Denmark received a visit from the French nuclear-powered carrier Charles de Gaulle. A presentation of the increased nuclear preparedness and response during the passing of the carrier was given, including the use of measurement teams and the use of two mobile measurement stations (GM) on land.

Norwegian emergency preparedness regarding passage of foreign ships with nuclear reactors (Inger Margrethe Eikelmann, DSA)
There have been significant changes in nuclear threats and hazards in the High North the last years. There has been an increase in military activities in the north and with operations of

naval reactor-powered vessels. The war in Ukraine also has implications in the north. There is a presence of nuclear-powered icebreakers and transports of nuclear and radioactive material. The use and transport of the floating nuclear power plant Academician Lomonosov is a new activity. Russia is currently developing and testing new nuclear-powered weapons systems. Terrorism, criminal acts and war are also relevant issues. Therefore, nuclear emergency preparedness is high on the agenda in Norway, and it is important to discuss future threats and hazards. Emergency preparedness challenges in the High North is an important topic for the Norwegian Radiation and Nuclear Safety Authority (DSA), and its strengthening is one of our main focus areas.

On numerous occasions, nuclear-powered vessels are sighted during passage or visits to Norwegian waters or harbours. These sightings are of high public interests, and are frequently reported by the media. Norwegian authorities' emergency preparedness related to this activity is also of high public interest. The local and regional emergency preparedness regarding nuclear-powered vessels in Northern Norway has been developed in cooperation between the country governors, the DSA, the Joint Rescue Coordination Centre (JRCC), the Norwegian Defence, the coastguard, the Civil Defence, local police, regional health authorities, the regional hospital in Tromsø and NOR VTS in Vardø.

There is an established emergency preparedness related to nuclear-powered vessels in or outside Norwegian territorial waters. In addition, on occasion additional emergency preparedness efforts are put in place. During the visit of the US reactor-powered Nimitz class super-carrier Harry S Truman to outer Vestfjorden in the autumn of 2018, this was the case. Mobile air filter stations and RADNETT stations were stationed at several locations surrounding the operation area of the visiting vessel. Sea water samples were taken both before and during the visit. Personnel from the Norwegian Coastal Administration and the Civil Defence were trained in operating monitoring instruments.

The ARPANSA reference scenario – assumptions and constraints, core inventory sensitivity analysis and current project on scenario update (Blake Orr, ARPANSA)
The original Reference Accident was created in 1976. In 1989, a Senate committee supported the use of the scenario for Reference accident. In 1996, the Visiting Ships Planel (Nuclear) requested an update to Reference accident, while still maintaining the overall scenario, and in 2000, an updated reference accident was published (ARPANSA 2000).

The 2000 Reference Accident covers visits from both nuclear-powered carriers and nuclear-powered submarines. The initiating event is a Loss of Coolant Accident (LOCA). core inventory is based on estimates of reactor power and operating history. Primary and secondary containment remain intact. There is a leak from the containment resulting in environmental releases. The consequence assessment in the Reference Accident is based on gaussian plume dispersion with simple weather.

In the 1989 Senate report, the likelihood for a contained LOCA was estimated to be no greater than 1 in 10,000 reactor years. The likelihood for an uncontained LOCA was estimated to be no greater than 1 in 1,000,000 reactor years. In the 2000 Reference Accident report, the likelihood for an accident during a 4-5 day visit was estimated to be less than 1 in 1,000,000 per reactor. The report stated that other events (e.g. vessel grounding, containment failure) need not be considered due to extremely low probability.

In the Reference Accident, the LOCA occurs essentially "instantly" and fission products are removed from the core into the containment. Fission products are removed from being "airborne" in the containment by three broad mechanisms:

- Radioactive decay
- Leakage out into the environment
- Deposition on the containment walls

Regarding the release from the containment, two levels of containment are being used. The primary containment is the reactor containment, with an estimated release of 1 % of the volume per day (VPD). The secondary containment is the vessel hull, with an estimated release of 10 % of the volume per day (VPD). The duration of the release is set to be the same as the port removal time according to emergency response plans, i.e. 2 hours for aircraft carriers and 4-24 hours for submarines.

Comparison of the ARPANSA source terms with others were made.

Using gaussian plume dispersion modelling, suitable sizes for emergency planning zones were calculated.

