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Inventory and Source Term Evaluation of Russian Nuclear Power Plants for Marine Applications

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April 2006

Abstract

This report discusses inventory and source term properties in regard to operation and possible releases due to accidents from Russian marine reactor systems. The first part of the report discusses relevant accidents on the basis of both Russian and western sources. The overview shows that certain vessels were much more accident prone compared to others, in addition, there have been a noteworthy reduction in accidents the last two decades. However, during the last years new types of incidents, such as collisions, has occurred more frequently. The second part of the study considers in detail the most important factors for the source term; reactor operational characteristics and the radionuclide inventory. While Russian icebreakers has been operated on a similar basis as commercial power plants, the submarines has different power cyclograms which results in considerable lower values for fission product inventory. Theoretical values for radionuclide inventory are compared with computed results using the modelling tool HELIOS. Regarding inventory of transuranic elements, the results of the calculations are discussed in detail for selected vessels. Criticality accidents, loss-of-cooling accidents and sinking accidents are considered, bases on actual experiences with these types of accident and on theoretical considerations, and source terms for these accidents are discussed in the last chapter.

Key words

accidents, inventory, source term, Russia, marine reactor, Helios, release fractions

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Inventory and Source Term Evaluation of Russian Nuclear Power Plants for Marine Applications

by

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This report discusses inventory and source term properties in regard to operation and possible releases due to accidents from Russian marine reactor systems. The first part of the report discusses relevant accidents on the basis of both Russian and western sources. The overview shows that certain vessels were much more accident prone compared to others, in addition, there have been a noteworthy reduction in accidents the last two decades. However, during the last years new types of incidents, such as collisions, has occurred more frequently. The second part of the study considers in detail the most important factors for the source term; reactor operational characteristics and the radionuclide inventory. While Russian icebreakers has been operated on a similar basis as commercial power plants, the submarines has different power cyclograms which results in considerable lower values for fission product inventory. Theoretical values for radionuclide inventory are compared with computed results using the modelling tool HELIOS. Regarding inventory of transuranic elements, the results of the calculations are discussed in detail for selected vessels. Criticality accidents, loss-of-cooling accidents and sinking accidents are considered, bases on actual experiences with these types of accident and on theoretical considerations, and source terms for these accidents are discussed in the last chapter.

Foreword

In 2003 Nordic Nuclear Safety Research (NKS) sponsored a seminar on the safety of Russian nuclear submarines and the risk for releases of radioactivity. The following recommendation was made at the seminar:

> The main recommendation made (…)was that there still is a need for analysing specific elements related to source term analysis of Russian marine reactors and naval fuel when considering possible accidents and consequences for the Nordic countries: if available, evaluating all available design information for marine reactors and fuel, complete studies of release fractions for specific accidents (LOCA, criticality accidents when refueling/ defueling) with releases to air and/ or sea, examine the possibility for recriticality in spent fuel configurations on shore (i.e. in storage at former naval bases) for PWR marine reactors and in spent removal blocks from liquid metal reactors.

On the basis of the seminar, NKS initiated a project with the objective to work out two scientific reports:

Report 1:	Russian Nuclear Power Plants for Marine Applications
Report 2:	Inventory and Source Term Evaluation of Russian Nuclear Power Plants for Marine Applications

The following paper is the second report, as the first report a result of cooperation between Risø Laboratories, Denmark and Norwegian Radiation Protection Authority, Norway.

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1 Introduction

The present report deals with source terms for accidents involving Russian marine nuclear reactors. The operation of a nuclear vessel fleet is a complex process involving a large number of smaller operations, including for example construction, operation, maintenance, refueling, decommissioning and defueling. For each of these processes, there is a certain risk of accidental releases of radionuclides. Such releases depends also on a number of other factors such as the type of accident, the type of reactor, the reactor power and the length of the operational time of the reactor prior to the accident etc. If the accident happens some time after reactor shut-down, the activity release depends also on the length of the shut-down period.

This report is based on considerations of Russian marine nuclear systems, more specific icebreaker and submarine nuclear reactors. As discussed in the other NKS-report from this project (NucVess), there are many different types of reactors. Considering the numerous accidents scenarios covering both releases to the marine and the terrestrial environment and all possible inventories, the number of relevant combinations relevant for further considerations as part of full scope impact assessments is too many to be included in this study. On this basis, this work has been divided into three parts as described in the following chapters; 1) analysis of relevant incidents and accidents, 2) calculation of reactor inventory taking the results from NucVess on reactor and core configuration into account in addition to operational data (calculated and reported in other sources), 3) source term considerations.

While Part 3 was a major motivation for this work, this part is the least developed part of this report. The reason for this fact, despite the initial project description as put forward from the NKS seminar, is that for the other relevant parts for describing a realistic source term, such as accident scenarios and inventory, a lot of new information surfaced during this work which has been duly analyzed and summarized. As described in chapter 5.1, the Norwegian government has agreed to continue the project, then also including impact assessments for the marine environment in case of releases to sea, in order to have a more careful description of the release mechanisms with regard to accidents involving Russian marine vessels taking the results in this report into account.

1.1 What is a source term?

The source term is used to describe the release of radioactive materials from a specific source. Therefore, data on several parameters related to the release are necessary to have precise knowledge of the source term;

- Inventory (types of isotopes, forms and composition);
- Release composition;
- Release as a function of time;
- Energy content (lift);
- Release point/ height;

The source term itself is thereby dependant on a number of different factors, such as the fuel matrix, cladding, pressure vessel and containment. Part of the source term is the release fraction, being established from information on the three first bullets points above. The release fraction is the fraction of the total activity of the fission product released to the environment during the accident. This report will not primarily consider the quantitative aspects of the risk itself, but focus the different factors contributing to the source term and the release fractions for different types of accidents involving Russian naval reactors and spent fuel.

2 Experiences with operation of Russian marine reactors

The risks connected to the operation of nuclear reactors, commercial power reactors as well as research reactors, are in general estimated by use of theoretical risk analyses since the number of accidents that has actually occurred, has been so low that they cannot be used for risk assessment. This is not the case when it comes to the nuclear vessels of the Soviet/Russian Navy. Here a significant number of accidents have occurred, and it is therefore reasonable to assess the risks of accidents and their consequences based on information of these accidents. To access which types of accidents should be considered, a review is made of the rather numerous number of accidents that have occurred with Russian nuclear submarines. From this review the relevant accident types are identified. A more detailed discussion of these accidents is presented and the source terms for such accidents are considered.

In total, 110 incidents have been reviewed in this study. However, this includes both major accidents with subsequent releases and loss of complete crew down to less serious incidents with no casualties and minor consequences for the submarine itself. It should therefore be remembered that there may well have been accidents that are not included in the present analysis, but also that some of the accidents considered may have been trivial events.[1] However, as these might result in incidents with more substantial consequences, they have been included. The distribution according to the three factors 1) incident type, 2) type and class of vessel, and 3) time, will be discussed in this report.

While the incident type is relevant for identifying relevant scenarios for future accidents, considerations has to be regarding which type of vessel involved in these incidents and in which time span they have occurred. This has been done in order to sort out if possible technologies or types of vessels are susceptible to certain types of incidents. It should be noted that in many cases no information is available on accident cause or possible consequences for the vessel itself, crew or local population if relevant. In addition the handling of the spent fuel, after it has left the reactor, may also give rise to accidents such as loss-of-shielding accidents and leakage of radioactive materials from damaged fuel, so a fourth type of accident, spent fuel accidents should also be considered. This is not part of the mandate for this report.

|The basis of the present analysis is [Kotcher], [Apalkov1,2,3,4] and [Oelgaard1]. The latter has been supplemented by media information on the two latest accidents. A summary of all the accidents considered is presented in Annex I on table form.

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[1] When comparing with other investigations as presented in [Olgaard1] the total number of accidents considered was 38, so much fewer accidents were considered than in [Apalkov]. On the other hand [Olgaard1] covers all classes of Russian nuclear submarines, not just the first generation. Most of the accidents with first generation submarines in [Olgaard1] are also included in [Apalkov], but a few are not. [Olgaard1] covers in general the most serious accidents, but here too some of the accidents may have been incidents. All of the accidents in [Olgaard1] except two occurred in nuclear submarines.

2.1 Distribution of incidents

The distribution of the incidents according to incident type is presented in table 2.1. The categories involve very different type of incidents, ranging from small fires to large, criticality accidents with substantial releases of radioactivity to the atmosphere.

The categories used have been decided on the basis of the goal of this work. Reactor system failures are, together with criticality accidents, self-evident categories due to the relevance for containing the radioactivity in the core. Fire seems to be an important initiating event in Russian submarines in particular, at several instances with a fatal result. In order to single out instances where the submarine has sunk, whatever cause, this has been included as separate category as part of the overall total and will be discussed separately in chapter 2.1.4.

It is seen from Table 2.1 that the most frequent accident as such is fire, which also killed most crewmembers and in two cases lead to the sinking of the submarine. The type of accident which caused the largest loss of life per accident is – hardly surprising – explosions. In the two cases listed the submarines sank. There were six cases of loss-of-cooling accidents which caused fuel damage and which lead to replacement of the reactor compartment or decommissioning of the submarines. Of the five criticality accidents two were related to refueling and three occurred during repair or tests of the reactor at the shipyard. They lead also to replacement of the replacement of the reactors or to decommissioning. The coolant solidification accidents all refer to the liquid metal cooled reactors. Propulsion failure deals with turbine or similar failures. Of the 5 sinking accidents the submarine was recovered in one case, but in the other cases it remains at the bottom of the sea. There have been a number of collisions between Russian submarines and other vessels, not the least caused by the tense relations during the Cold War. But since submarines are vessels of war they are built to withstand powerful mechanical actions from the outside and consequently collisions will usually not lead to serious damage (see chapter 2.1.5).

Table 2.1 Distribution of Incidents with Russian Nuclear Ships According to Type of Incident

Type of accident	**No. of accidents**	**Release of radioactivity**	***Number of persons killed***
Fires and explosions	**34**	**1-2**	***326***
Explosion	(6)		*(124)*
Criticality	**5**	**3-5**	***17***
Reactor system failure	**39**	**6-14**	***18***
LOCA	(6)	(3)	*(12)*
Leaks/ fuel failure	(21)	(2-4)	*(1)*
Coolant solidification	(3)	(1-2)	
Other	**32**	**0-1**	***54***
Propulsion/ turbine failure	(4)		
Collision	(10)		*(27)*
Flooding	(8)		*(16)*
Total	**110**	**14-26**	***415***
Sinking	*(5)*		*(225)*

2.1.1 Fires and explosions

Fires and explosions, even though they will usually not affect the reactor system directly, may lead to the sinking of the submarine. If the submarine is not recovered this will sooner or later lead to the release of radioactive material. The first serious accidents were K 3 in 1967 with 39 fatalities. Then a hydraulic pipeline in the first compartment sprang a leak, the inflammable oil caused a short-circuit in a lamp whereby the oil was ignited and the fire started. The fire spread to the second compartment either because a oil beam broke through a bulkhead or in connection with an attempt to evacuate the crew of the first compartment. The crew of the first and part of the crew of the second compartment died from suffocation, either caused by the CO produced by the fire or by CO2 used in the automatic fire extinguishing system. The second fatal fire occurred April 11, 1970 at K 8 a couple of days before the vessel sank in Bay of Biscaya. 52 crew members died during the accident due to toxic fumes.[2] The next fatal fire occurred when K-278 (Komsomolets) sank April 7, 1989, and 38 sailors drowned as the sub sank. None of the fires seems to have affected the reactor system to the extent that extensive releases of radioactivity were a result.

2.1.2 Reactor system failures

According to this categorization, reactor system failure is the most common reason for a release related incident involving Russian marine reactors. Regarding the different subcategories, LOCA represents the most serious incident, with leaks as relevant initiating event. There were six LOCA's, which caused fuel damage and which lead to replacement of the reactor compartment or decommissioning of the submarines. Coolant solidification was relevant for the liquid-metal cooled Russian submarine reactors which have all been taken out of service. The leak accidents are leaks that could have lead to a LOCA, but did not. They may have been trivial.

LOCA is definitely extremely serious, in particular in the context of this work since releases of radioactivity is a well-known consequences. The first major leak in a Russian submarine occurred, according to Ølgaard, already October 13 1960 involving one of the steam generators and probably also the pressurizer, directly or through the leaking steam generator. Helium and steam was then released in the turbine compartment. The reactor was shut down and arrangements made for cooling of the core, however, radioactive gas leaked into all compartments. 13 personnel were exposed to 180-200 rem and hospitalised, one sailor died two years later. The sub reached its base on own power, but was subsequently decontaminated.

The first LOCA occurred July 3 1961 in K 19, also called "Hiroshima" due to a reputation for being accident prone. A major leak in a pipe of the pressurizer system developed when the submarine was returning form an exercise. Coolant temperature was at about 300 ^{o}C and pressure

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[2] Two fires started simultaneously on April 8th, one in the third and one in the eighth compartment when the K8 was sailing submerged, returning from an exercise. The reactors were shut down and K8 surfaced. The diesel power plant could not be started, so the submarine lay dead in the sea. The crew tried in vain to fight the fires. The control room and several of the other compartments were filled with toxic fumes. To keep K8 floating air had to be pumped into the aft ballast tanks. On April 10th the air supply was exhausted and water started floating into the 7th and 8th compartments. K8 sank on April 11th at a depth of 4680 m.

at 200 atm. The pressure decreased and coolant started to boil. The reactor was shut down automatically. However, the temperature in reactor compartment reached at least 140 ^{o}C. Radioactive air dispersed in the sub, dose rate in the control room was up to 50 R/h, and very high in the reactor compartment. The cooling of the core was insufficient due to no or a defect emergency core cooling system (ECCS). The temperature of the fuel reached 800 ^{o}C. To avoid a core meltdown an improvised ECCS was installed in a few hours by crew members working in periods of 5-10 minutes in the reactor compartment. After returning to base, the sub was decontaminated and repaired. The reason for the leak was probably exposure by a mistake of the primary system to 400 atm. at the pressure testing during the commissioning. Another LOCA, this time claimed not to result in any human fatalities, occurred July 2 in 1979 in the Pacific near Russia. The operator at the control panel turned by mistake the main circulation pumps off, the emergency core coolant system did not work and due to the confusion in the control room the pumps were not restarted. The core was exposed and part of the fuel melted. No activity escaped to the environment.

The LOCA which occurred in 1966 when three reactors of Lenin underwent refuelling is the only incident in this report registered for civilian Russian nuclear vessels. The water was then drained from the second reactor before the spent fuel had been removed, probably due an operator error. The decay heat and the lack of cooling resulted in melting and/or deformation of some of the fuel elements. After this accident it was only possible to remove 94 of the fuel elements while the remaining 125 could not be removed. The damaged fuel had to be removed by removing the core insert or basket, which carried all the fuel. After the accident the three OK-150 reactors were replaced by two OK-900 units.

The coolant solidification accidents all refer to the liquid metal cooled reactors and will often lead to a loss-of-cooling accident. This submarine was provided with two Bi-Pb cooled intermediate reactors. In-leaks of steam from the steam generators into the primary circuit caused oxidation of the liquid metal coolant whereby oxide particles were formed. Therefore the coolant had to be cleaned of these particles at regular intervals. In May 1968 the coolant needed a cleaning, but the K27 was nevertheless ordered to participate in a naval exercise. Protests from the crew were not accepted. On May 24 K27 was sailing at full power when the power meter of the starboard reactor started to oscillate and the power of the port reactor went down to 7% of full power, after which the reactor was shut down. The reason was that after a leak, presumable in a port steam generator, the oxide particle concentration had increased to a point, where the particles blocked the coolant flow to part of the core and the fuel melted. Fission products were released from the primary circuit to a safety buffer tank and from here to the reactor compartment where the radiation level increased to 100 R/h. Later contamination spread to the other compartments. The submarine returned at the surface to its base by use of the starboard reactor.

