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THE ENVIRONMENTAL IMPACT OF THE SUNKEN SUBMARINE KOMSOMOLETS

HØIBRÅTEN Steinar, HAUGAN Are, THORESEN Per

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Director of Research

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The report is an analysis of the environmental effects of the sunken nuclear submarine Komsomolets. It presents the facts about the submarine and its nuclear inventory as these were known in 1995 and discusses the distrubution of these radionuclides in the environment. This discussion is still generally valid today. In conclusion, the Komsomolets represents no significant hazard to man, today or in the future.

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PREFACE

This report contains a case study on the nuclear submarine *Komsomolets*, which sank in Arctic waters in 1989. The study was originally published as part of the NATO report *Radioactive Contamination*,[1] which was one of the reports resulting from a pilot study known as *Cross-Border Environmental Problems Emanating from Defence-Related Installations and Activities*. The overall pilot study was chaired by the Norwegian Ministry of Foreign Affairs. The *Komsomolets* study was made and edited at FFI based on contributions commissioned from other institutions, both within NATO and in Russia.[2] These sources are referenced throughout the report.

"The NATO Study" of the *Komsomolets* accident has become a "classic" as one of very few independent studies of this event. In spite of the eight years that have passed since the original publication of the study, the analysis and conclusions presented in this report are still generally valid.

The *Komsomolets* study is reprinted here because its evaluation of possible environmental effects is relevant to FFI's current project on Weapons of Mass Destruction, and also because it has never before been published at FFI in spite of the large efforts invested at FFI during its original creation. Moreover, the study was important for our assessment of the *Kursk* accident in 2000, and its relevance was further emphasised by the sinking in August 2003 of K-159 while this decommissioned submarine was being towed from Gremikha to Polyarnyy. This publication is made in agreement with the Ministry of Foreign Affairs. The reader should keep in mind that "now," "presently" and similar expressions in the report refer to 1995.

The *Komsomolets* still rests on the ocean floor as it did in 1995.

Kjeller, October 2003

Steinar Høibråten, Ph.D.
Principal Scientist
Editor of the original report on *Radioactive Contamination*

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[1] NATO/CCMS Report No. 204, April 1995.

[2] FFI's participation in the pilot study was financed by the Norwegian Ministry of Foreign Affairs.

CONTENTS

THE ENVIRONMENTAL IMPACT OF THE SUNKEN SUBMARINE KOMSOMOLETS

1 INTRODUCTION

On April 7, 1989, the Soviet submarine *Komsomolets* (*K278*) suffered an internal fire. At that time the submarine was running submerged, 180–190 km west-southwest of Bear Island in the Norwegian Sea. The fire started either in compartment 6, the turbine room which contained reduction gear and/or diesel engines, or in compartment 7 behind this (the aft compartment) [OLG94]. Less than fifteen minutes later, the submarine reached the surface. By that time, the reactor had already been automatically shut down. The flames spread forward towards compartments 5 and 4 which contained the pumps of the primary circuit and the nuclear reactor, respectively. Another fire started at a control desk in compartment 3. More than five hours after the outbreak of the first fire, several explosions were heard, and the submarine began to sink. The vessel sank in international waters at 73°43'16" N and 13°16'52" E at a depth of 1 655 m, where it is lodged 2.5–3 m into the muddy ground [KHL94]. Of the 69 crew members on board, 42 were killed in the accident [OLG94].

The *Komsomolets* was the only Mike-class submarine ever built. It was unique in that its hull was made of titanium, and it was this feature that made it possible for the submarine to dive to depths around 1 000 m [OLG94].

Possible releases of nuclear materials from the *Komsomolets* to the marine environment and the effects of such releases are discussed in some detail below. The discussion is based upon three studies that were commissioned by FFI, one of which is a Russian study of the radionuclide inventory and the processes by which these radionuclides can be released into the surrounding environment [KHL94], one is a Norwegian study of ocean transport of released radionuclides [ADL94], and one is a Danish report on the experiences with plutonium in the marine environment near Thule [AAR94].