The 2000 Reference Accident has recently been reviewed by Vysus group, jointly commissioned by ARPANSA and DSA. The final report was delivered in November 2020. The main findings of the review were presented. Based on this analysis, a number of areas for improvement have been identified. The current reference accident requires updating, and the estimated timeframe for this work is three years.

How the RASTEP methodology can be extended or modified to cope with accidents in unknown systems in a marine environment (Anders Riber Marklund, Vysus group)
A presentation of the background and basic idea of RASTEP was given. RASTEP (Rapid Source TErm Prediction) is a software tool for nuclear emergency preparedness and response, using tailored probabilistic models based on Bayesian Belief Networks together with pre-calculated source terms, for decision support in situations with scarce or uncertain information. Vysus Group (previously Lloyd's Register) has developed the tool, the methodology and various plant models over more than ten years in cooperation with SSM, the EU Horizon 2020 FASTNET project, DSA and RINPO.

For marine reactor systems, the RASTEP method bring a structured way of using small amounts of known boat and event information to select a reasonable total source term and uncertainty estimate. Plant types and variations are abundant. Model-building can be based on available statistics, logical relations as well as pre-determined in-principle decisions on what assumptions to use in what situations.

The full set of possible source terms for use in an emergency situation with a marine reactor can be built into a RASTEP model without problem. A Bayesian Belief Network (BBN) model can also be built easily. However, statistics are scarce and informative observations are few. A RASTEP model of a known commercial plant typically helps in identifying the most likely outcome in a complex set of possible scenarios, based on Probabilistic Safety Assessment (PSA), pointing out a representative source term. A RASTEP model of unknown systems in the marine environment will typically help in structuring the choice of a reasonable source term and uncertainty estimate for a complex set of possible plant types, based on pre-

determined in-principle decisions. Model building effort is judged to be low, but setting up the in-principle decisions to be modelled might take some discussion time.

Ship accidents and potential ship accidents (Stein Haugen, Safetec AS)
The presentation briefly presents some accidents that have occurred and where the consequences have been severe or potentially could have been severe. Examples of collisions, grounding and fires are included, in particular the collision between the Norwegian frigate KNM Helge Ingstad and the oil tanker MT Sola TS in 2018 should be mentioned as a recent example of the vulnerability also of naval ships. The collision led to the sinking and subsequently wrecking of the frigate.

Types of accidents are discussed and they can be broadly grouped into three categories: Impacts, Fire and explosion, Stuck in ice and stability-related accidents (several). In general, the consequences can be loss of buoyancy, loss of stability, loss of integrity of the ship or fire/explosion damage. The probability of serious accidents is quite high, with an annual probability of loss per shipyear of $4.2 \cdot 10^{-4}$ per year since 2019.

Of the impact accidents, grounding have the potential to be most severe, mainly because the damage length can be extensive when grounding on rocks. Collisions can cause larger penetration into the ship side but is normally not that severe and is not very likely to penetrate to a reactor located around the centerline of the ship. A specific aspect of ship accidents is that the duration can be very long.

Hazard analysis of sunken Komsomolets (Naeem Ul Syed, DSA)
The Russian sunken submarine Komsomolets, which sank on 7th of April 1989 and currently rests on the seabed at a depth of 1673 meters south west of Bear Island in the Barents Sea, has been subject of numerous expeditions and investigations. Radioactive leakage from the wreckage has recently been discovered. The reactor safety of the ship has previously been evaluated, and focus has been on the environmental monitoring around the ship.

A project has now been initiated to review the nuclear safety of the sunken Komsomolets. The project is divided into five main tasks and other subtasks. The main tasks are

- Task A: Detailed Hazard analysis on the present safety condition of nuclear material in Komsomolets
- Task B: Simulating and determining the present source term
- Task C: Long term safety analysis including material degradation and oceanographical calculations
- Task D: Determination of list of possible scenarios with expected outcomes
- Task E: Recommendations of necessary mitigation plans

The project will be finalized within 2022.

New offsite dose calculations for NuScale and VTT's LDR-50 heating reactor, and NKS proposal for 2023 (Mikko Ilvonen, VTT)

Nuscale is a near-deployable, small modular reactor. There is great interest in the design, particularly in Finland, and public data is available. A presentation of NuScale was given, including hypothetical accidents and escape route of fission products. Low leak rates make

the atmospheric release very slow and facilitate retention/depletion of aerosol fission products by deposition processes, chain decay and dilution. However, larger releases are possible e.g. by containment bypass.