While K192 was in transit from the Mediterranean Sea to Severomorsk a leak developed in a component in the primary circuit. The reactor was shut down, the submarine surfaced, the auxiliary diesel engine started and the submarine continued at a speed of 5 knots. However, the leak was of such magnitude that the cooling was not sufficient and part of the fuel was damaged. Further the submarine did not have sufficient water supplies so ships were sent out with extra water supplies. The leaking water was collected in tanks. Due to lack of power the air-condition system was switched off and the temperature in the submarine increased. In the reactor compartment it reached 150oC. After the return to base the submarine was transferred to the No. 10 Shkval shipyard where compressed air is pumped into the hull to maintain buoyancy.

The second type of nuclear accident is the loss-of-cooling accident or LOCA. These accidents will usually occur when the reactor is operating. If the cooling fails at this stage, e.g. because of a coolant leakage, the control system will shut down the reactor. But the decay heat from the decay of the fission products will continue to produce power in the reactor core and if the emergency core cooling system does not work properly (or does not exist), the fuel will heat up and possibly melt and contaminate the primary system. If there is a leak in the system or the safety valves open due to too high a pressure, contaminated steam and water will enter the reactor compartment. If this compartment is not closed, the rest of the submarine may also be contaminated. A LOCA may also occur if the reactor has very recently been shut down and the cooling system does not work properly.

Of the six LOCA's of Russian nuclear vessels three occurred in first generation submarines, one in the icebreaker Lenin, one in the Project 645 submarine (liquid metal cooling) and one in a first or second generation submarine. In two cases a leak developed in the primary circuit, in one case an operator drained the reactor tank by mistake, in another an operator stopped by mistake the main cooling pumps and in one case a valve failed to close. The final case involved the Project 645 submarine where impurities in the coolant blocked the inlet to part of the core. In all cases the fuel was damaged and in the five submarine accidents the interior of the submarines was contaminated. The five submarine accidents occurred with the reactor at power. The accident of the NS Lenin occurred shortly after reactor shutdown.

It seems that little radioactivity escaped from the submarines during and after the accidents even though all the interior of the submarines were more or less contaminated. The reason is presumably that the pressure hull of the submarines acts as a good containment. It is strong, has few openings and a large part of it is in close contact with the ocean which acts as a heat sink that helps to condense the steam and reduce the pressure, thereby reducing the leakage from the submarine.

A special type of LOCA is the solidification of the coolant in liquid metal cooled reactors. While this type of accident may not lead to escape of radioactive material from the reactor, it will usually lead to damage of the fuel.

2.1.3 Criticality

The first criticality accident involving a Russian submarine occurred February 12 1965. The accident occurred at the end of a refuelling when the reactor lid was put back on top of the reactor tank, but not quite correctly so that it had to be repositioned. To do this the lid had to be relifted with the control rods connected to the lid. To avoid lifting the lid too high up so that the reactor would go critical a beam was placed over the lid. Unfortunately the beam was by mistake placed too high up so that the reactor went critical. According to one source it was not understood what had happened, so some days later on a new attempt was made to lift the lid and the reactor went critical again. This time radioactive steam was ejected from the reactor and the lid fell down in a tilted position on top of the tank. A fire started in the reactor compartment. It was fought with water, which spread to the other compartments. Seven crew members suffered radiation injuries, while one of the reactors was destroyed. Later on the complete reactor compartment was replaced.

August 23, 1968, another criticality incident occurred, again at a Russian shipyard in Northwest-Russia. During repair/maintenance work on the submarine the wiring of the control rods were not performed correctly. When a mechanical test was performed on the rods - without the neutron monitoring system working - the rods moved out of the core rather than into the core and the reactor went critical. The power level has been claimed to reach 20 times the nominal level and the pressure went up to 800 atm., 4 times the nominal pressure. While the primary circuit was strongly contaminated, there has not been reported any casualties or extensive contamination. But apparently there were no leaks. Less than two years later, January 18 1970 at the “Krasnoye Somovo" shipyard in Gorki, now Nizhniy Novgorod, K 320 was being constructed. At the end of its construction hydraulic tests were performed with fuel in the core. However the reactor was only provided with provisional control rods which had not been fixed sufficiently, so that they were lifted out of the core when the coolant velocity reached high values and the reactor went critical. Activity was released into the factory hall and the reactor and its fuel was replaced. No information is available on doses to the shipyard staff. Another criticality incident, also with no information on releases of activity to the environment, occurred autumn 1980 at a shipyard in Severodvinsk when K222 was undergoing a major overhaul. When the crew had left for lunch and only personnel from the shipyard was present, they supplied power to the control rod drives while the instrumentation system was not working. The control rods moved out of the core, and the reactor went critical. There were no casualties and no release of activity to the environment.

The most serious accident to date involving a Russian submarine was the criticality accident in Chazma Bay August 10, 1985. After reloading the reactors with new fuel the reactor tank lid was placed on top of the tank. However, the lid had not been properly placed so it had to be relifted with the control rods attached. The beam above the lid to prevent lifting the lid too high up had not been placed properly so the lid went up too far and the reactor became supercritical. The steam explosion destroyed the forward and aft rooms, damaged the pressure hull and ejected part of the fuel out of the submarine. A fire broke out immediately after the explosion and was only extinguished in four hours. The release properties are further discussed in chapter 5 of this report.

Of the five criticality accidents two were related to refueling and three occurred during repair or tests of the reactor at the shipyard. They lead also to replacement of the replacement of the reactors or to decommissioning. All criticality accidents of the Russian Navy have occurred when the reactor was shut down and the control system was not operational. To start moving control rods or fuel under such conditions may easily lead to criticality accidents since the personnel involved has no knowledge of how close the reactor is to criticality. When the reactor becomes supercritical, the chain reaction starts and reactor power increases very rapidly, in particular if the reactor becomes prompt supercritical. The power increase will usually lead to overheating and melting of the fuel whereby fission products are released to the primary circuit. It will also lead to a rapid pressure built-up in the reactor system, which will open the safety valves of the system so that radioactive steam will be released into the reactor compartment. The pressure may even become so high that the primary circuit ruptures and contaminated steam and cooling water are released into the reactor compartment. If this compartment is not sealed, the other compartments of the submarine are likely to be contaminated too. However, if the compartment is sealed, the contamination should be limited to the reactor compartment.

During re/defueling the hull above the reactor is removed so that the reactor vessel can be opened, the burned fuel removed and new fuel elements loaded into the reactor. If a criticality accident occurs at this stage the criticality accident will cause an excursion of steam, hot water, fuel element parts and radionuclides, which will rapidly reach the environment outside the submarine...

To prevent criticality accidents during defueling of decommissioned submarines, it has been proposed to drain the reactor and the primary system of water prior to the defueling. If this is done the reactor cannot go critical due to the lack of moderator. It has been found that drainage of the primary system is permissible provided the reactor has been shut down for more than two years. In that case the fuel elements will not overheat even if all coolant is removed. Whether this procedure is actually/always used is not clear, but if so it is of vital importance that it is really ensured that the water has been completely removed from the reactor tank before it is opened.

As seen from Annex I the two criticality accidents which have occurred in the Russian Navy during refueling involved first generation submarines. In both cases they occurred after the reactors had been refueled, i.e. contained new fuel, and the lid of the reactor tank was to be placed on top of the tank. In both cases the lid was not placed quite correctly. Therefore it had to be relifted. At this stage the control rods were connected to the drive mechanisms on the lid, the lid was lifted too highly up and the reactors went critical. According to [Elatomtsev] such an event cannot occur at second and third generation submarines. The neutron monitoring and the control system were not operational during the accidents.

The other three criticality accidents all occurred when the submarines were undergoing maintenance or tests at shipyards. None of them were first generation submarines. The neutron monitoring and the control systems were not operational, so they could not shut down the reactors once they became critical. Under normal operational conditions the control system will shut down the reactor when it becomes supercritical.

It is obvious that the worst criticality accidents are those during re/defueling when the reactor is open to the environment. Fortunately, the two criticality accidents, which occurred during refuelling, occurred after the new fuel had been loaded into the reactor. If a criticality accident occurs during defueling, the fuel in the core is burned fuel, which contains large amounts of fission products. In this case the release of activity will be significantly increased.

After a criticality accident the reactor is beyond repair. The reactor compartment has to be replaced by a new compartment or the submarine has to be decommissioned.

Criticality accidents may also occur during handling of spent fuel in connection with transport and storage. Since the amount of fuel handled at one time is usually limited, 49 fuel elements per transport container, and the geometry is “safe”, such accidents are very unlikely. Another possibility is the flooding of a facility for dry storage of spent fuel. If the fuel is not placed in a safe geometry, flooding could possibly make the facility critical.

2.1.4 Sinking Accidents

Nuclear accidents in Russian submarines have not lead to the sinking of submarines, but other accidents have. Most if not all of the 11 fire accidents seems to have started while the submarines were sailing submerged, but the submarines managed to reach the surface. Nevertheless two of the submarines sank later. In the two explosion accidents the submarines were both sailing submerged. In one case the submarine managed to reach the surface, but it sank later on. In the other case it went straight to the bottom of the sea, from where it was later salvaged (Kursk). So fires and explosions can certainly lead to the sinking of submarines, but other accidents have also lead to sinking. In one case the reason was an operator error, but in this case the submarine was later salvaged. In another a decommissioned first generation submarine with limited buoyancy sank while being towed during a storm from its base to the shipyard where it should be dismantled. Other accidents could of course also lead to the sinking of a submarine, e.g. collisions, but so far this has not been the case.

If a submarine sinks and is not salvaged its content of radioactive materials, e.g. the fission products and the transuranium elements of the fuel and activated parts of the reactor, will at some point in the future start leaking into the ocean due to corrosion of the salt sea water. From the experience so far this leakage is slow and at the same time the activity of the submarines will gradually decay. When the activities start to leak, it will, if soluble, leak out in the seawater where it will mix with the very large amounts of seawater in the ocean. Sea currents and diffusion will disperse the activity.

2.1.5 Other

This category includes instrumentation failure, propulsion failure – including turbine failures, collisions and flooding of the submarine. There have been a number of collisions between Russian submarines and other vessels, not the least caused by the rather aggressive US nuclear submarines. But since submarines are vessels of war they are built to withstand powerful mechanical actions from the outside and consequently collisions will usually not lead to serious damage. The case of collision in the table was included because of the large loss of life. It involved a collision between a submarine and an oceanographic research vessel where compartment 2 in the submarine was completely flooded and resulted in 27 fatalities. Flooding is in-leakage of salt water in one of the submarine compartments. Also the incident where the decommissioned submarine K-181 was being towed and 9 sailors drowned are included in this category.

2.2 Distribution of incidents vs. class of vessel/ vessels in operation

It may be noted that of the 28 fires, 8 eight occurred in first generation, one in a second generation, and one in a third generation submarine. One fire occurred in a submarine of unknown class. So the first generation submarines were much more fire prone than the later generations.

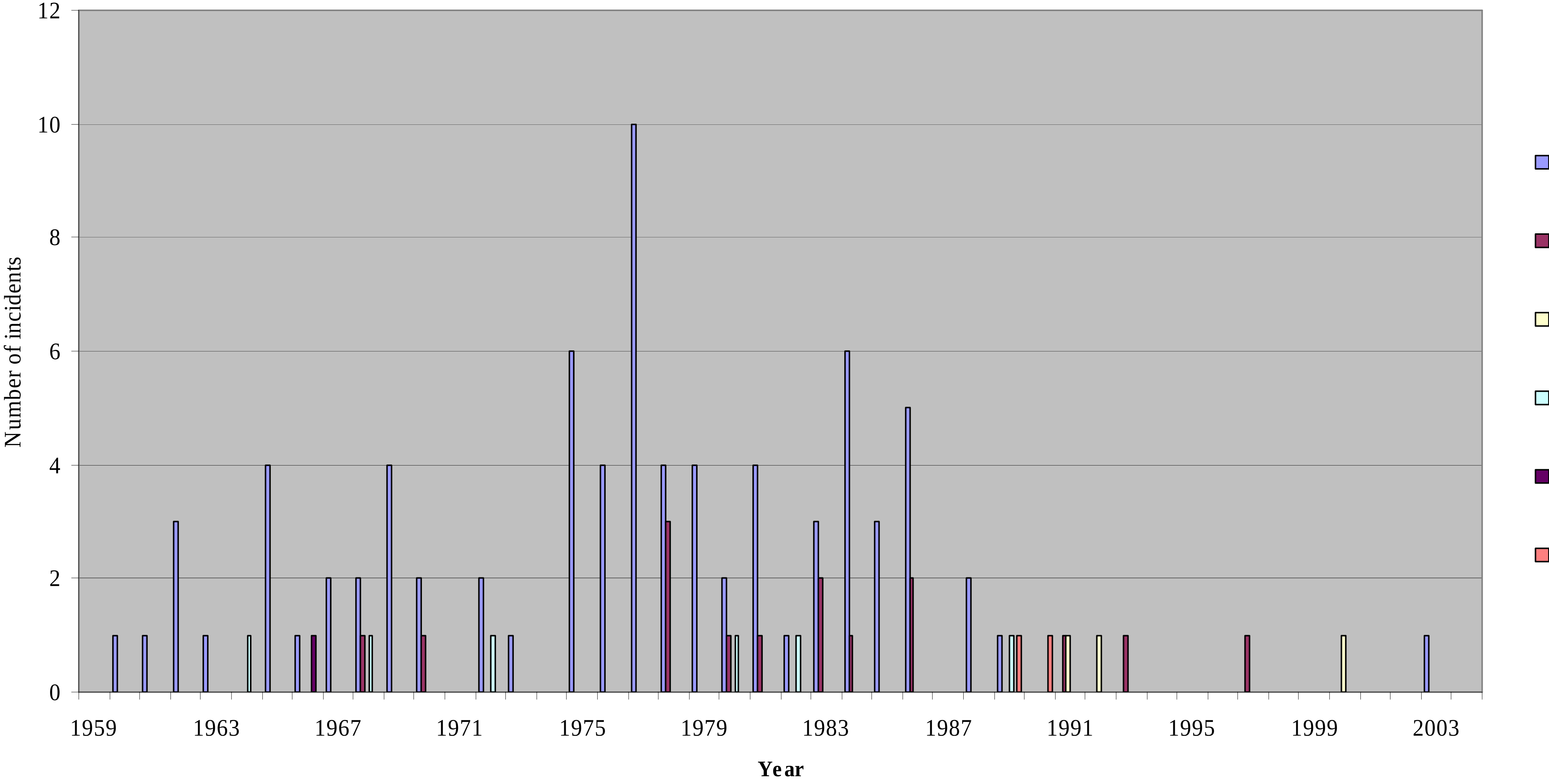
During the Soviet era the largest nuclear fleet in the world was built. The Soviet submarine fleet soon consisted of attack or multi-purpose submarines for attacks on enemy vessels, cruise missile submarines for attacks on enemy convoys or coastal facilities, and strategic or ballistic missile submarines for deterrence and – if need be – strategic attacks on enemy territory. In the 1980s came the four Kirov class missile cruisers and a fleet command ship all of which were powered by twin reactors. The Soviet Navy built an additional three submarines of different designs, of which only one vessel of each type was made: Project 645, Papa, and Mike. These prototypes may be considered experimental submarines. The Soviet Union also built three types of small, deep-water nuclear submarines: Project 10831, the X-ray and the Uniform class. In total, from the inception of its naval nuclear program, the Soviet Union/Russia built 255 nuclear propelled surface and submersible military vessels, many of which were fitted with two reactors. As of early 2005, less than 50 of Russia's nuclear powered vessels remained in operation.