2 CONSTRUCTION AND CONDITION OF THE SUBMARINE AND THE WEAPONS

The condition of the nuclear submarine *Komsomolets* has been investigated in five Russian research expeditions in which the special “deep submersible manned vehicle” *Mir* was used. These expeditions took place in 1989, 1991, 1992, 1993 and 1994.

Shortly after the accident, concerns about the potential radio-ecological hazards from the nuclear submarine led to the development of plans for raising it and burying it on land. However, at that time the nature and extent of the damages to the pressure hull of the submarine were unknown. Later, when the vast destruction to the bow part of the pressure hull

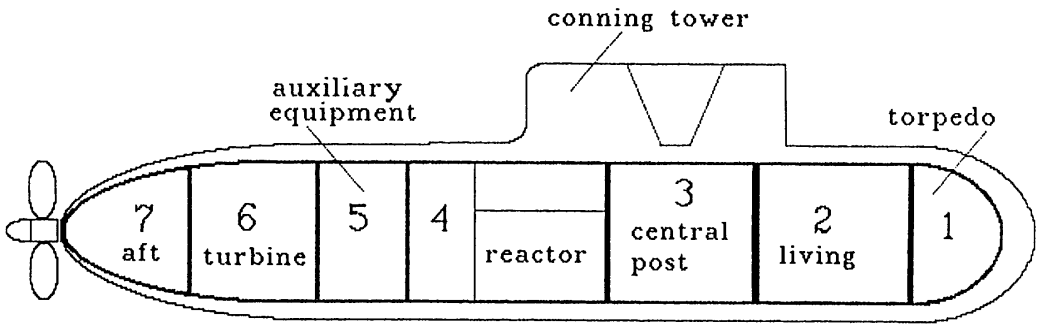

Figure 2.1. Layout of the nuclear submarine Komsomolets *showing the position and use of the various compartments [KHL94]. The escape capsule is attached inside the V-shaped structure in the conning tower.*

became evident, raising the submarine was eventually considered unrealistic. Currently, different methods of isolating the submarine or parts of it from the marine environment are being considered.

2.1 The hull

The *Komsomolets* has a double hull consisting of an inner pressure hull (thick) and a light outer hull. Both hulls, as well as all bulkheads, are made of a titanium alloy. According to oral communication from Rubin, the construction firm that built the vessel, the pressure hull is approximately 10 cm thick, and the outer hull has a thickness of 9.8 mm. As indicated in Figure 2.1, the pressure hull contains seven compartments. The weapons are located in compartment 1 in the bow, and the reactor is in compartment 4, beneath and behind the conning tower ("sail"). The reactor compartment is separated from the central post by an especially thick bulkhead.

The front part of the submarine is the most seriously damaged. There are holes in both the inner pressure hull and the outer hull. Videotapes taken during the Russian expeditions in the summers of 1991, 1992 and 1993 show a large hole (about 20 m^2) on the top of the front part of the pressure hull. This is just above the torpedoes in the first compartment. There is also a large crack, approximately 2–3 cm wide, on the port side of the submarine. The crack goes all the way from the large hole on top of the torpedo compartment at least to the front of the third compartment beneath the sail. In addition, there are several smaller cracks that can be seen on the above-mentioned videotapes [YAB93]. An artist's conception of the present state of the *Komsomolets* is shown in Figure 2.2. The outer hull of the submarine in the vicinity of the reactor compartment appears not to have been seriously damaged. The pressure hull and the forward bulkhead of this compartment are intact despite the fact that they were not designed to endure the water pressure at the depth where the submarine rests [KHL94]. During the sinking, sea water entered the submarine through an open hatch leading to the escape capsule (cf. Figure 2.1) as well as through holes in the aft compartments (due to the fire) and through a ventilation tube from the reactor compartment. This must have equalised the pressures inside and outside the submarine and thus contributed strongly to minimising damage to the hull.

Figure 2.2. Artist's conception of the sunken submarine Komsomolets *resting on the sea bottom.*

2.2 The nuclear reactor

The *Komsomolets* has one pressurised-water reactor (PWR) on board [KHL94]. The reactor installation includes a gas system to compensate for volume changes. The reactor was shut down before the submarine was abandoned. The following description of the reactor and its surroundings are based on [KHL94].