The LDR-50 heating reactor is a novel VTT reactor design. It is based on a 50 MW_{th} reactor with the purpose of low-temperature district heating and desalination. It can be built above ground, underground in rock caverns or used to retro-fil fossil fuel plants. It has a very small power, is easy to cool and has a very small core reactor inventory. LDR-50 passive decay heat removal was described, as well as assumed release fractions with dose calculations using ARANO with statistical weather data. Doses were calculated as linear combination from nuclide group release fractions.

A new NKS project for 2023 was proposed, related to a review of radiological threats near the Nordic countries. The aim of the project is an attempt to quantify the threats.

Consequence assessment for scenarios related to visits from nuclear-powered vessels to Tromsø industrial harbour (Øyvind Gjølme Selnæs, DSA)
In preparation to receive visits from naval nuclear-powered vessels to Tromsø industrial harbour at Tønsnes in Northern Norway, a consequence assessment was made for the visits by the Norwegian Radiation and Nuclear Safety Authority (DSA) (DSA 2021a).

The consequence assessment is based on ARPANSA's 2000 Reference Accident (ARPANSA 2000). Atmospheric dispersion prognoses were made based on 478 different weather situations the previous year. Of these, four different weather situations were singled out as having an impact in different ways. These were:

- Passage of plume towards the municipalities north of Tromsø
- Plume having impact on Tromsøya (with Tromsø city centre) and Kvaløya (the largest two islands)
- Plume having impact locally, the population closest to the harbour
- Plume having impact over large geographical areas, and most of Tromsø municipality.

Consequences were assessed with emphasis on doses to humans and consequences for food production on land. Distances for relevant protective actions were calculated, based on dose criterias following the Nordic recommendations and guidelines (Nordic Flagbook 2014). Maritime dispersion of radioactivity or consequences for maritime food production, doses to biota, and local conditions, such as demographics, critical infrastructure, local food production etc. was not considered as part of the assessment.

Part 2: Work on credible release scenarios

Discussions (chair: Øyvind Gjølme Selnæs, DSA)

Main topics for the discussions were:

- Choice of scenarios
- Implications of the scenarios on release pathways and source term estimations

The probability of serious accidents impacting a ship is quite high. Conventional accidents which initially is not related to the reactor, may still have reactor safety implications, with a corollary impact on e.g. the reactor itself, reactor compartment, reactor safety systems, or reactor personnel. Collisions, groundings, fires, explosions etc. may have severe

consequences even on large naval ships, with the collision between the Norwegian frigate KNM Helge Ingstad and the oil tanker MT Sola TS in 2018 as a recent example. The collision led to the sinking and subsequently wrecking of the frigate.

When it comes to what kind of ship accident scenarios are the most critical, a 90 degrees impact (collision) may possibly breach containment directly. A sideways collision may rip the ship open, but it is not likely that the containment will be breached. A grounding is also unlikely to breach containment.

Of the impact accidents, grounding have the potential to be most severe, mainly because the damage length can be extensive when grounding on rocks. Collisions can cause larger penetration into the ship side but is normally not that severe and is not very likely to penetrate to a reactor located around the centerline of the ship. A specific aspect of ship accidents is that the duration can be very long.

There are specific aspects of ship reactors that are different from land-based reactors. On board a ship, there is much more vibrations. Equipment qualified for onshore use is not necessarily acceptable on a ship. The hull beam is not a static structure. It can distort quite extensively in high waves or at depths, giving forces in the equipment of the vessel.

An explosion may have a significant impact on the hull of a vessel, e.g. as in the Kursk accident in 2000. If the ship hull no longer offers as much protection against a radioactive release, this will clearly have an impact on the source term, and assumptions regarding how much is released and the release rates.

It is probably too easy to conclude that groundings and collisions need not be considered. There is a need to understand the scenarios better and to determine if they need to be taken into account. Fires on ships can last for a long time, up to weeks. Fires are credible threats to the nuclear power plant onboard. Separation as a barrier against impact from fires is not possible in the same way on a ship as on land, simply due to space restrictions. Long-lasting fire protection of a reactor and support structures may also be more difficult to achieve. Fire can also weaken the support structure under the reactor. Steel that is exposed to fire will weaken rapidly and will lose its strength, and start to stretch and/or bend. This may have a significant effect on reactor safety.

A key issue is where an accident happens. A fire can start at any time and in any location, grounding can only happen during inshore navigation, collisions can in principle happen anywhere, although most likely fairly close to shore or inshore, where traffic is most dense. Collisions, at least serious collisions, are unlikely in port due to low speed. Handling of the situation also depends on the location of the accident.