The distribution of accidents according to submarine class is presented in Table 2.2. From Table 2.2 it is clearly seen that the risk of accidents has decreased with newer, safer designs. For the first generation the number of accidents per submarine built was 0.33, for the second generation 0.10 and for the third generation 0.07. The submarines with liquid-metal cooled reactors represent a special case of advanced technology, which was hardly mature for submarine application when used, and this is the reason for the high accident rate, 0.71. The high value for the Mike class is due to the fact that only one vessel of this class was built. It should also be noted that many of the newer submarine classes, e.g. the Typhoon, the Akula, the Sierra, and the Victor classes, have as far as is known not suffered any accidents. It may be noted that of the 34 fires and explosions 30 occurred in first generation, one in a second generation, and one in a third generation submarine. One fire occurred in a submarine of unknown class. So the first generation submarines were much more fire prone than the later generations. The type of accident which caused the largest loss of life per accident is – hardly surprising – explosions.

Table 2.2 Distribution of Incidents with Russian Nuclear Ships According to Vessel Class

	Submarine vessels					**Surface vessels**		***No. of accidents***
Type of accident	**1. gen.**	**2. gen**	**3. gen**	**LMC**	**Other/ unkn.**	**Military**	**Civilian**	
Fires and explosions	**30**	**1**	**1**		**2**			***34***
Explosion	(5)		(1)					*(6)*
Criticality	**2**	**2**		**1**				***5***
Reactor system failure	**30**	**2**		**4**	**1**	**1**	**1**	***39***
LOCA	(3)			(1)	(1)		(1)	*(6)*
Leaks/ fuel failure	(21)							*(21)*
Coolant solidification				(3)				*(3)*
Other	**20**	**9**	**2**	**1**				***32***
Propulsion/ turbine failure	(3)			(1)				*(4)*
Collision	(6)	(4)						*(10)*
Flooding	(5)	(3)		(1)				*(8)*
Total	**82**	**14**	**3**	**6**	**3**	**1**	**1**	***110***
Sunken	*2*	*3*	*1*		*1*		*1*	*(8)*

Figure 2.1 Distribution of incidents vs. time

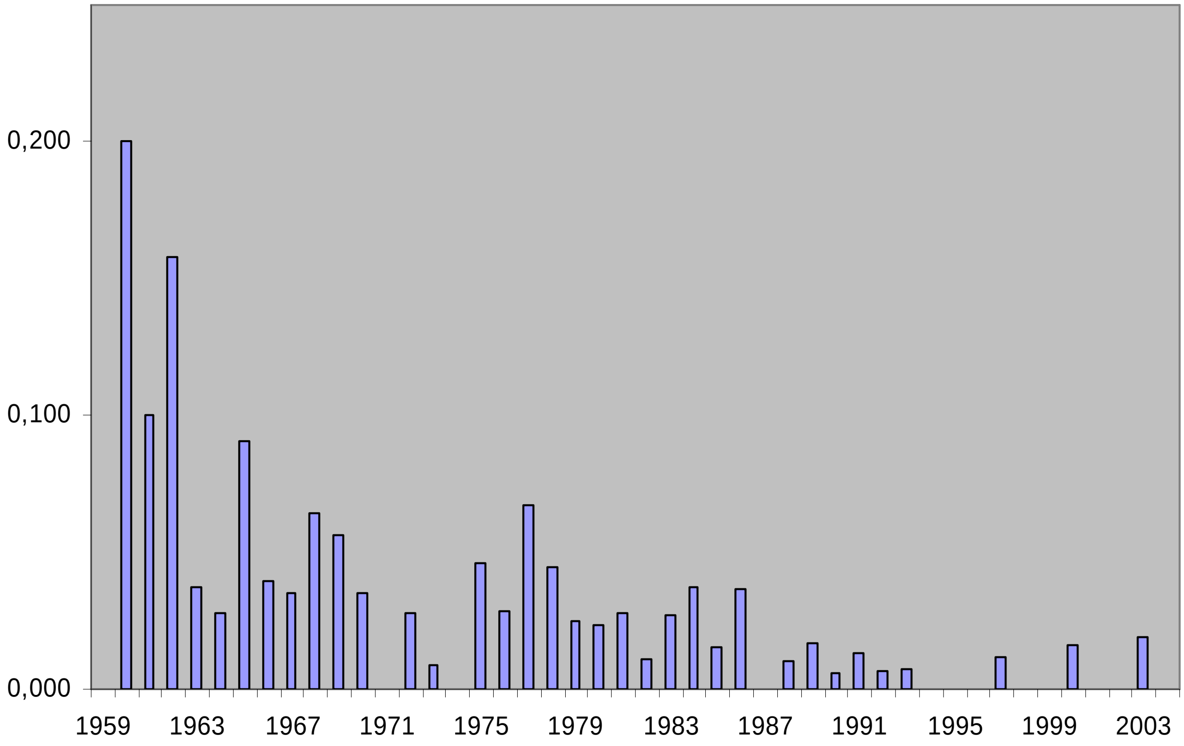


Here too the number of accidents is quite significant, one to two per submarine built. In particular it seems that the Hotel class was quite accident prone.

2.3 Distribution of incidents and class of vessel vs. time of incident and operating experience

The distribution of the 110 incidents between 1959 and 2004 is presented in figure 2.2. We see that a large number of accidents occurred in the period from the start of the submarine program until the end of 1980. The steep fall in absolute numbers was probably due to considerable reduced sailing time for the Russian submarine fleet due to economical constraints. However, if considering the number of accidents vs. the number of vessels in operation, the picture is considerable different.

Figure 2.2 Distribution of Incidents with Russian Nuclear Ships According to Time of Accident and Number of Nuclear-propelled Vessels in Operation



The relative number of incidents has steadily decreased from a very difficult initial phase until present. When considering the nature of the incidents after 2000, this reveals several extraordinary incidents such as collisions between Russian vessels or between US and Russian vessels. These are incidents less serious, if considering possible releases, than the multiple reactor accidents in the first two decades of the operation of a nuclear fleet.

It is seen from Table 2.1 that the number of accidents, also taken per number of operational submarines, is quite significant. It might be expected that the number of accidents per submarine in operation would have decreased with time as experience with this type of vessel was gained, and this trend is obvious in figure 2.2. However, this is the general trend, for the first generation of Russian submarines, the trend was initial downwards, however, it started to increase again after 10-15 years. The overall average still decreased due to the massive introduction of new and modern submarines with a considerable lower absolute incident rate and also relative incident rate pr. submarine in operation.

When evaluating the distribution of accidents as a function of time the number of operational nuclear vessels during the decades considered in Table 2.1 should also be taken into account since a larger number of ships are likely to increase the number of accidents. On the other side, the increased experience with the operation of nuclear ships and new and safer designs should reduce the risk. That this is so is demonstrated in Table 2.1. During the first decade considered the number of accidents was high, nine, while at that time the Soviet nuclear Navy was still of modest size (about 40 vessels). In addition, at this time more emphasis may well have been placed on rapid build-up of the Soviet nuclear Navy than on safety due to the cold war. During the next two decades the number of accidents are 12 (about 130 vessels) and 14 (about 195 vessels), still high, but – taken per operating nuclear vessel - decreasing. The reason for this is presumably new and safer submarine designs and more operational experience. However, looking at the reasons for the accidents it is clear that the safety culture of the Soviet nuclear Navy was not impressive. During the 1990es (about 130 operational vessels) the number of accidents was low due to safer designs, due to a reduced number of operational submarines and due to reduced operation with the nuclear vessels because of lack of funds.

It is hardly surprising that the most dangerous accident is the sinking of a submarine. In the case considered here it was actually a fire that caused the sinking. However, criticality accidents, fires, explosions and loss-of-cooling accidents (LOCA) are also quite dangerous. Three of the “Reactor system leak” were probably LOCA’s since in two cases the reactor compartment and in one the reactor core were replaced. It may be mentioned that regarding collisions in most cases very little happens since submarines are built to operate under war conditions and therefore to withstand rather violent actions like depth charges. The 27 killed in collisions all were killed in the same accident.

3 Inventory of radionuclides in Russian naval vessels

During the operation of nuclear submarines the nuclei of the fissile material of the reactor cores, ^{235}U, undergo fission, whereby highly radioactive fission products are produced. Transuranium elements will also be produced though to a significantly smaller extent. It is these radionuclides that may be released to the environment in connection with accidents of naval vessels.

The radionuclide inventory might be divided into four parts: 1) noble gases, 2) fission products, 3) transuranic elements, and 4) other. The latter contain in this connection activation products in structure materials and reactor coolant isotopes in cladding and structure materials. When considering the risk for criticality, the inventory and geometry of transuranic elements is of vital importance. However, as the transuranic elements often are less soluble than fission products, the latter group are considered more interesting for marine and atmospheric releases. The fission products have in addition other properties related to the uptake mechanisms in nature that makes them especially relevant for any impact assessment involving spent nuclear fuel. This group might be divided into several groups denoted by the main characteristic isotopes in the group; iodine (^{131}I), caesium (^{137}Cs) and strontium (^{90}Sr).

The amount of fission products produced is proportional to the number of grams of ^{235}U that has undergone fission in the reactor core, which again is proportional to the integrated power production of the core, the so-called burn-up. The burn-up is usually measured in Mega-Watt-days or MWd. 1 g of ^{235}U destroyed through fission corresponds roughly to the production of 1 MWd of thermal energy in the reactor core, however, this ratio should be calculated for the system in question.

The basis for assessing the inventory of transuranic and other elements as given above is the reactor design including fuel enrichment and composition. The fission products depend primarily on the reactor power operation histories, however, to a limited extent also on design information. The reactor design and fuel inventory are discussed in [Reistad] and will be summarized below before the discussion of power operation histories and core inventories.

3.1 Methods

In this report, HELIOS – a detailed reactor physics transport and burn-up code developed and supported by Studsvik Scandpower – has been applied to identify the inventory. HELIOS has many applications and is presently used by a number of research laboratories, nuclear power utilitiy companies and engineering companies in various countries [Casal]. HELIOS is characterised by its geometric flexibility allowing calculations of fuel designs, such as that of naval reactors, which differ considerably from conventional power reactor fuel.

Reactor physics concerns the prediction of the ‘neutronic’ behaviour of configurations intended as reactors of neutron chain reactions, in this case, of ship propulsion reactors based on fission in uranium. The reactor physics methods of HELIOS include descriptions of the fission process, the interaction of neutrons with the various materials in the reactor core such as capture, elastic and inelastic scattering, fission, and so forth, in terms of ‘slowing down’, ’thermalization’, ‘resonance absorption' and 'neutron transport'. The primary objective is to solve a set of equations describing these phenomena, resulting in a detailed space/energy neutron distribution within the considered system. Characteristic parameters, such as k_∞, are then easily calculated.

In more precise terms, HELIOS is a 2-D transport theory program for fuel burn-up and gamma-flux calculation. It solves the neutron and gamma transport equations in a general, 2-D geometry bounded by a 'polygon' of straight lines. The surrounding medium is described in terms of given boundary conditions. The system to be calculated may be subdivided into a large number of 'flat flux' regions or space meshes to support the numerical solution. Material properties may be assigned freely to any mesh. The geometric description of the system is user input controlled; thus almost any fuel cell, fuel assembly or larger areas of a reactor core may be described. Typical applications include BWR, PWR, VVER, CANDU and various test reactor fuel assemblies or larger core regions [Hark]. However, due to the inherent flexibility of HELIOS, other reactor types (such as the ship reactors studied in this report) may be treated with the same accuracy as the more common applications.

The isotopic properties with respect to neutron and gamma interaction are contained in a 'nuclear data library' derived from ENDF/B-VI [Brookhaven]. 271 different isotopes and 'mixtures' are included. The energy dependence of the nuclear data is accounted for by means of group theory. The entire energy range (0 - 10 MeV neutron energy) is subdivided into a certain number of energy groups. Energy averaged data are used within each group. Several energy group structures are possible in HELIOS. There are separate energy group structures for neutron and gamma spectra. The HELIOS library has three available group structures: 34/18, 89/18 and 190/48 neutron/gamma energy groups, respectively. The multigroup transport equations are solved directly in the energy group structure of the library. The 34/18 groups library is used in most applications and also in this report.

HELIOS has been extensively qualified by comparisons with experimental data and international benchmark problems for reactor physics codes as well as through feedback from applications [Stamm`ler]. Some of these benchmarks include fuel enrichments up to 90% [Perry].

3.2 Reactor and core design

The considerations described in this chapter, mainly taken from NKS Report 1 as referred to in the foreword, has provided the arguments for the input parameters in the inventory calculations as given in Table 3.1 below.

The operation of the different marine reactors connects directly to the development of vessels and the hostile climate in the cold war. In the development of Russian marine reactor systems, two specific avenues have been pursued: (1) civilian reactor systems with conventional designs and materials, (2) military reactor systems, much less transparent, but with more advanced technologies and materials. The development of military naval reactors soon branched into two separate tracks: water-cooled and water-moderated reactors vs. liquid-metal-cooled reactors (without moderations using intermediate neutrons)

From the very beginning, the main feature of both civilian and the military systems was the use of two identical reactors in each vessel – in contrast to US nuclear submarines, where one reactor was considered sufficient. Given the limited operation of the first generation of Russian submarines outside Russian coastal waters, the use of two reactors seems to be a measure of deliberate operational redundancy. This is a logical consequence when one recalls the many failures experienced in the first decades of submarine reactor operation, as also stated in Russian scientific sources. This in turn might have been a consequence of the lack of testing of these early versions of the military reactors.

Since the Kurchatov Institute has played an important role in the design of pressurized water reactors for both naval and icebreaking vessels, it seems reasonable to assume that the general designs were probably quite similar. On this basis the assumption was made that the design of fuel assemblies in the first generation of submarine reactors was similar in naval vessels and in icebreakers: however, the validity of this is hard to judge. However, the overall tendencies for the civilian program should apply to the military realm as well, even if there are distinct differences between important elements in the civilian and military technology.

The first civilian marine propulsion system installed in the icebreaker *Lenin* was based on low-enriched ceramic fuel, uranium dioxide, in Zr-cladding. The amounts of U-235 varied from 75 to 85 kg, 5% enriched. Apparently, there was a need to improve the cladding, as several other types of cladding were introduced as part of the second fuel load for the reactor, at least stainless steel and Zr-Nb alloy. After the accident with *Lenin* in 1967, important developments were identified, and today the icebreakers use a uranium-zirconium alloy as fuel in Zr-cladding. The precise amount of fuel is not known except for the freighter *Sevmorput,* where the safety report specifies 150.7 kg. enriched to 90% as one fuel load. The changes can be summarized as follows:

- Increased amount of fuel in the core (from 80 kg to 150.7 kg. U-235) and increased enrichment levels (from 5% to 90%)
- improved heat-transfer characteristics (from ceramic – UO-2 – to metal fuel – U-Zr alloy);

Regarding the number of fuel pins pr. Assembly, no data, except for 36 in the first icebreakers reactors, has been noted in public sources. In total, this accounts for improved output with regard to reactor power, 90 to 171 MWt, and optimalization of the operational characteristics, as the number of reactors was reduced from two to one. As seen, safety provisions were also dramatically increased from OK-150 to OK-900.