2.2.1 The reactor compartment

The reactor vessel and the steam generators are made of low-alloy steel. They are placed inside cylinders made of stainless steel, and their inside surfaces are clad by a layer of chromium-nickel stainless steel. The primary circuit is made of stainless steel, and so are also the pressuriser system and auxiliary circuits of the primary circuit.

The pressuriser system includes high-pressure gas tanks situated outside the pressure hull. These gas tanks are connected to the primary system by pipes penetrating the pressure hull. The reactor room is sealed. Aft of the reactor room, there is another sealed room containing auxiliary equipment, separated from the neighbouring compartment 5 by a strong aft bulkhead. See the sketch in Figure 2.3. A ventilation tube passes from the auxiliary equipment room through the pressure hull to the aft end of the top of the conning tower. This tube is now open to the sea. All pipes penetrating the pressure hull are made of titanium alloys.

Lead is widely used in the shielding elements of the reactor compartment. There is no direct contact between perlitic steel and titanium alloys. Therefore, chemical interactions between these materials can only take place at some distance.

The reactor vessel and the steam generators, as well as the connecting pipes, are in good condition. They were designed for long endurance, and they were relieved during the sinking

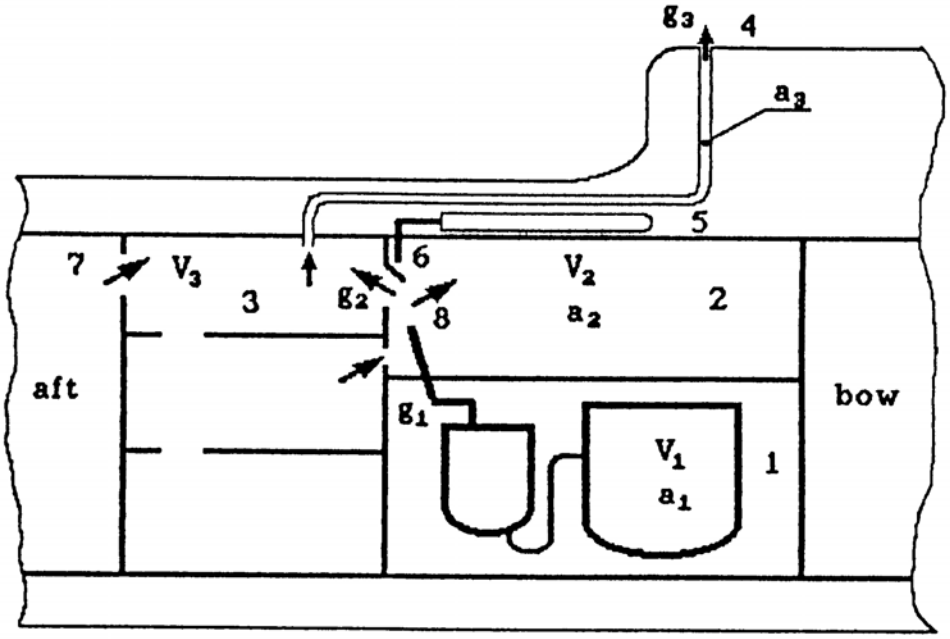

Figure 2.3. Schematic representation of the reactor compartment (compartment 4) and possible damages to it [KHL94]. The numbered features are: (1) Reactor room; (2) Reactor regulation equipment room; (3) Auxiliary equipment room; (4) Outlet of ventilation tube; (5) High-pressure gas tank for the pressuriser system; (6, 7) Sites where the bulkheads may be damaged; (8) Damage of the gas compensation pipe which is connected to the primary circuit. The remaining symbols denote various quantities to be used in calculations: (V_1) Volume of the primary circuit; (V_2) Volume of the reactor regulation equipment room; (V_3) Volume of the auxiliary equipment room; (a_1, a_2, a_3) Concentration of ^{137}Cs in the corresponding volumes; (g_1, g_2, g_3) Flow rate from the volumes.

by their high internal pressure. As a result of the damage to the piping of the pressuriser system at the aft bulkhead of the reactor regulation equipment room (cf. Figure 2.3), outside water entered the primary circuit, and the pressures inside and outside this circuit were equalised. The piping in question has a length of about 5 m.