It may be possible to establish a qualitative description of a set of scenarios and rank them according to likelihood (plausible, credible, etc.). Simple quantitative analysis of ship accidents may support this.

5. Conclusions

The aim of the NKS-B CRESCENT project was to review and update existing information, exchange views and discuss credible release scenarios for nuclear-powered vessels operating in Nordic waters. The project facilitated two workshops, one in Norway in October 2021 and one on Iceland in June 2022. In total 26 people participated in the workshops. APRANSA, Vysus group (former Lloyd's Register) and Safetec AS gave valuable contributions to the project. The contributions from Vysus group and Safetec AS were financed by the Norwegian Radiation and Nuclear Safety Authority (DSA).

A number of previous NKS projects have been fully or partly related to understanding the hazard represented by these vessels. This is once again raised as a topic due to the increased activity of these vessels in the High North. New emerging technologies and designs are not necessary covered in the previous projects, and knowledge and experience withers as time passes. Having a good understanding of the risk and hazard represented by these vessels, is an important fundament for both regulation and emergency preparedness and response.

In the CRESCENT project, we have reviewed past minor and major incidents and accidents, the experience from previous NKS projects, current reference scenarios in use and experience from other ships accidents not related to nuclear propulsion. The project aimed to define credible release scenarios for radioactive material from the reactor during possible incidents or accidents, and was meant as a foundation for a possible future project on source term estimations for nuclear-powered vessels and floating nuclear plants in operation today.

The probability of serious accidents impacting a ship is quite high. Conventional ships accidents can be broadly grouped into three categories: Impacts, Fire and explosion, Stuck in ice and stability-related accidents (several). In general, the consequences can be loss of buoyancy, loss of stability, loss of integrity of the ship or fire/explosion damage. Conventional accidents which initially is not related to the reactor, may still have reactor safety implications, with a corollary impact on e.g. the reactor itself, reactor compartment, reactor safety systems, or reactor personnel. The reactor may e.g. be impacted by being turned over, having the reactor compartment flooded with seawater, receiving impact damage or by fires/explosions on board. Safety and control systems may be damaged, which again can have implications on reactor safety. Collisions, groundings, fires, explosions etc. may have severe consequences even on large naval ships.

Of the impact accidents, grounding have the potential to be most severe, mainly because the damage length can be extensive when grounding on rocks. Collisions can cause larger penetration into the ship side but is normally not that severe and is not very likely to penetrate to a reactor located around the centerline of the ship. However, a 90 degrees impact (collision) may possibly breach containment directly. A sideways collision may rip the ship open, but it is not likely that the containment will be breached. A grounding is also unlikely to breach containment.

A specific aspect of ship accidents is that the duration can be very long. Fires on ships can last for a long time, up to weeks. Fires are credible threats to the nuclear power plant onboard. An explosion may have a significant impact on the hull of a vessel. If the ship hull no longer offers as much protection against a radioactive release, this will clearly have an impact on the source term, and assumptions regarding how much is released and the release rates.

There are some specific aspects of ship reactors that make them different from land-based reactors. These are based on the conditions and constraints onboard the ship. For instance, separation as a barrier against impact from fires is not possible in the same way on a ship as on land, simply due to space restrictions. Long-lasting fire protection of a reactor and support structures may also be more difficult to achieve. Fire can also weaken the support structure under the reactor. Steel that is exposed to fire will weaken rapidly and will lose its strength, and start to stretch and/or bend. This may have a significant effect on reactor safety.

A possible follow-up of the NKS-B CRESCENT project would be to establish a qualitative description of a set of scenarios based on simple quantitative analyses of conventional ships accidents, and calculate source term estimations based on this. This, however, has been out of scope for the current project.

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Bibliographic Data Sheet **NKS-463**

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Abstract max. 2000 characters	The Nordic countries are surrounded by large ocean areas where there is frequent traffic of foreign nuclear-powered vessels, both naval and civilian. Increased activity of these vessels in the High North, new emerging technologies and designs, and experience from events have given a need for updating existing information, exchange views and discuss credible release scenarios for nuclear-powered vessels operating in Nordic waters. In that regard, the NKS-B CRESCENT project facilitated two workshops held with NKS funding – one in Asker, Norway, 5-6 October 2021 and one in Reykjavik, Iceland, 8-9 June 2022.
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