Russia started developing submarine reactors in 1952, about the same time as the civilian marine reactor program was initiated. For the PWR platform, an alumina-based metal fuel was developed. The use of two reactors compensated for the low-enriched uranium used in the fuel. Changes here can be summarized in the same way as for the civilian sphere:

- increased amount of fuel in the core (from 30 kg to possibly 200 kg. U-235) and increased enrichment levels (6% to 45%);
- increased number of fuel pins pr. assembly and increased number of assemblies in the core (180–280 – presumably even higher for third-generation submarines);

- different fuel compositions and cladding materials (U-Al with stainless steel cladding, unknown matrix with zirconium cladding)

As the composition and geometry of the submarine fuel are rarely made public, it is hard to evaluate whether and how the heat-transfer characteristics of submarine fuel have been improved. It is reasonable to assume, however, that considerable effort has been devoted to this. The strategies have possibly been to improve heat production capabilities by increasing the amount of metal and the heat-producing area in the fuel matrix. The latter implies employing other fuel shapes than rods, for example plate fuel as used in US submarines or advanced geometries based on the rod shape, e.g. hollow pins, extremely small pins, use of fins, etc.

A pertinent question when considering enrichment levels in Russian submarines is why higher levels have not been used in order to boost the operational properties of the submarines – improving overall economy by reducing re-fueling operations to zero, as the US Navy has achieved, and reducing the time the submarine is not operational at sea. The explanation might lie in the inherent inertia in the Russian military-industrial complex and the absence of financial constraints in military spending until fairly recently. Under conditions of the same societal laws as in the West, one might expect to see future Russian submarines consisting of one single reactor with highly enriched fuel.

Table 3.1 Relevant design parameters for inventory calculations with certain fuel and reactor geometries

	Icebreakers		Submarines	
	OK-150 (1. gen)	KLT-40 (3. gen)	VM-A (1. gen)	OK 650 (3. gen)
Core configuration	“Lenin”	“Sevmorput”	“Lenin”	“Sevmorput”
Amount of fuel (^{235}U)	80	150,7	50	200
Fuel type	UO_2	U-Al	U-Al	U-Al
Enrichment (%)	5	90	20	45

3.3 Reactor power operation histories

The burn-up at the time of the accident may vary between zero and maximum burn-up. While the first submarine vessels usually had a low burn-up, as for example shown when considering the inventory of the dumped reactors, the more modern submarines could be operated in much longer periods and thereby giving larger relative content of fission products in the reactors as a result.

The operation of the first design of the Russian icebreaker Lenin has been carefully documented, and to a certain extent this is the case with the more modern icebreaker generations. However, the modus operandi differs considerably from the submarines.

Table 3.2 Operational parameters for Russian icebreakers and submarines

	1. generation	2. generation						3. generation		
Type of reactor	OK-150	OK-900	OK 900 A					KLT 40		
Vessel name	Lenin		Arktika	Sibir	Russia	Soviet Union	Yamal	Taimyr	Vaigatch	Sevmorput
Operating period	1958 - 1966	1970 - 1989	1975 -	1977 - 1992	1985 -	1990 -	1993 -	1989 -	1990 -	1989 -
Yearly average operating period	- [3]	230	235	232	208	273	298	300	288	275
Total energy produced by the reactor (GWh) [4]	- [5]	6523/ 6398	9378/ 8502	6095/ 6934	5073/ 5270	4134/ 4071	2244/ 2917	5609	5467	3744
Number of reloadings (each reactor)	1/ 1/ 1	5/ 6	5/ 4	2/ 3	2/ 2	1/ 1	1/1	2	2	1
Average energy produced pr. reloading (MWd)	-[5]	45298/ 38083	65125/ 70850	84652/ 72229	70458/ 73194	86125/ 84813	46750/ 60770	77902	75930	78000
Average operating level (MW_t)[5]	-/ 0,59/ -	0,35/ 0,36	0,38/ 0,35	0,53/ 0,46	0, 39/ 0,41	0,37/ 0,36	0,26/ 0,34	0,43	0,45	0,38

Icebreakers – all generations

The first generation of civilian Russian marine reactors consists of one vessel, Lenin, using the reactor OK-150. The first operating period, 1959-62, resulted in burn-up values for the three reactor cores from 17800-18000 MWd [Afrikantov]. The second operating period, 1963-65, resulted in burn-up values in the range of 17500-22500 MWd for the three reactors. In February 1965 a melt-down occurred as a result of drainage of N2, one of the three reactors (as described in Annex I), and the fuel could only be partly removed from the reactor. This accident gave the final

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[3] For the first reactor system in Lenin, only data on specific periods for specific reactors are available. Due to the lack of accuracy, global average figures for the complete operating period from 1959-65 has been calculated.

[4] Time period from the moment of installation on the ship (GWh) (commissioning) till the year 2000.

[5] In per cent of reactor power capacity.

impetus for a full replacement of the reactor compartment, then introducing OK-900 as a replacement for OK-150, which was further developed to OK-900 A.

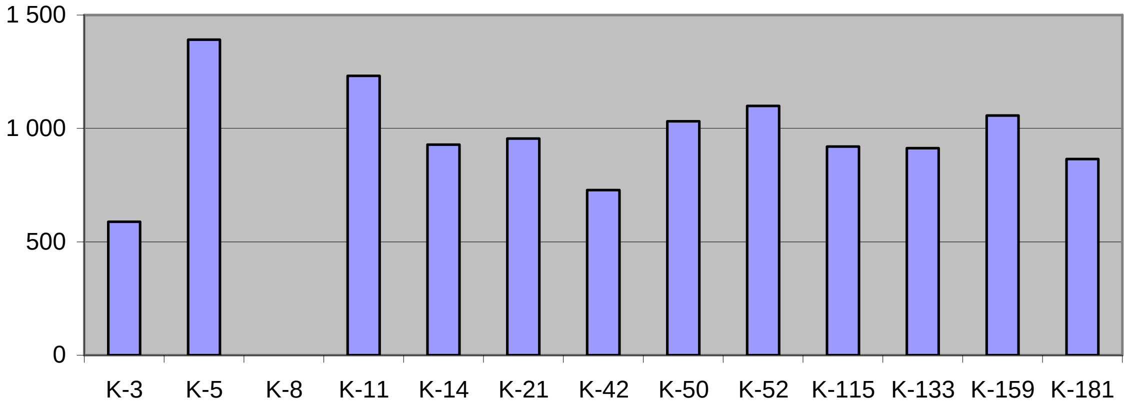
The need for the icebreaker to operate with great flexibility led to a search for ways and means how to increase the burn-up of the reactor cores. The operation of second and third generation of icebreakers was based on the fact that the first cores, then probably the OK-900, reactors "*could produce an energy of 0.7-0.9 million MWh*" [Makarov], while "*they now can produce 2.1-2.3 million MWh*" [Makarov]. This corresponds to a burn in the area 29100 – 37500 MWd for the first cores (OK-900), and 87500 – 95100 MWd for the present cores. With a nominal power on 171 MWt, the latter corresponds for the first cores to 170 – 218 full power days.

Based on [Makarov], basic operating parameters for the nuclear powered icebreakers and cargo ship from 1970 to 1999 have been summarized in table 3.1.

Submarines - first generation

In [Barinov] it is assumed that the reactor of a first generation submarine operates for 40,000 hours at full power with two refuelings before decommissioning. According to [Elatomtsev] the power level of first generation reactors was 72 MWt, so that the burn-up per core becomes 40,000 MWd. However, when considering the actual power operating histories for first generation submarines, these figures seems to overestimate the burn-up and thereby the inventory of medium-lived isotopes like Cs-137 Sr-90 and the transuraniums.

Figure 3.1 # operational days for all November submarines



For the first generation of Russian submarines, the burn-up might be reconstructed using available data in Figure 3.1-3.4 for the submarine models in question. We see that all models November, Hotel, Echo I and II all have been operating with a global average of about 1000 days, the including 1 or even 2 fuel changes. The underlying figures show that the operating history depend mostly on the experiencing with accidents since almost all of the vessels experienced some kind of accidents that required extensive maintenance. Refueling was often performed in conjunction with accidents repairs.

If considering that most of the operating history might be assumed to be at an average level of 25% of full power and one refueling, this would result in the following 8750 MWd as the average fuel burn-up (500 power days, 25% of full power). More conservative estimates have been presented in the relevant literature (750 power days, 40% of full power, i. e. 21000 MWd pr. core), but this seems less relevant taking the actual operational data presented in this report into account. When considering power operating histories for Russian submarines of first generations, the conservative estimate seems reasonable only for very few submarines, possibly only K-5 and K-74 as seen in figure 3.1 and 3.4. These submarines are decommissioned already.

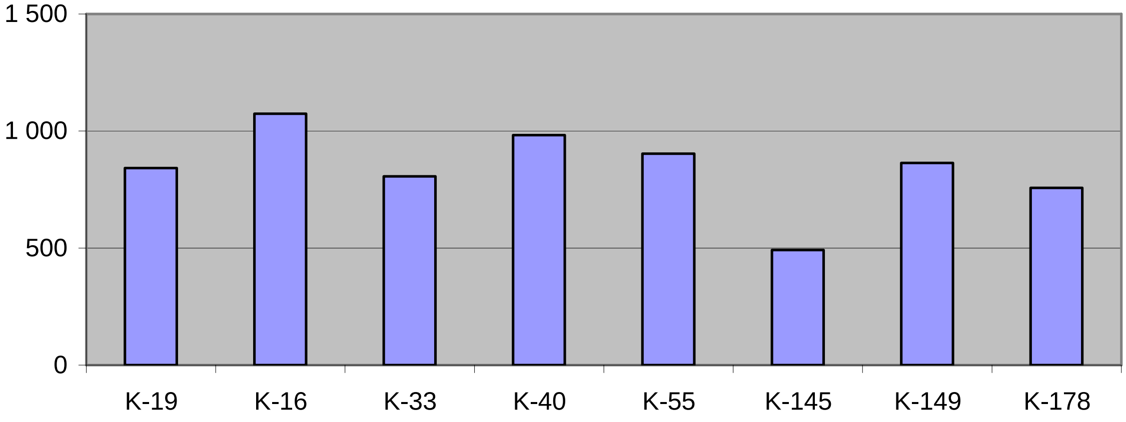


Figure 3.2 # operational days for all Hotel submarines

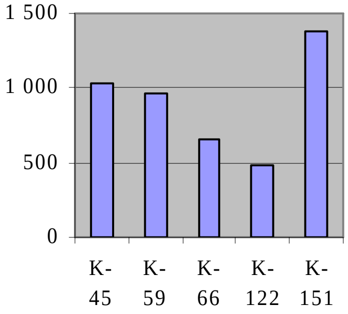


Figure 3.3 # operational days for all Echo I submarines

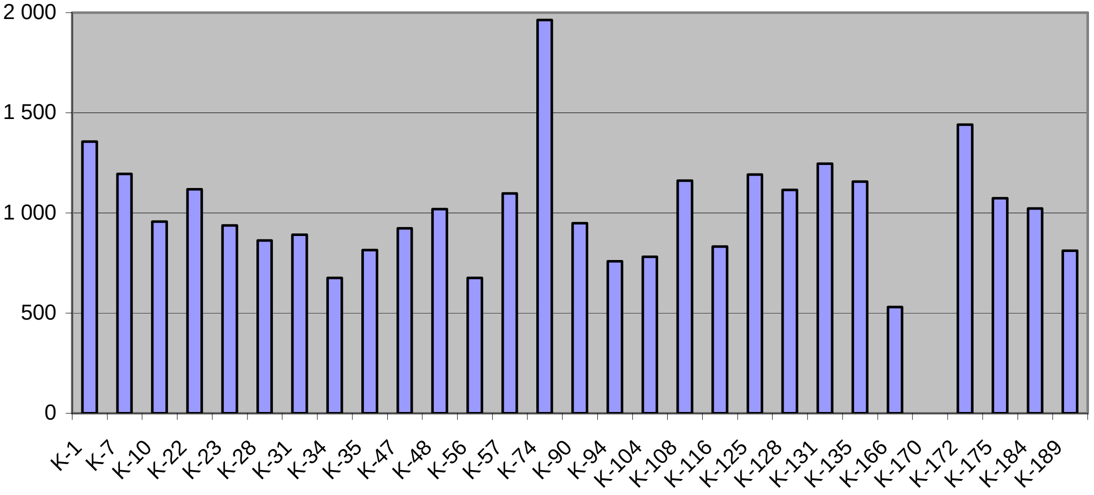


Figure 3.4 # operational days for all Echo II submarines

Submarines - second generation

Regarding second generation submarines, the overall reactor power level increased from 70 MWt in the first generation to 90 MWt. Second generation vessels have also been involved in much fewer accidents that the first generation, often resulting in change of fuel or even the complete reactor compartment. As noted, reactor failure including fuel leaks has reported to be a major problem in the first generation Russian submarine reactors, however, the same problems has not been reported for the second generation or seen as a result of the accident evaluation. This might indicate larger burn-up values for this generation vessels, in this study 50% increase in the number of power days has been chosen as the basis for inventory calculations, resulting in a doubling of burn-up values (750 power days, 25% of full power) from the first generation, to 16875 MWd. This is corresponding to [Bakin], suggesting 17 000 MWd per core. More conservative estimates, in line with similar assumptions for first generation submarines, would be 1000 power days at 40% of full power, i. e. 36 000 MWd pr. core, as a maximum.

Submarines - third generation

The overall reactor power level for third generation submarines was probably nearly doubled compared with the second generation; from 90 MWt to 190 MWt. Regarding operational uses, this was substantially reduced after Soviet Union broke into parts and the Russian financial crises started in the beginning of the 90-ties. A sharp reduction in the number of operational days at sea has to be expected; however, on the other hand improved fuel behaviour might increase the potential burn-up for one single core. Taking the limited number of vessels belonging to the third generation into account, we have to calculate burn-up values based on the number of days in operation pr. year and the days in operation each year. While several vessels have virtually been decommissioned after 1990 due to lack of resources for their operation, the oldest vessels has been systematically decommissioned as new vessels have been put into operation. A reasonable value for operational activity should be 50 days every 18 months to reflect the economical crises in the Russian navy. With a maximum operational period on 17 years, average 15 years, for any vessel of third generation, this corresponds to burn-up value (750:power days/ 1,5 (operational factor), 25% of full power) 23750 MWd. A similar conservative estimate as for the other generations of Russian submarines, with a lower operational factor, approximately 1, and increased power output to 30% of maximum power, the burn-up would be approximately 42000 MWd for a period of 15 years, an average maximum value. These values have been used for inventory calculations for third generation submarines being the largest military vessel considered in this report.

3.4 Core inventory – fission products

Based on the design properties and the survey of operational characteristics, a radionuclide inventory for the different civilian marine reactors types has been calculated as part of this project (se Annex II for example complete set of isotopes), also including short-lived isotopes, in addition to the long-lived fission products and actinides discussed below.

Important for the production of a given fission product is the yield of that particular nuclide in the fission process. Fission produces in addition to the neutron emitted two fission products, the light and the heavy fission product. The fission products with the highest yield are those with mass numbers in the range of 85-105, the light, and of 130-150, the heavy. The total yield of fission products with a given mass number A may be obtained from the fission yield curves with the characteristic double hump. The yield of the fission products at the top of the humps is around 6%.