The reactor core is situated in the lower part of the reactor vessel. The distance between the fuel elements is small. All connections to the reactor vessel enter the vessel in its upper part and are made of stainless steel. At the present time with low residual heat production in the core, the water in the primary circuit is almost stationary with very low natural circulation. The low circulation is due to the fact that the temperature of the water is such that its volume-expansion coefficient is close to zero.

2.2.2 Nuclear inventory

Soviet and Russian authorities have released very little information about the reactor construction and the reactor core. They have revealed that the reactor was equipped with "modestly enriched fuel," and that the contents of plutonium, cesium and strontium in the core

Table 2.1. Contents of transuranic nuclides in the Komsomolets *reactor core [KHL94]. (The value given for ^{241}Pu in 2079 was inconsistent and has been recalculated.)*

Nuclide	Activity (TBq)		
	1989	1994	2079
^{239}Pu	4.4	4.4	4.4
^{240}Pu	1.7	1.7	1.7
^{241}Pu	310	240	9.1
^{242}Pu	0.0010	0.0010	0.0010
^{241}Am	0.044	0.26	11
^{242m}Am	0.0015	0.0015	0.00093
^{243}Am	0.0017	0.0017	0.0017
^{242}Cm	5.6	0.0028	0
^{243}Cm	0.00048	0.00041	0.000074
^{244}Cm	0.031	0.026	0.00074

were 1.9 kg of Pu, 3.0 PBq of ^{137}Cs and 2.8 PBq of ^{90}Sr [NEG]. The quoted content of plutonium presumably includes all relevant plutonium isotopes. [KHL94] reports 2.2 kg of Pu (including 1.9 kg of ^{239}Pu), 3.1 PBq of ^{137}Cs and 2.8 PBq of ^{90}Sr, in fair agreement with the above values. It should be noted that the Yablokov Report [YAB93] presents a nuclear inventory which predates and is inconsistent with the above information.

It is commonly assumed that Russian submarine reactors are quite similar in design to the second generation of nuclear icebreaker reactors. Some information about the latter is available through the safety report of the nuclear icebreaker/cargo ship *Sevmorput*. This report is available in English [SEV]. All icebreaker reactors are of the PWR type. The fuel used in the *Sevmorput* reactor is 90% enriched uranium metal alloyed with zirconium and clad in zirconium. The thermal power of the icebreaker reactors vary between 135 MW and 180 MW.

The contents of transuranic radionuclides in the *Komsomolets* reactor core have been calculated at the Kurchatov Institute [KHL94]. All radiologically significant transuranic isotopes are listed in Table 2.1. Presently, the most important alpha emitters are ^{239}Pu, ^{240}Pu and ^{242}Cm. Due to the beta decay of the relatively short-lived plutonium isotope ^{241}Pu (half-life 14.4 years), the activity of its daughter nuclide ^{241}Am (an alpha emitter with a half-life of 433 years) will significantly increase for about 73 years to a maximum value of about 11 TBq. The total alpha activity of the spent fuel at that time will not exceed 2.5 times the initial alpha activity.

Activities for the most important activation products (^{55}Fe, ^{60}Co and ^{63}Ni) are also presented in [KHL94]. These radionuclides were produced by interaction between neutrons from the nuclear reactor and the materials in the reactor itself and its shielding (that is, mostly steel). The mass percentages of iron, cobalt and nickel are 68%, 0.050% and 10%, respectively, in the internal reactor parts and 96%, 0.002% and 0.4%, respectively, in the reactor vessel [KHL94]. The activation calculations made use of published data on activation cross sections [GER89,

Table 2.2. Calculated activities of the most important activation products in the internal parts of the Komsomolets *reactor [KHL94].*

Nuclide	Activity (TBq)	
	1989	1994
^{55}Fe	130	36
^{60}Co	59	31
^{63}Ni	4.4	4.4

Table 2.3. Contents of the most important radionuclides in the reactor of the submarine Komsomolets *(from Figure 2.4). The values at the time of the accident have been calculated from the 1990 values.*

Nuclide	Half-life (y)	Activity (TBq)	
		1990 (from plot)	1989 (calculated)
^{55}Fe	2.73	100	130
^{60}Co	5.272	46	53
^{63}Ni	99.6	4.5	4.5
^{85}Kr	10.72	450	480
^{90}Sr	28.78	2700	2800
^{106}Ru	1.020	450	890
^{134}Cs	2.062	1300	1800
^{137}Cs	30.254	3000	3100
^{144}Ce	0.7800	4000	9800
^{147}Pm	2.6234	4900	6400
^{241}Pu	14.353	250	260

GUS88] and assumed a neutron spectrum similar to that used in published calculations for the reactors on board the icebreaker *Lenin* [SIV93]. The results for the internal reactor parts are shown in Table 2.2. The activity of the reactor vessel, which is protected from the neutron flux by layers of water and stainless steel, is estimated to be approximately 200 times less than the activity of the internal reactor parts [KHL94].

[KHL94] does not list values for the contents of fission products other than ^{137}Cs and ^{90}Sr. In Figure 2.4, however, which presents the time dependence of the activity of several long-lived fission products, activation products and actinides in the reactor fuel, some further radionuclides are indicated. The figure shows, as noted above, that the activity of ^{241}Am first increases, then reaches a maximum and eventually decreases. The figure also shows that for most of the first 200 years, ^{137}Cs and ^{90}Sr are the dominating radionuclides. After about 200 years, the activity of ^{241}Am will be then the highest.

The inventory of the nuclides shown in Figure 2.4 at the time of the accident, can be calculated by reading the activities at time = 1 year from the figure and calculating the corresponding activities one year earlier. The results of these calculations are listed in Table 2.3. Note that