Fission products with a given A are produced with different atomic numbers or Z-values. Since they are all neutron rich nuclei they will undergo β-decay until they are transformed into the same stable nucleus. In less than 1% of the decays the so-called delayed neutrons will be emitted, but they will be ignored in this context. An example of such a series of β-decays of fission product is

$$^{137}_{50}Sn \rightarrow ^{137}_{51}Sb \rightarrow ^{137}_{52}Te \rightarrow ^{137}_{53}I \rightarrow ^{137}_{54}Xe \rightarrow ^{137}_{55}Cs \rightarrow ^{137m}_{56}Ba \rightarrow ^{137}_{56}Ba$$

where ^{137}Ba is the stable end-nucleus. On the average a fission product formed in the fission process will undergo about 3½ β-decays before becoming a stable nucleus. In the series given above, 46% of the fission products will start their decay chain at ^{137}Xe, 45% at ^{137}I and 7% at ^{137}Te and 2% at ^{137}Cs. These yields may be obtained from the literature, e.g. [Meek], or they may be calculated by use of a theoretical distribution function. It should be noted that all fission products of A=137 will pass ^{137}Cs which has a much longer half-life than all of the others. In general the half-life of the fission products become the larger, the closer the nucleus is to the stable nucleus, but there are exceptions, e.g. ^{137m}Ba.

50-60% of the fission products produced has half-lives of seconds or less. About 75-80% have half-lives of minutes or less and about 85-90% have half-lives of hours or less. But about 5% have half-lives of years. Some of these have very long half-lives, 10^5 years or more, and the activity of these fission products is therefore quite small.

The long-lived fission products are usually formed with a Z-value 1 or 2 less than the corresponding stable nuclei, into which they will ultimately transform. This means that all fission products with a lower Z will rapidly transform into the long-lived fission product. Therefore, it is a reasonable assumption that the long-lived fission products are formed immediately after fission with the full yield of all fission products,γ, with the given mass number.

The number of fissions produced in a reactor per unit time, N_f, is

$$N_f = \frac{P}{E_f}$$

where P is the power level of the reactor and E_f is the total energy produced per fission, about 200 MeV. If P is measured in MW, N_f becomes

$$N_f = 3.1\ 10^{16} P$$

Here N_f is the number of fissions per second. With the assumptions made above the number of a given long-lived fission product in the reactor, N_{fp}, is obtained by the following differential equation:

$$\frac{dN_{fp}}{dt} = \gamma\ N_f - \lambda_{fp}\ N_{fp}$$

where γ is the total yield of fission products with the mass number of the long-lived fission product considered and λ_{fp} its decay constant. It is here assumed that there will be no neutron capture in the fission products. The solution to this equation is

$$N_{fp} = \frac{\gamma\ N_f}{\lambda_{fp}} \left[1 - e^{-\lambda_{fp}\ t} \right]$$

and the activity of the long-lived fission product is

$$\lambda_{fp} N_{fp} = \gamma\ N_f \left\lfloor 1 - e^{-\lambda_{fp}\ t} \right\rfloor$$

The activity of the long-lived fission product considered a period τ after final shut-down is

$$\lambda_{fp} N_{fp} = \gamma\ N_f \left\lfloor 1 - e^{-\lambda_{fp}\ t} \right\rfloor e^{-\lambda_{fp}\ \tau}$$

By use of this formula the activity of a number of long-lived fission products was calculated and compared to the values given in [Pologikh3] and [Lystsov]. In the calculation it was assumed that t=50 000 h, τ=3 yr, and that the burn-up was 42 000 MWd. The yields of [Meek] were used. The results of the calculations are presented in Table 4.1 together with the results from calculations using HELIOS completed as described in the next chapter.

Table 3.3 Activities of Long-lived Fission Products in Spent Naval Fuel

Nuclide	λ	γ	Theoretical	Calculations	Pologikh	*Lystsov*
	(s^{-1})	(%)	(PBq)	(PBq)	(PBq)	*(PBq)*
^{90}Sr	7.63 10^{-10}	5.92	4.22	3,88	4.15	*4.2*
^{106}Ru	2.18 10^{-8}	0.392	0.29	0,23	0.32	
^{137}Cs	7.28 10^{-10}	6.26	4.29	4,03	4.9	4.4
^{144}Ce	2.83 10^{-8}	5.46	2.24	1,36	2.3	
^{147}Pm	8.39 10^{-9}	2.28	4.81	2,45	6.3	

Since the calculations of [Lystsov] were performed on the basis of a burn-up of 21,000 MWd, his activity values were increased by a factor of two. The agreement found is quite good. Note also, that the decay of ^{90}Sr is followed by the decay of ^{90}Y which has a much shorter half-life than ^{90}Sr, so that the activity of ^{90}Y is very nearly the same as that of ^{90}Sr. The same is true for ^{106}Ru and ^{106}Rb, ^{137}Cs and ^{137m}Ba and ^{144}Ce and ^{144}Pr. When considering the fission product with longer half-life, the calculations for submarine inventory show that it is formed about 1 PBq of ^{137}Cs and ^{90}Sr for every 10 GWd in burn-up.

3.5 Core inventory – transuranic isotopes

The production of transuranium element depends on the burn-up, on the enrichment of the fuel and on the reactor design. Since Russian submarines normally use quite highly enriched uranium, 20 – 90%, the production of transuranium elements is limited. In this chapter, results of calculations of transuranium inventory for selected vessels are presented with a brief introduction of transuranium production process in reactors.

Transuranium elements are produced by the following processes. Neutron capture in ^{235}U will in about 15% lead to the production of ^{236}U. The half-life of ^{236}U is long, 2.3 10^{7} year and its thermal absorption cross section is small, about 5 barn, but neutron capture will produce some ^{237}U which will rapidly decay into ^{237}Np ($T_{½}$=6.8 d). ^{237}Np has a long half-life ($T_{½}$= 2.1 10^{6} year), but a reasonable large absorption cross section (170 b), and neutron capture leads to production of ^{238}Np, which will rapidly decay into ^{238}Pu ($T_{½}$=2.1 d). ^{238}Pu has a half-life of about 88 years and it is one of transuranium elements, which will occur in burned submarine fuel.

Neutron capture in ^{238}U will produce ^{239}U, which rapidly is transformed into ^{239}Pu after two β-decays. Neutron capture in ^{239}Pu will usually cause fission, but in some cases ^{240}Pu is formed. Neutron capture in ^{240}Pu produces ^{241}Pu, which relatively rapidly ($T_{½}$=14 yr) decays into ^{241}Am.

Icebreaker reactors

From [Pologikh3] and [Lystsov] the following values for the activity of some transuranium elements in a submarine core that has a burn up of about 40 000 MWd can be obtained. These values are given in Table 3.4.

The Lystsov values have been corrected for a lower burn-up. From the table it is seen that he activity of the transuranium elements in submarine fuel is most cases several orders of magnitude

Table 3.4 Transuranium Elements in Spent Fuel

Nuclide	Pologikh3 (TBq)	Lystsov(TBq)	Calculations (TBq)
^{238}Pu	41	26	
^{239}Pu	6.5	6.6	
^{240}Pu	4.1		
^{241}Pu	1100		
^{241}Am	11		

lower than that of the long-lived fission products. However, the transuranium elements listed are α-emitters except for ^{241}Pu, which is a β-emitter.

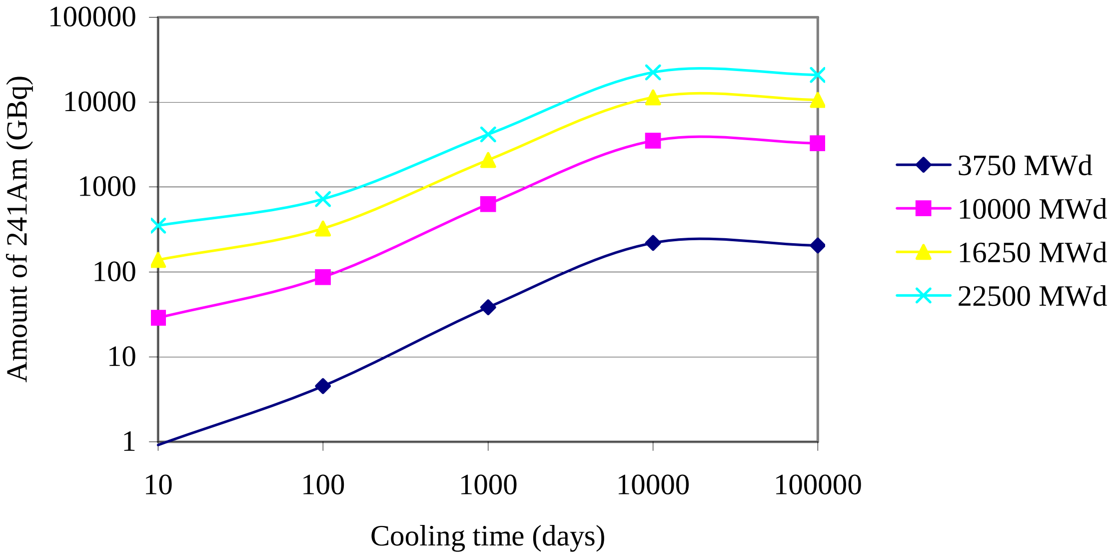


Figure 3.5 Amount of 241Am (GBq) as a function of burn-up (MWd) and decay (days) for reactor fueled with 8% enriched (235U) U-Al alloy

An example of the relative importance of actinides is spent fuel from decommissioned Russian submarine reactors. Since the reactors of the first generation of Russian submarines have not been in operation for years, no short-lived isotopes will be left in the fuel. Because of the production of Pu, the production of ^{241}Am as seen in figure 3.5, continues up to a level of 10 TBq 30 years after the reactor has been shut off. Many of the Russian submarines of first and second generation will reach this level the coming five to ten years, and cause increased difficulties in the handling of the spent fuel. A criteria used for evaluating the self-protectiveness of irradiated nuclear fuel, is that the dose rate at 1 meter unshielded is below 100 R/hour. In case of the Russian spent marine fuel, the dominating radiation sources are ^{137}Cs and – to some extent – ^{241}Am and other actinides. After 100000 days, or 30 years, one fuel assembly will no longer be self-protecting but the radiation level will not be more than one decade below the limit mentioned. However, certain operation histories might give other results, in IAEA (1996) also shorter burn up than used in figure 3.5 are registered for certain reactors, for example there have been several incidents where the reactor has had to be replaced because of accidents. These cores, which are stored at the bases in the Northern or in the Pacific area, must be given high priority in the efforts to secure the spent fuel.

Submarine reactors

This part is divided into three parts: A) the amounts and quality of ^{239}Pu, B) the amount and enrichment of ^{235}U, and C) the amount of fission products and actinides in the spent fuel. The thermal power has been varied from 20 MW to 90 MW, but with no significant effect on the amounts of material in focus for this paper.

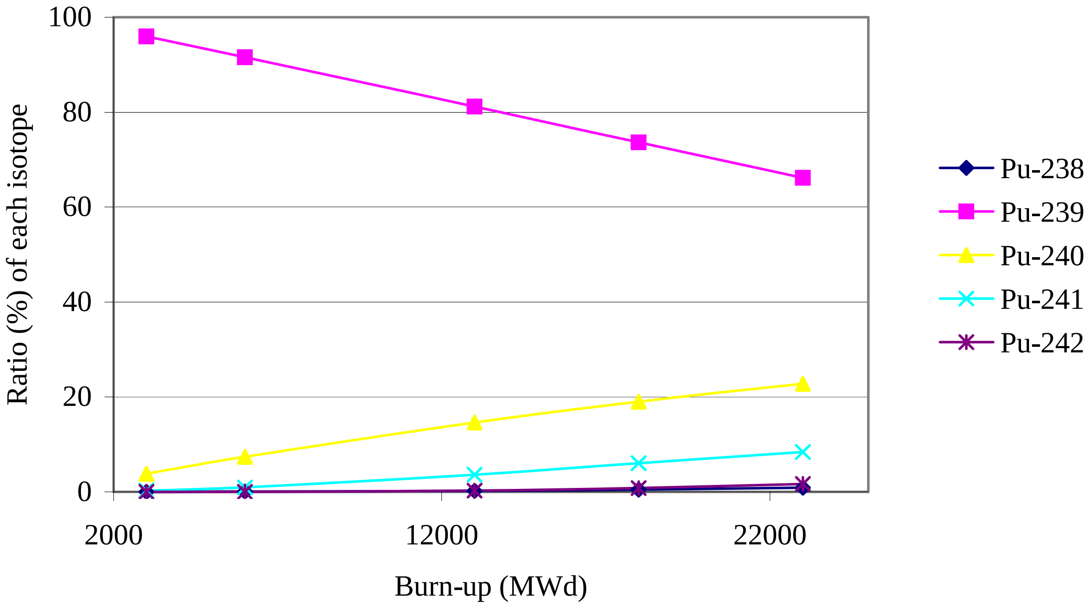


Figure 3.6 Ratio of quantity (g) of each Pu-isotope to the total quantity of Pu vs. burn-up (MWd) for a naval reactor with 50 kg. initial ^{235}U enriched to 20%

For light enriched fuel (5% and 7.5%) one can observe a substantial production of Pu compared to the other cases. As seen from figure 3.6, in a core with 50 kg 235U, initially enriched to 5%, up to 3.5 kg ^{239}Pu can be produced. The calculations show that the k_{ef} is going below 1 about the same time as the consumption rate of Pu exceeds the production rate, i.e. at the time of fuel change. Moreover, modestly enriched uranium fuel give significant positive results in the context of nonproliferation considering the amount produced of ^{239}Pu, and in case the fuel is enriched to 10%, less than 2 kg ^{239}Pu is produced in the core with an initial load of 50 kg ^{235}U. In case of the low and modestly enriched spent fuel, the amount of Pu in each assembly with the reactor and fuel data proposed, will be in the area of 0,02- 0,011 kg. In a fully burned submarine reactor the quality of the Pu will similar to the quality of Pu in commercial reactor fuel as seen in figure 3.7: with about 60% ^{239}Pu and a substantial proportion of ^{240}Pu and ^{241}Pu, which make the fuel not very attractive to handle. It should be emphasized however, that the plutonium quality in a

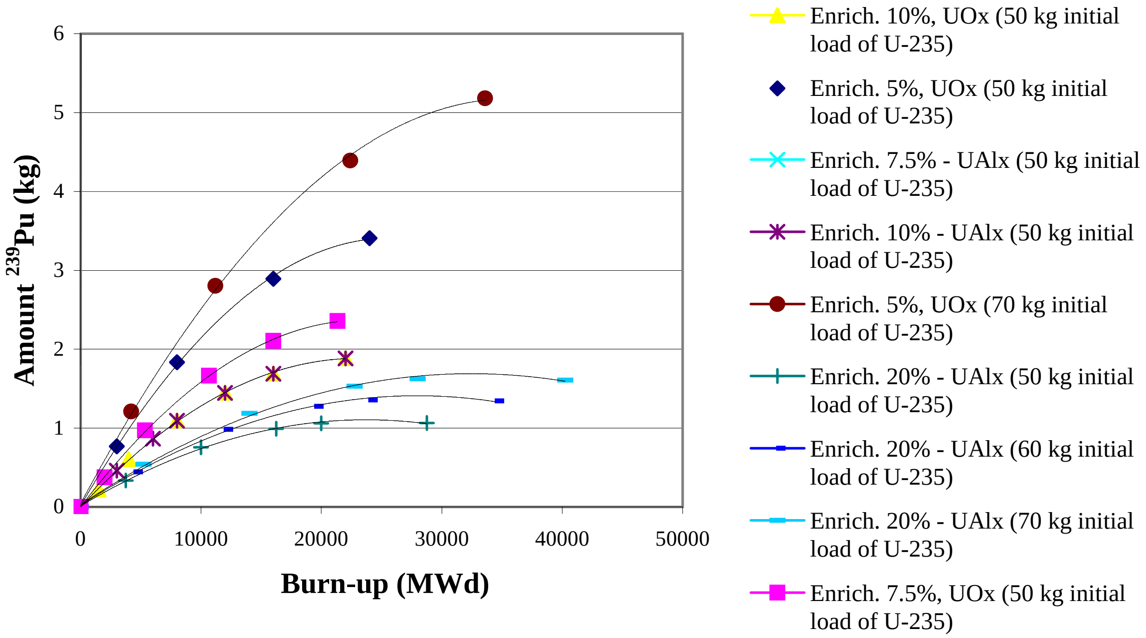


Figure 3.7 Amount of ^{239}Pu (kg) vs. burn-up (MWd) in Russian spent naval (UOx and UAlx) - first generation submarine with 50 to 70 kg ^{235}U initial fuel load.