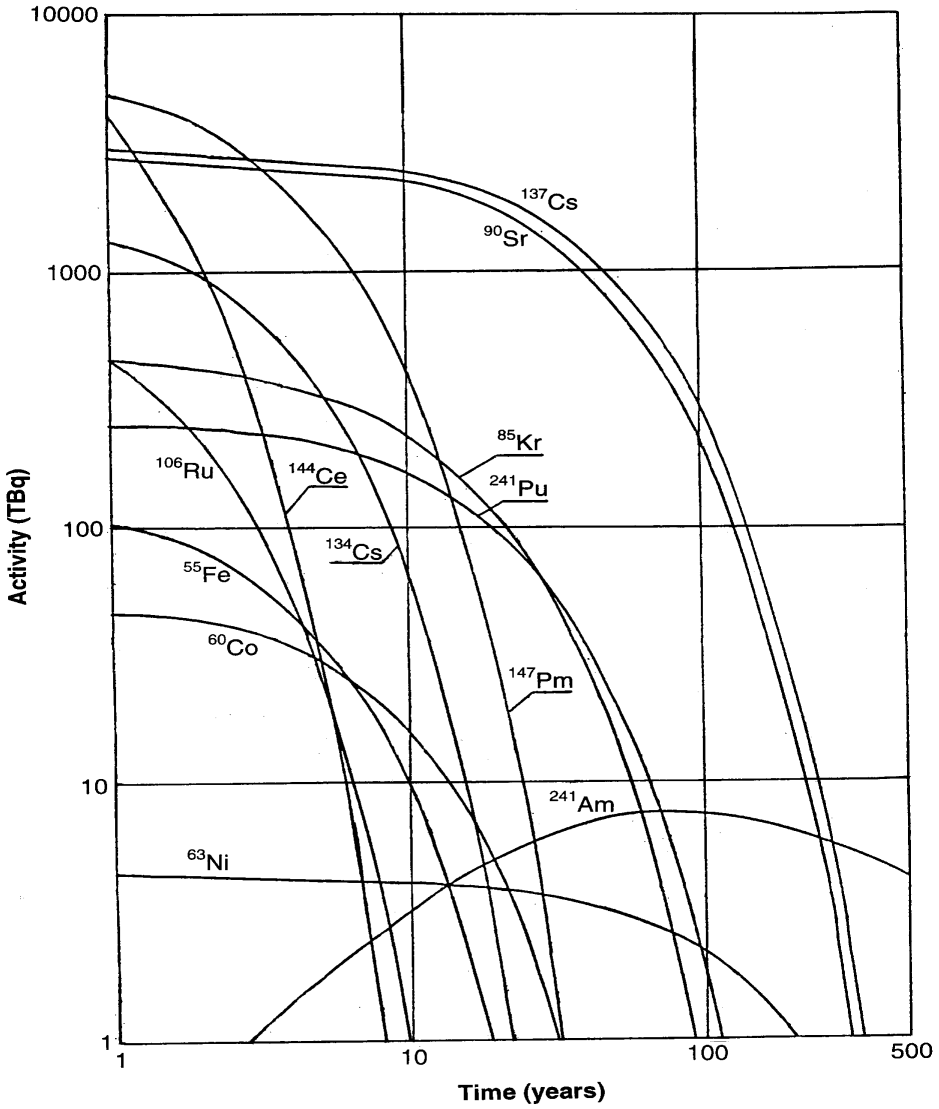

Figure 2.4. Contents of the most important radionuclides in the reactor of the submarine Komsomolets *as a function of time [KHL94]. The radioactivity of the long-lived fission products corresponds to permanent operation of the* Komsomolets *reactor for a period of 5 years.*

the activity of ^{241}Pu as listed in Table 2.1 is not in very good agreement with the value given in Table 2.3.

Independently of the calculations in [KHL94], the contents of selected radionuclides in the *Komsomolets* have been estimated based on data from the *Sevmorput* reactor [HVA91]. In these calculations, the reactor parameters were varied in such a way that the contents of ^{137}Cs, ^{90}Sr and Pu agreed with the contents given in [NEG]. Good agreement was achieved for a hypothetical reactor operating on 35% enriched uranium oxide in mixture with an alloy primarily consisting of zirconium. The density of ^{235}U in the fuel was 0.446 g/cm^3. The fuel was clad in steel and placed in hexagonal fuel elements with 55 fuel pins in each. The total mass of ^{235}U in the hypothetical reactor was 100 kg. With a total thermal effect of 135 MW