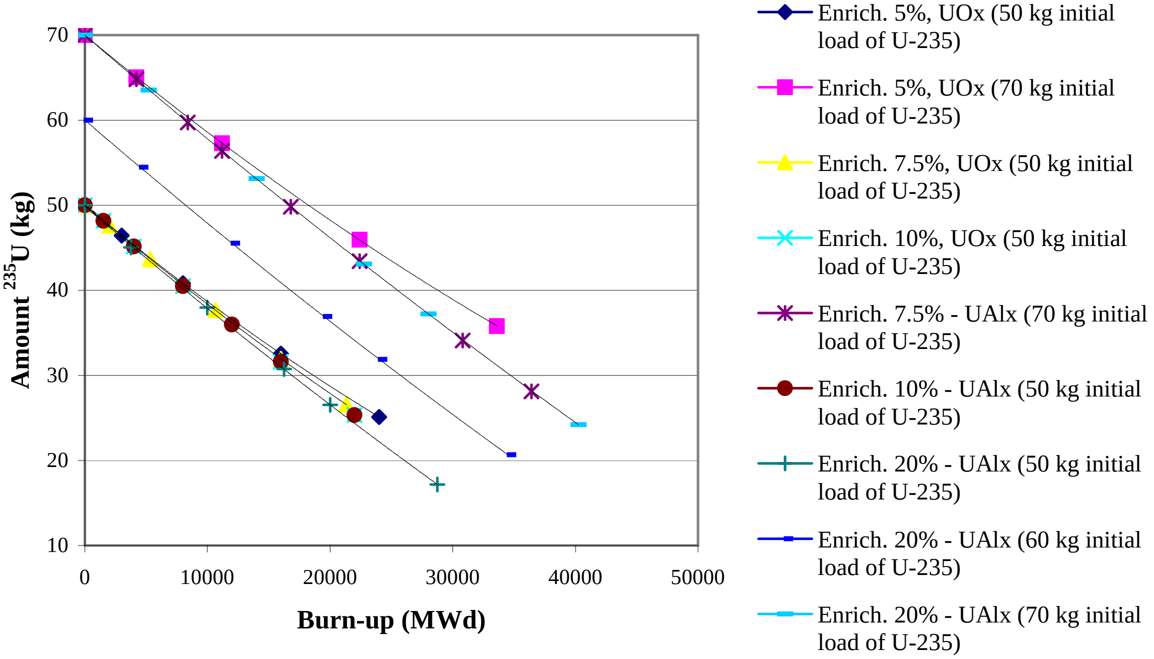


Figure 3.8 Amount of ^{235}U (kg) vs. burn-up (MWd) in Russian spent naval fuel (UOx and UAlx) - first and second generation submarine with 50 kg - 70 kg ^{235}U initial fuel load

half burned out reactor core, can be more than 80% ^{239}Pu. As seen from figure 3.7, as much as 2-3 kg ^{239}Pu may be produced in one half burned reactor core. The fuel composition has no significant effect on the Pu-content, as observed in figure 3.7 for similar initial conditions for fuel uranium oxide and uranium aluminium alloy. In case 2, with fuel enriched to 20%, the content of Pu gets less important. In a reactor with 20% initial enrichment of ^{235}U (initial load of 50 kg ^{235}U), the largest content in one core will be less than 1.1 kg. The quality of the Pu in this case continues to be like the quality of Pu in commercial reactor fuel, however, with a 10% higher share of ^{239}Pu, and a similar lower share of the other Pu-isotopes.

The amount of ^{235}U in this case for the different enrichment levels follows a similar development as it decreases from the initial quantity. There are insignificant differences between fuel loads with different initial enrichment as seen in figure 3.8. The effects of higher initial content of ^{235}U are seen to be important for how long to burn the reactor. While the content of ^{235}U after operation for a reactor with enriched fuel to 20% and 50 kg initial load of ^{235}U, decreases to 30-40 kg pr. core, or 0,17-0,22 kg pr. fuel assembly, the final enrichment in ^{235}U end up at 7-12%.

3.6 Overall inventory – submarine and icebreaker vessels

Regarding all relevant reactors, average burn-up values as presented in chapter 3.2 have been chosen in the modelling of fission inventory. The calculations have been based on two different geometries and fuel materials:

A. The “Lenin” configuration (uraniumdiokside, circular fuel pins and assembly, hexagonal): Lenin, first generation submarine;
B. The “Sevmorput” configuration: (uranium metal (U-Al), circular fuel pins and assembly, hexagonal): second and third generation icebreaker, second and third generation submarine

The main difference in the model configurations used for the calculations below is related to the enrichment level and the amount of fuel material in the reactors, ranging from 50 kg. (U-235)/ 20% in the first generation submarines to 150,7 kg (U-235)/ 90% (third generation icebreaker) to 200 kg (U-235)/ 45% (third generation submarine).

Table 3.5 Summary of operational data and radionuclide inventory calculated for different types of Russian marine reactors – decay time: 0,1 day

	Icebreakers		Submarines	
	OK-150 (1. gen)	KLT-40 (3. gen)	VM-A (1. gen)	OK 650 (3. gen)
Burn (MWd) (average)	14200[6]	78000	8750	23750
Burn-up (MWd/ t iHM[7])	8875	465826	35000	53491
Days of oper. pr. year	-[5]	275	50	33
Fission products (Bq)				
^{90}Sr	1,58E+15	8,68E+15	8,71E+14	2,34E+15
^{137}Cs	1,69E+15	8,83E+15	8,91E+14	2,40E+15
^{106}Ru	5,14E+15	5,41E+15	4,13E+14	8,19E+14
^{144}Ce	4,67E+16	6,55E+16	4,83E+15	9,78E+15
^{147}Pm	5,38E+15	1,45E+16	1,40E+15	2,80E+15
Transuranic elements (Bq)				
^{239}Pu	9,88E+12	7,50E+11	1,26E+12	3,18E+12
^{240}Pu	2,99E+12	1,05E+12	3,46E+11	1,00E+12
^{241}Pu	3,48E+14	3,20E+14	1,98E+13	9,52E+13
^{241}Am	6,08E+10	6,00E+11	6,83E+10	5,22E+11
^{242}Pu	5,27E+08	4,16E+09	3,03E+07	1,38E+08

The amount of actinides, than considering the fissile material in particular, in Russian submarines of first and second generation is naturally primarily dependent on the initial loading of ^{235}U in the reactor and the burn-up. With 50 kg initial load of ^{235}U enriched to 20%, and operation to the limit of the fuel in the reactor, the content of ^{235}U might be reduced to 27 kg in case of high burn-up. The enrichment is then reduced to 10%, and the Pu produced is 1.1 kg. For a reactor with substantially lower enrichment, 5% in ^{235}U, however, with the same initial amount of ^{235}U, again considering an operating history lasting until k_{eff} goes below one, the content of ^{235}U will be 26 kg, enriched to 3%, but with a Pu content on 3.4 kg. The perhaps most plausible reactor and fuel

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[6] [Sivintsev], p. 11.
[7] iHM = initial heavy metal (in metric tons).

data set for the largest number of submarines, 20% enriched fuel with 50 kg initial load of ^{235}U, give a core content of ^{239}Pu on 1.6 kg, or 0.029 kg pr. fuel assembly.

A short burn-up gives reasons to concentrate on the content of ^{137}Cs, while in the opposite case, the ^{241}Am will dominate after several hundred years, as for commercial power fuel. For low enriched submarine fuel the proliferation concern is associated with plutonium. For high enriched fuel the concern is associated with ^{235}U and crude uranium.

4 Release Properties for Various Accidents

The emphasis has been put on identification of possible releases of radioactivity as being the main focus of this report. The two main scenarios for contact between the surrounding environment and the radioactivity in the fuel, are:

1. Deliberate removal of all barriers between fuel and environment and subsequent accidents, i. e. refueling/ defueling;
2. Undeliberate removal of all barriers between fuel and environment as a result of an accident;

The main preliminary conclusion regarding source-term relevant submarine accidents which may give rise to release of radioactive materials must directly or indirectly involve the reactor and the primary circuit. The accidents that affect the reactor system directly are criticality accidents and loss-of-cooling accidents (including solidification accidents). Regarding the first scenario, a special emphasis has been put on criticality incidents which have occurred at several instances, where no barriers are in place for preventing mitigation of radionuclides in case of an accident. Accidents with nuclear weapons on board the submarines are not considered in this context.

4.1 Criticality Accidents

During a criticality accident the reactor becomes unintentionally supercritical, a significant amount of energy is produced in the associated power excursion and this energy will destroy some or most of the fuel and part of the reactor system. It may also eject fuel particles and radioactive steam and water droplets into the surrounding areas.

Criticality accidents are unlikely to occur during normal operation of reactors since during this period the flux monitoring and the control systems are operational. These systems will shut down the reactor, should the reactor for some reason become supercritical. However, when the submarine is at a shipyard for repair, refueling and/or tests, the safety systems may not be in operation, when control rods or fuel elements are moved and a criticality accident may occur. Such an accident is in particular dangerous if it occurs during re- or defueling, when the submarine hull has been opened and there is free access from the reactor tank to the environment.

The release of activity in connection with a criticality accident consists primarily of fission products. There are two sources of fission products; those present in the fuel prior to the accident and those produced during the power excursion caused by the accident.

4.1.1 Fissions produced during the power excursion

The number of fissions produced during the power excursion depends on a number of factors, e.g. the degree of supercriticality achieved and the speed with which it is added. It has for submarine reactors has been estimated by a number of authors:

[Lystsov]:	about 10^{18} fissions

[Sivintsev]:	about 5 10^{18} fissions
[Pologikh2]:	about 10^{19} fissions
[Oelgaard2]:	about 5 10^{19} fissions
[Soyfer]:	about 5 10^{19} fissions

A reasonable average of these values may be 10^{19} fissions. (få inn Sivintsevs artikkel om hva some r sannsynlig…)Since each and every fission result in an energy release of about 200 MeV, this corresponds to an energy production of about 0.004 MWd or the energy equivalence of about 80 kg TNT

The contribution of the fission product produced during the power excursion may seem negligible as compared to that due to burn-up, which amounts to an energy production of up to 40 000 MWd. This is correct as regards the fission products with long half-lives. But if the accident occurs in connection with re/defueling the release of fission products with short half-lives will be dominated by those produced during the excursion, since re/defueling will usually take place about one year or more after the shut-down of the reactor. At this time the short-lived fission products produced during ordinary operation have decayed. Further, if the accident occurs in a core with fresh fuel the only fission products in the core are those produced during the power excursion.

4.1.2 Production of short-lived fission products during the excursion

Criticality accidents are not likely to occur during reactor operation as mentioned earlier, since the control system will shut the reactor down once it becomes sufficiently supercritical. They are much more likely during re/defueling or repair work at shipyards. This type of work will usually be performed some time after close-down of the reactor, e.g. one year. At this time the short-lived fission products have decayed. However, immediately after the power excursion of a criticality accident the short-lived fission products produced by the excursion will be of importance. This is in particular true for noble gases such as krypton and xenon, which have high release fractions (cf. section 4.2.6), and which can easily be carried away from the place of accident by the wind.

Here the case is considered where a short-lived fission product (the first), produced in the fission process, decays into another fission product (the second), also produced in the fission process. If there are any precursors nuclei to the first fission product they are assumed to decay into the first fission product immediately. Under this assumption the activity of the first fission product is

$$\lambda_1 \; N_1 = \lambda_1 \; \gamma_1 \; N_{fe} \; e^{-\lambda_1 t}$$

Here N_1 is the number of the first fission product, λ_1 its decay constant, γ_1 the yield per fission of the first fission product and its precursors (the so-called cumulative fractional yield) and N_{fe} the number of fissions produced during the excursion. The activity of the second fission product consists of nuclei produced either directly by fission or by the decay of the first fission product. The expression of the former is quite similar to that of the first nuclei:

$$\lambda_2 N_{2a} = \lambda_2\ \gamma_2 N_{fe}\ e^{-\lambda_2 t}$$

Here λ_2 is the decay constant of the second fission product and γ_2 its fractional yield. The number of the second nuclei produced by decay of the first is given by the equation

$$\frac{dN_2}{dt} = \lambda_1\ \gamma_1 N_{fe} e^{-\lambda_1 t} - \lambda_2\ N_2$$

The solution of this differential equation is

$$N_{2b} = \frac{\lambda_1}{\lambda_2 - \lambda_1}\ \gamma_1\ N_{fe}\left[\ e^{-\lambda_1 t} - e^{-\lambda_2 t}\right]$$

so that the total activity of the second fission product becomes

$$\lambda_2\ N_2 = \lambda_2\ \left(N_{2a} + N_{2b}\right) = \lambda_2\ \gamma_2\ N_{fe} e^{-\lambda_2 t} + \frac{\lambda_1\ \lambda_2}{\lambda_2 - \lambda_1}\gamma_1 N_{fe}\left[e^{-\lambda_1 t} - e^{-\lambda_2 t}\right]$$

By use of these formulas the activity of a number of noble gas fission products and their daughter nuclei, produced during the excursion, was calculated and compared with results presented by [Pologikh3]. The γ-values used in the calculations were those of [Meek] and the half-lives those of [Lederer]. The cumulative fractional yield was used for γ_1. N_f was assumed to be equal to 10^{19} fissions (cf. 4.2.1) and the activity was calculated 10, 100 and 600 seconds after the excursion. The results of the calculations are presented in Table 4.2.

Table 4.1 Activity of Short-lived Fission Products (in PBq) after a criticality excursion

Isotopes	**Present**	**Pologikh**	**Present**	**Pologikh**	**Present**	***Pologikh***
	10s		**100s**		***600s***	
^{89}Kr+^{89}Rb	1.66	1.25	1.30	0.985	0.435	*0.318*
^{91}Kr+^{91}Rb	15.40	13.10	2.13	1.510	0.0054	*0.003*
^{137}Xe	1.80	0.91	1.37	0.70	0.302	*0.165*
^{138}Xe+^{138}Cs	0.52	0.23	0.500	0.215	0.400	*0.171*
^{139}Xe+^{139}Cs	7.69	5.82	2.08	1.600	0.340	*0.253*
^{140}Xe+^{139}Cs	*14.78*	*12.20*	*2.636*	*1.720*	*0.012*	*0.007*

The values obtained in the present calculations (“Present” in Table 4.2) differ from those of [Pologikh3] (“Pologikh” in Table 4.2) by up to a factor of two, but the variation with time is quite similar. The difference is probably due to different yield values and to differences in the assumptions made.

4.1.3 Production of long-lived fission products during the excursion

The activity of long-lived fission products produced during the excursion may be calculated by use of the formula

$$A_{fp} = \lambda \, \gamma \; N_f$$

Here again N_f is assumed to be 10^{19} fissions, λ is the decay constant of the fission product considered and γ is the cumulative fractional yield. This formula assumes that the long-lived fission products are formed directly by fission which is nor quite correct. The activity values obtained are given in Table 4.3.

Table 4.2 Activity of Long-lived Fission Products Produced during the Excursion

^{90}Sr	0.45 GBq
^{106}Ru	0.85 GBq
^{137}Cs	0.46 GBq
^{144}Ce	15.42 GBq
^{147}*Pm*	1.91 GBq

It is seen that these activities are six orders of magnitude lower than the corresponding activities of the long-lived fission products of Table 4.1. However, if the fuel in the reactor, which suffers a criticality accident, contains fresh fuel the long-lived fission products are those of Table 4.3.

4.1.4 Release fractions

An important factor in the release of activity from a criticality accidents is the fraction of the fission products which is released to the environment during the accident. This fraction varies with the chemical nature of the individual fission products. [Pologikh2] gives values for the release fractions in case of a criticality accident. They are listed in Table 4.5.

Table 4.3 Russian Release Fractions for Submarine Criticality Accidents

Kr, Xe:	*0.1*
I, Br, Ru, Te, Cs:	*0.01*
All other elements (including transuranium elements):	*0.002*

It is of interest to compare these release fractions with those of the Chernobyl criticality accident, taking into account the differences in the two types of criticality accidents. For the Chernobyl accident [NEA] gives the following (rounded off) values:

Table 4.4 NEA Release Fractions for the Chernobyl Accident

Xe:	*1*
I:	*0.6*
Cs:	*0.3*
Te:	*0.4*
Sr, Ba:	*0.05*
Zr, Mo, Ru, Ce:	*0.04*

These figures can not directly be compared with figures for a criticality accident with a submarine reactor (PWR). In the case of the Chernobyl reactor the melted fuel caused the graphite moderator to burn and this caused the activity emission of continue for 10 days until all graphite was burned. In a PWR the release will stop when the fuel solidifies, i.e. after a period of the order of one hour. According to [NEA] 24% of the total release occurred on the first day. A significant part of this release is likely to have have occurred during the first hour, e.g. 50%, after which the release became more or less constant. Thus, the Chernobyl release figures should be reduced by a factor of about 10 to correspond to a PWR accident. If this is done, it yields the following comparison between the figures of [Pologikh2] and [NEA]:

Table 4.5 Comparison of Russian and Corrected NEA Release Fractions

	Pologikh2	*”NEA”*
Xe, Kr:	0.1	*0.1*
I, Br, Ru, Te, Cs:	0.01	*0.03-0.06*
All other elements:	*0.002*	*0.004-0.005*

With the reduction of a factor of 10 and taking into account the uncertainty involved in the deduction of the factor 10, the agreement between [Pologikh2] and [NEA] seems to be quite reasonable.

4.1.5 Release heights

In the excursion much of the activity together with the hot steam is lifted up into the atmosphere from where it is dispersed by the wind and by diffusion. In dispersion models the effective release height is introduced and the following values for this height are reported in the literature:

Table 4.6 Effective Release Height

[Lystsov]	*50-100 m*
[Pologikh2]	*30 m*
[Smetsers]	*75 m*

4.2 Loss-of- Cooling Accidents

Loss-of-cooling accidents (LOCA) usually occurs when the reactor is running at power and the cooling is reduced or totally stopped due to a leakage (caused by e.g. corrosion or maloperation of valves) in the primary system or the stoppage of the main circulation pumps. Stoppage of the circulation pumps in the secondary circuit can also cause a LOCA. In the case of a leakage, the cooling water will be drained from the primary circuit through the leak, the fuel will no longer be cooled sufficiently, the fuel temperature will increase and the fuel may ultimately melt and release fission products into the primary circuit and the reactor compartment. In the case of pump failure the coolant pressure will increase, the safety valves will be activated and a steam/water mixture will flow out into the reactor compartment, gradually draining the reactor tank and reducing the cooling of the fuel, which may ultimately melt.

Usually the chain reaction will be stopped as soon as the leakage starts or the pumps stop. However, even when the chain reaction stops the heat production in the core will continue, though at a reduced level, due to the decay heat from the decay of the fission products. For a reactor which has been running at power for some time the power level will immediately after shut-down drop to 6-7% of the level before shut-down. After one hour it will be around 1% and after one day around 0.5% of the power level before shut-down. The decay heat DH may be obtained from the following formula:

$$DH = 0.0667\ P \left(\tau^{-0.2} - (T + \tau)^{-0.2} \right)$$

Here T is the time operation prior to the accident (in seconds), τ is the time after the accident has occurred (in seconds) and P the reactor power level prior to the accident (in MW). Using these unite DH is obtained in MW. The validity of the formula is limited to τ= 1 day. For longer periods of time other, but similar relations should be used.

If this decay heat is not removed, the fuel will overheat and fission products will be released. To avoid damage to the fuel in case of a leakage of the primary system reactors are usually provided with an emergency core cooling system (ECCS), which will ensure that the core is all the time covered with water and thereby sufficiently cooled. However, it seems as if the first generation of Russian nuclear vessels were not provided with such a system or at least not with a sufficiently effective system so that a number of LOCAs occurred in Russian vessels.

LOCAs may also occur shortly after reactor shut-down when the decay heat is still significant. Such an accident happened at the icebreaker Lenin, when the reactor had been shut down for refuelling and an operator by mistake opened a valve and drained part of the reactor core. Even if there is no leakage the stopping of the coolant flow immediately after shut-down may lead to fuel damage. However, after some hours natural circulation in the primary system will usually provide the necessary cooling of the reduced power production. Two years after shut-down the reactor may be drained without any damage to the fuel.

When a LOCA occurs and the fuel is damage, radioactive gases and particles will be released into the reactor compartment by the leaking steam-water mixture, and the pressure in the reactor compartment will increase. This could lead to the dispersion of the radioactive materials. What happens depends on the design and integrity of the submarine, but there are two features that will counteract the dispersal. Firstly, large areas of the submarine surface are in excellent thermal contact with surrounding sea, and this feature will act as a pressure suppression system, because the steam will condense on the inner side of the pressure hull together with most of the fission products. Secondly, the submarine is divided up into a number of compartments with bulkheads between the compartments. These bulkheads can be closed and should prevent the spread of the radioactive materials. However, experience show that it is difficult to keep the bulkheads closed during an emergency. But the pressure hull of the submarine will act as an efficient containment since it has to be tight and has in practice only one opening, the hatch to the sail or conning tower, which is usually closed. This means that even if the contamination spreads to most of the submarine, very little will get out of the submarine. That this is so was observed in the case of the Echo-II class submarine, which suffered a LOCA 110 km north west of Sørøya of northern Norway. Water samples taken by the Norwegian authorities close to the submarine indicated very little if any contamination of the sea.

It seems therefore reasonable to conclude that due to the pressure suppression property and containment efficiency of the pressure hull of the nuclear submarines, very little activity will in the case of a LOCA escape from the submarine and that it will only result in very local contamination.

4.3 Sunken Nuclear Submarines

A number of nuclear submarine accidents has happened which resulted in the sinking of the vessel. Two US submarines and three Russian submarines rest today at the bottom of the sea. In 1963 the US Thresher sank off the coast of Cape Cod at a depth of 2600 m - presumably due to in-leakage of water - during sea trials after it had undergone an overhaul at a shipyard. It was crushed by water pressure. In 1968 the US Scorpion sank at a depth of 3600 m – presumably killed by one of its own homing torpedoes – when crossing the Atlantic Ocean. In 1970 a Russian November class submarine sank - due to a fire - at a depth of 4700 m in the British Channel. In 1986 a Russian Yankee class submarine sank in the Atlantic Ocean – due to an explosion – at a depth of 5-6 km. In 1989 a Russian Mike class submarine sank in the Norwegian Sea - due to a fire – at a depth of 1680 m.

Further from the sixties to the beginning of the eighties Russian dumped six submarine reactor compartments, four of them with fuel in one or both of the reactors. They were dumped in the Kara Sea off the coast of Novaya Zemlya. The four submarines with fuel in one or both reactors are believed to be a Hotel, a November, a Yankee and a Project 645 class submarine, and they had all suffered accidents whereby the fuel had been damaged. Before the dumping the reactors were in general covered chemical compounds to delay release of fission products to the sea.

Measurements of the release of radioactive isotopes to the sea have been made both for the US and the Russian sunken submarines and the dumped reactor compartments. Very small concentrations of fission products and cobalt-60 have been detected, so the release has been slow and the released radioisotopes are transported away from the submarines by the sea currents of the sea, hereby decreasing the activity concentration, but increasing the volume of contaminated seawater.

However, as the corrosion of the reactor system and the fuel caused by the seawater proceeds, more radioisotopes will be released. On the other hand the materials used in the reactors are in general rather corrosion resistant, so the release will be slow, and the content of radioactive material will also gradually decrease due to the radioactive decay.

The importance of the release depends also on where it happens. If it occurs in an area of the sea important for fishing, its effect may well be significant, not so much because of actual contamination of the fish, but because fear of contamination may make it difficult to sell fish from this area.

If a submarine sinks close to areas of significant human activity, e.g. cities or summer resorts, the psychological effect may also be significant. However, here the depth will in general be shallow and the salvage of the submarine fairly simple. In two cases the submarines sank at shallow depth and were later recovered. One case involved a Russian Charlie-1 class submarine that sank in 1983 at a depth of 35 m due to an operator error near Kamchatka. The other involved an Oscar class submarine (Kursk) that sank in 2000 at a depth of 108 m due to a torpedo explosion in the Barent Sea. In both cases the submarines were recovered.

From the considerations given above it may be concluded that the sinking of a nuclear submarine will result in source terms that are very small, if not negligible. However, if the sinking occurs near areas of human activity the psychological effect may nevertheless be quite significant.

The Komsomolets submarine sank in 1989 in the Norwegian Sea, south of Bear Island. Minor releases of radioactivity from the reactor compartment have been detected, but large scale releases are thought to be unlikely because the engineered barriers will prevent corrosion of reactor fuel for some time. The latest accident involving a Russian submarine, the Kursk in August 2000, with subsequent rescue operations, raised considerable concern along the coastline about possible consequences, and represented a significant challenge for the Norwegian nuclear emergency preparedness organisation from the day the accident happened until the larger part of the submarine had been brought in dock in Roslyakovo. The Norwegian Radiation Protection Authority completed an environmental risk assessment for four scenarios combining two calculations of inventory and two release scenarios.

The calculations of the inventory of Kursk were based of the description of the Russian cargo ship Sevmorput with some adjustments of the technical input data, as have been the basis for the inventory calculations in this report. The hypothetical release rate of radionuclides depends heavily on the release conditions. These conditions may range from instantaneous release as a result of explosions of torpedoes or cruise missiles left in the submarine, to the slow long-term corrosion of the fuel material. The latter may occur when seawater has penetrated the fuel cladding. If the cladding is zirconium, penetration may take several hundred years or more.

However, if conditions for galvanic corrosion are present, the cladding may perhaps be corroded through in less than a year.

The following two scenarios for releases of radionuclides have been selected for the wide range of possibilities in the present situation:

- Scenario 1, corresponding to an abnormal event one year after the accident, i. e. during the salvage operation, 100% of the inventory in both reactors is released instantaneously.

- Scenario 2, corresponding to the assumption that all barriers, for all practical purposes, have been removed after 100 years, and 100% of the inventory in both reactors are released at this point.

With respect to fuel burn-up, two different versions of the operational history, resulting in a burn-up on 12000 respectively 24000 MWd, have been considered with each scenario. Both versions are based on the submarine being operative for an average of 50 days per year, for each year since commissioning at the end of 1994. However, scenario 2 includes extensive operation of the reactors for production of electrical power when in port as reported in several sources during recent years. It should be noted that an estimated release of 100% of the inventory is a very conservative approach chose to demonstrate the consequences of a simple scenario, even if not realistic, to the concerned public, new approaches are being established as part of the follow-up activities as described in the introduction to this report.

Estimations of the radiological consequences in the marine environment after potential releases of radionuclides from the Kursk submarine were performed on this basis. The elements for the modelling work are the two given scenarios, and a box model, which estimates radionuclide transport over large distances (> 1000 km) and over long time-scales (up to centuries or millennia). The present model is based on the box modelling approach, which includes terms that describe the dispersion of radionuclides into oceanic space with time. The present model is a revised version of the box model covering the European coastal waters, Arctic and the North Atlantic Oceans.

The model calculation of transport, transfer to fish and collective doses to humans following the given scenarios is performed for a range of different radionuclides, which are present in the reactors. However, most attention is focused on ^{137}Cs release. This is due to the fact that ^{137}Cs has a relatively long physical half life (30 years), is readily dissolved in the water phase and accumulates readily in edible parts of fish and shellfish. Dispersion of ^{137}Cs in the oceanic surface water, corresponding to the worst case of the potential accidental releases with immediate release of spent fuel with high burn-up, show that 0.5 years after a hypothetical accidental release of 100% of the inventory, the average water concentration in the Barents Sea will be in the range 160 – 210 Bq/m^3 for areas in close vicinity to the submarine. ^{137}Cs activities will decrease rapidly, and after 10 years it is estimated that the average water concentration in the Barents Sea will be in the range 0.1 – 2.8 Bq/m^3.

Regarding the dynamics for the ^{137}Cs concentration in fish for the Barents Sea region (corresponding to the same scenario), the calculations indicate that during the first years of potential dispersion, the ^{137}Cs activity concentration in fish varies widely depending on the habitat of fish. During the early stages of the dispersion, the Barents Sea contains regions with relatively high contamination and regions that are not affected by the release of radionuclides. The model calculation of transfer to fish is subject to large uncertainties, and other more hypothetical transfer pathways (e.g. ingestion of particles) have not been considered. Calculations show a maximum activity concentration of ^{137}Cs in fish, during the first year following a hypothetical leakage from the Kursk, in the range 0-100 Bq/kg. For comparison, the intervention level for concentrations of ^{137}Cs in basic foodstuffs (as recommended by EC and adopted by several countries, e.g. Norway) is defined as 600 Bq/kg.

The calculations of the collective dose to man correspond to releases of all radionuclides from both reactors according to the aforementioned scenarios. The collective dose to man is dominated by the contribution from ^{137}Cs for Scenario 1. The calculations showed that a collective dose of 61 manSv was attributable to the intake of ^{137}Cs from the Barents Sea alone for the “worst case scenario”, while the total collective dose from all radionuclides from the whole marine area was estimated to be 97 manSv. In this case, contributions from ^{137}Cs and ^{239}Pu correspond to a total dose of 69 manSv and 5.5 manSv, respectively. For comparison, collective doses from other radionuclides for the “worst case” scenario are estimated to be 6.5, 4.3, 2.2, 0.37 and 0,27 manSv for ^{90}Sr, ^{134}Cs, ^{241}Am, ^{147}Pm and ^{106}Ru, respectively. Considering scenario 2, with corrosion leading to release after 100 years, the total collective dose was estimated to be 8.4 manSv for an operational period of 12000 MWd. The results from this work suggests that the radionuclide inventory is one important factor that needs to be adjusted in future impact assessments. Furthermore, approximately 80% of the collective dose from the Barents Sea is attributable to ^{137}Cs exposure. ^{239}Pu does not contribute significantly to the collective dose for Scenario 1. For Scenario 2 however, the contribution of ^{239}Pu to the total collective dose is comparable to that of ^{137}Cs. This is mainly due to the short radioactive half-life of ^{137}Cs.

5 Conclusions

This report has considered the elements for establishing revised source terms for Russian marine vessels. While earlier assessments have been troubled with lack of relevant data, this work has taken forward specific information on the relevance of the different accident scenarios and on revising the inventory calculations as the basis for further considerations on source term composition.

It is hardly surprising that the most severe nuclear accident type is criticality accidents during re/defueling since in this case the reactor vessel is open to the environment and there is very little to prevent the release of activity contained in the fuel. The loss-of-cooling accident may have serious consequences to the submarine crew since the whole submarine may be contaminated, but it will result in little activity release to the environment due to the condensation of the active steam on the hull and the limited openings in the submarine. The sinking accidents will leave a significant amount of activity at the bottom of the sea, but its release to the environment will be very slow and therefore result in very small activity concentrations in the surrounding water.

5.1 Recommendations for further study

The present study has, due to the wide initial scope, been concentrating on some of the elements of the source term for Russian marine reactors. However, increased focus has to be put on applying these results for full-scope impact assessments, in particular for vulnerable areas for example in the Arctic areas where most of the Russian marine reactors actually is operating. In addition, while considerable effort has been devoted to the source term for decommissioned reactors, additional emphasis has to be put on vessels in operation and the associated release mechanisms and source terms. Earlier studies have concentrated on either the releases from sunken submarines to the marine environment ([IASAP], [Eriksen]) or releases from decommissioned, non-defuelled submarines to sea and air. However, considerations of submarines in operation, such as for example Kursk, might give additional insight when taking the relevant information on the vessels themselves – and related constructions such as the vessels now being decommissioned – into account. One relevant issue is the amount of short-lived radionuclides present due to the possible continued operation of the reactors in well-defined areas such as fjords and bays fenced off by natural means, at least close to the naval bases in Russia, possibly also in neighbouring areas..

In addition, spent fuel accidents – which has been briefly considered earlier - may well give rise to important contamination of areas of the naval bases, and this question may be analysed now when information on fuel and storage conditions are more readily available. The main concern is a criticality accident with spent fuel, in particular with unknown burn-ups and fuel geometries.

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ANNEX I. RUSSIAN NUCLEAR SHIP ACCIDENTS

Water cooled and water moderated submarine reactors - first generation									
Date	**Project. nr./ name**	**Class**	**Place**	**Type of accident**	**Cause of accident**	**Release of radioactivity**	**Casualties/ consequences**	**Source**	**Entry nr.**
19620000	K-003	November		Leakage in the reactor systems	Technical malfunction	Yes	Reactor out of operation from 1962 to november 1965	Apalkov 1996, s. 62	2
19670908	K-003	November	Norwegian Sea	Fire			39 fatal	Ølgaard, NKS-project Apalkov 1996, s. 62	8
19750200	K-003	November		Fire			Fire in compartment 7, 2 fatal	Apalkov 1996, s. 62	41
19810108	K-003	November		Fire			Cables replaced during repair	Apalkov 1996, s. 62	42
19650000	K-005	November		Leakage in the reactor systems	Technical malfunction	Yes	The reactor compartment were cut out and replaced	Apalkov 1996, s. 65	43
19601013	K-008	November	Barents Sea	Leak in steam generator	Technical malfunction	Yes	Exposure to radioactivity	Ølgaard, NKS-project	1
19700411	K-008	November	Bay of Biscayan	Fire/ sinking			52 fatal	Ølgaard, NKS-project, Apalkov 1996, s. 68	11

19650212	K-011	November	Zwesdochka	Criticality during refueling	Human error	Yes	7 fatal	Ølgaard, NKS-project, Apalkov 1996, s. 70	5
19620000	K-014	November		Damage of emergency shielding of one reactor.			Reactor compartment was cut out and replaced.	Apalkov 1996, s. 71	44
19880212	K-014	November		Fire			1 fatal.	Apalkov 1996, s. 71	45
19690321	K-042	November		Turbine leakage				Apalkov 1996, s. 73	46
19620000	K-052	November		Leakage in reactor systems		Yes, also the crew, unknown to which extent	Repair of reactor rest of 1962, and again in 1965 and 1967.	Apalkov 1996, s. 77	49
19690618	K-052	November		Flooding of salt water to parts of the reactor compartment				Apalkov 1996, s. 77	47
19770715	K-052	November		Leakage in reactor systems			Salted water penetrated to the second circuit, repaired of the crew at sea.	Apalkov 1996, s. 77	48
19770116	K-115	November		Fire			1 fatal.	Apalkov 1996, s. 78	50

19650203	K-159	November		Leakage in reactor systems				Apalkov 1996, s. 84	51
20030830	K-159	November		Sinking while being towed			9 fatal	Ølgaard, NKS-project	40
19860522	K-016	Hotel		Flooding			The electrical equipment of the compartment were damaged	Apalkov 1996, s. 124	55
19610703	K-019	Hotel		LOCA			8 fatal	Ølgaard, NKS-project, Apalkov 1996, s. 119	3
19691115	K-019	Hotel		Collision			Damage in the back end of the front part of the Russian submarine.	Apalkov 1996, s. 119	54
19720224	K-019	Hotel	North-Atlantic	Fire			30 fatal	Ølgaard, NKS-project, Apalkov 1996, s. 119	13
19781115	K-019	Hotel		Fire				Apalkov 1996, s. 119	52
19820817	K-019	Hotel		Fire			3 people injured	Apalkov 1996, s. 119	53
19630411	K-033	Hotel		Fire				Apalkov 1996, s. 126	56
19770000	K-055	Hotel		Fire				Apalkov 1996, s. 130	58

19780000	K-055	Hotel		Fire				Apalkov 1996, s. 130	59
19860000	K-055	Hotel		Leakage in reactor systems			Submarine taken permanently out of service	Apalkov 1996, s. 130	57
19751125	K-149	Hotel		Leakage in reactor systems				Apalkov 1996, s. 138	60
19771221	K-149	Hotel		Fire			Lost propulsion	Apalkov 1996, s. 138	62
19780303	K-149	Hotel		Fire			1 injured	Apalkov 1996, s. 138	63
19751200	K-178	Hotel		Flooding			Left reactor became inoperationable	Apalkov 1996, s. 139	64
19760700	K-178	Hotel		Leakage in reactor systems			Compensators replaced	Apalkov 1996, s. 139	65
19880125	K-178	Hotel		Fire in the turbine compartment where personal respiratories/ breathing systems were stored.			1 fatal. One pipeline lost its strength properties.	Apalkov 1996, s. 139	66
19770000	K-?	Echo-II	Indian Ocean	Fire				Ølgaard, NKS-project	18

19860113	K-?	Echo-II	450 km north west of Okinawa in East China Sea	Propulsion failure				Ølgaard, NKS-project	32
19780808	K-001	Echo-II	Near Rockall 225 km north west of Scotland	Propulsion system failure				Ølgaard, NKS-project, Apalkov 1996, s. 176	19
19790601	K-010	Echo-II		Explosion			One officer cabin was destroyed	Apalkov 1996, s. 179	86
19830121	K-010	Echo-II		Collision			Submarine taken out of service	Apalkov 1996, s. 176	61
19770828	K-022	Echo-II		Collision			Water penetration into the pressure hull	Apalkov 1996, s. 180	84
19750000	K-023	Echo-II		Reactor accident			Main propulsion unit out of operation	Apalkov 1996, s. 184	79
19770127	K-023	Echo-II		Leakage in reactor systems			Taken out of service, reconstruction.	Apalkov 1996, s. 184	82
19751207	K-035	Echo-II		Explosion			2 injured	Apalkov 1996, s. 188	80

19760924	K-047	Echo-II	Barents Sea	Fire in compartment 8			8 fatal	Ølgaard, NKS-project, Apalkov 1996, s. 189	17
19840924	K-047	Echo-II		Leakage in reactor systems			Submarine taken of operation	Apalkov 1996, s. 189	92
19730614	K-056	Echo-II	Pacific Ocean near Nahodka	Collision		No	27 fatal, large holes in compartment II of submarine.	Ølgaard, NKS-project, Apalkov 1996, s. 191	15
19770714	K-056	Echo-II		Reactor accident		???		Apalkov 1996, s. 191	83
19770714	K-056	Echo-II		Leakage in reactor systems			The submarine was out of operation	Apalkov 1996, s. 191	96
19750125	K-057	Echo-II			Human error		2 fatal	Apalkov 1996, s. 192	97
19840520	K-057	Echo-II		Fire				Apalkov 1996, s. 192	91
19801221	K-057?	Echo-II	140 or 460 km east of Okinawa	Fire			9 fatal, 3 injured	Ølgaard, NKS-project, Apalkov 1996, s. 192	23
19651111	K-074	Echo-II		Run-away of steam turbine				Ølgaard, NKS-project	6
19790000	K-090	Echo-II		Leakage in reactor systems			Reactor out of operation twice during 6 days.	Apalkov 1996, s. 194	85

19830811	K-094	Echo-II		Leakage in reactor systems				Apalkov 1996, s. 195	88
19840321	K-094	Echo-II		Leakage in reactor systems			The submarine was taken out of service.	Apalkov 1996, s. 195	89
19670908	K-116	Echo-II		Failure of cooling system			Reactor taken out of operation for some time (?)	Apalkov 1996, s. 199	72
19760418	K-116	Echo-II	gorlje avachinska gubje	Collision			Bulk in the ballast tank (0,5x1 m).	Apalkov 1996, s. 198	98
19790702	K-116	Echo-II	Pavlovskbukten	LOCA	Human error	yes		Ølgaard, NKS-project, Apalkov 1996, s. 198	22
19720619	K-131	Echo-II		Collision			Damage of breakwater and failure of leakproofness of the front part.	Apalkov 1996, s. 202	76
19820928	K-131	Echo-II		Explosion			2 fatal, 4 injured	Apalkov 1996, s. 202	77
19840618	K-131	Echo-II		Fire in compartment 7				Apalkov 1996, s. 202	78
19840618	K-131	Echo-II	Arctic Sea	Fire			13 or 14 fatal	Ølgaard, NKS-project, Apalkov 1996, s. 202	29

19760311	K-144	Echo-II		Flooding				Apalkov 1996, s. 210	81
19690000	K-166	Echo-II		Leakage in reactor systems			Reactor core had to be replaced	Apalkov 1996, s. 204	74
19701210	K-166	Echo-II		Oil leakage			Weapons and equipment failure	Apalkov 1996, s. 204	75
19680300	K-172	Echo-II		Contamination			126 people got poisoned with quicksilvergas.	Apalkov 1996, s. 206	99
19750000	K-172	Echo-II		Leakage in reactor systems				Apalkov 1996, s. 206	100
19780000	K-172	Echo-II		Generator failure				Apalkov 1996, s. 206	101
19680000	K-175	Echo-II		Leakage in reactor systems				Apalkov 1996, s. 208	73
19850929	K-175	Echo-II		Reactor accident	Human error	Yes	Due to wrong actions of the crew.	Apalkov 1996, s. 208	94
19861100	K-175	Echo-II		Reactor accident		Yes		Apalkov 1996, s. 208	102
19810320	K-184	Echo-II		Collision				Apalkov 1996, s. 209	87
19840326	K-184	Echo-II		Reactor accident				Apalkov 1996, s. 209	90
19850607	K-184	Echo-II		Reactor accident				Apalkov 1996, s. 209	93

19860300	K-184	Echo-II		Reactor accident			Repair and limited operation regime was decided.	Apalkov 1996, s. 209	95
19890615	K-192	Echo-II	350 km south of Bear Island, 110 km north west of Sørøya	LOCA of the left reactor		Yes	Higher doses to personnel, submarine was taken out of operation.	Ølgaard, NKS-project, Apalkov 1996, s. 207	35
19850810	K-431	Echo-II	Chazhma Bay 60 km south south east of Vladivostok	Criticality	Refueling		10 fatal immidiately	Ølgaard, NKS-project, Apalkov 1996, s. 186	30
19791216	K-045	Echo-I		Leakage in reactor systems				Apalkov 1996, s. 159	67
19860000	K-059/K-259	Echo-I		Leakage in reactor systems				Apalkov 1996, s. 160	69
19660506	K-066	Echo-I		Fire				Apalkov 1996, s. 165	71
19810000	K-066	Echo-I		Leakage in reactor systems			Submarine taken out of operation	Apalkov 1996, s. 165	70
19800820	K-122	Echo-I		Fire				Apalkov 1996, s. 167	68
Water cooled and water moderated submarine - second and subsequent generations									

19680823	K-140	Yankee	Severodvinsk	Criticality				Ølgaard, NKS-project	10
19861003	K-219	Yankee	800 km east of Bermuda	Explosion and sinking			4 fatal	Ølgaard, NKS-project	33
19780902	K-451	Yankee	(Pacific Fleet)	Fire				Ølgaard, NKS-project	20
19910927	K-?	Typhoon	White Sea	Misssile failure				Ølgaard, NKS-project	38
19800030	K-222	Papa	Severodvinsk	Criticality	Human error			Ølgaard, NKS-project	24
20000812	K-141	Oscar-II	Barents Sea	Explosion			118 fatal	Ølgaard, NKS-project	39
19890407	K-278	Mike	180-190 km south west of Bear Island in the Norwegian Sea.	Fire and sinking			42 fatal	Ølgaard, NKS-project	34
19800000	K-?	Delta-III		Reactor accident			2 fatal	Ølgaard, NKS-project	25
19781228	K-171	Delta-I	(Pacific Fleet)	Reactor accident			3 fatal	Ølgaard, NKS-project	21
19830624	K-429	Charlie-II	Krasheninnikov Bay at the Kamchatka peninsula		Human error		2 fatal	Ølgaard, NKS-project	27
19851200	K-314?	Charlie-I?	Near Vladivostok	LOCA				Ølgaard, NKS-project	31

19700118	K-320/ K-429	Charlie-1	Krasnoye Somovo shipyard in Gorki	Criticality				Ølgaard, NKS-project	12
19760000			Near Petropavlovsk, Pacific Ocean	Fire				Ølgaard, NKS-project	16
Liquid metal cooled submarines									
19640000	K-027	LMC - Project 645		Coolant solidification.				Ølgaard, NKS-project	4
19680524	K-027	LMC - Project 645		LOCA		Yes		Ølgaard, NKS-project, Apalkov 1996, s. 92	9
19720000	K-377	LMC - Alfa	Arctic Sea	Coolant solidification				Ølgaard, NKS-project	14
19820408	K-123	LMC - Alfa	Barents Sea	Coolant solidification				Ølgaard, NKS-project	26
19831221	K-123	LMC - Alfa		Fire			14 fatal	Ølgaard, NKS-project	28
19890717	K-?	LMC - Alfa	Barent Sea 120 east of Vardø in northern Norway	Instrumentation failure				Ølgaard, NKS-project	36
Other vessels									

19660000	Lenin			LOCA				Ølgaard, NKS-project	7
19900100	Surface, "Ushakov"	Cruiser	Mediterranean	Leak				Ølgaard, NKS-project	37

ANNEX II. RADIONUCLIDE INVENTORY – RUSSIAN THIRD GENERATION SUBMARINE 42000 MWD (94594 MWD/ T HM) – SELCETED 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 III. 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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Abstract

This report discusses inventory and source term properties in regard to operation and possible releases due to accidents from Russian marine reactor systems. The first part of the report discusses relevant accidents on the basis of both Russian and western sources. The overview shows that certain vessels were much more accident prone compared to others, in addition, there have been a noteworthy reduction in accidents the last two decades. However, during the last years new types of incidents, such as collisions, has occurred more frequently. The second part of the study considers in detail the most important factors for the source term; reactor operational characteristics and the radionuclide inventory. While Russian icebreakers has been operated on a similar basis as commercial power plants, the submarines has different power cyclograms which results in considerable lower values for fission product inventory. Theoretical values for radionuclide inventory are compared with computed results using the modelling tool HELIOS. Regarding inventory of transuranic elements, the results of the calculations are discussed in detail for selected vessels. Criticality accidents, loss-of-cooling accidents and sinking accidents are considered, bases on actual experiences with these types of accident and on theoretical considerations, and source terms for these accidents are discussed in the last chapter.

Key words accidents, inventory, source term, Russia, marine reactor, Helios, release fractions

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