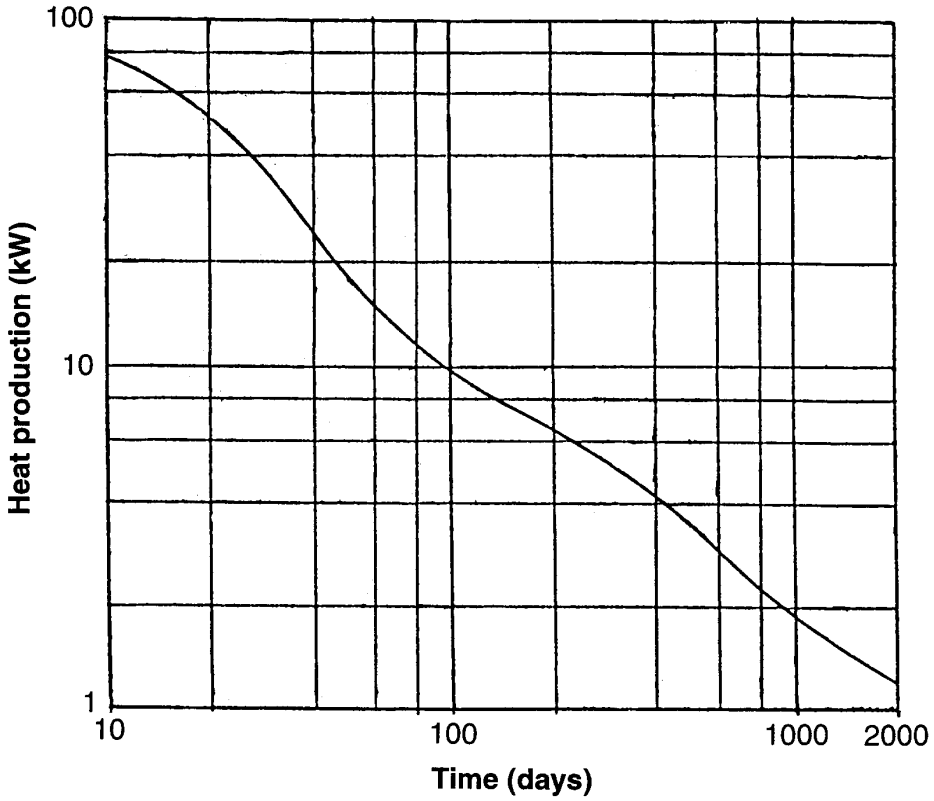

Figure 2.5. Residual heat production in the Komsomolets *reactor as a function of time after the accident [KHL94, KAZ89]. 1 000 days after the accident was January 2, 1992, and 2 000 days after the accident was September 28, 1994.*

and a burn-up of 90 000 MWd/tU, this resulted in 3.00 PBq of ^{137}Cs, 2.79 PBq of ^{90}Sr and 1.97 kg of Pu (including the isotopes ^{239}Pu, ^{240}Pu, ^{241}Pu and ^{242}Pu).

Such a hypothetical reactor may be a poor model of the real *Komsomolets* reactor. However, the activity of some fission products that were calculated based on this reactor do match those given in Table 2.3 within an order of magnitude and confirm that the most important radionuclides are indeed accounted for in the table. A similar agreement was obtained for the production of actinides.

2.2.3 Residual heat production

The term “residual heat” refers to the heat generated in a reactor after it has been shut down. It is created by absorption in the reactor core or in the surrounding water of the kinetic energy of the decay products from the decay of the radionuclides still present. The heat production is therefore closely related to the remaining radioactivity in the reactor core. Residual heat may be important for the spreading of radionuclides from the reactor in the sea (by a “heat plume”). This heat has been calculated as a function of time for the *Komsomolets* by considering the individual contribution from each radionuclide (see Figure 2.5).

In the residual-heat calculations, it was assumed that water which is heated in the reactor core reaches the steam generator which is next to the reactor itself (cf. Figure 2.3). Then, due to the damaged gas pipe, it enters the reactor regulation equipment room (water exchange between the volumes V_1 and V_2). Furthermore, the breach in the bulkhead between the reactor regulation equipment room and the auxiliary equipment room enables the exchange of water between the volumes V_1 and V_3. Since heat production in the reactor core decreases with time, the temperature of the fuel assemblies will also decrease and lead to a slowing down of the natural circulation in the primary circuit. On the first day after the accident, the temperature of the fuel assemblies was calculated to be about 90 °C; after 50 days, it was reduced to about 25 °C [KHL94].

As of late 1994, the residual heat production in the reactor core was about 1.2 kW (cf. Figure 2.5). The natural circulation in the primary circuit evidently remains. The calculations were based on experimental data on natural circulation in such a primary circuit at different levels of energy production and on data on the hydraulic resistance of this circuit at low water velocities. The fact that the point of density inversion in sea water is at a temperature below 0 °C was also taken into account. The calculations indicate that the temperature of the fuel assemblies in the autumn of 1994 was about 7 °C and the temperature gradient in the reactor core about 2–3 °C [KHL94]. The temperature gradient on the surface of the reactor core is very low because of the small level of heat production and the large size of the heat-conducting surface.

2.3 The weapons

According to Russian authorities, *Komsomolets* carried two torpedoes that were equipped with nuclear warheads. These torpedoes were designed for use at great depths. Therefore they were probably quite new and technologically rather advanced.

Several projections have been made regarding the present condition of the nuclear warheads. It has been claimed that the outer shell of the warheads may have been damaged by the impact when the submarine hit the bottom of the sea, that they may have imploded on the way down, and that they may be penetrated by corrosion in a short time. The Yablokov Report [YAB93] states that the hatches are open, and that the nuclear materials in the warheads are in contact with sea water.

It is impossible to predict exact time frames for the corrosion of the warheads without more detailed information about the materials used, the protective coating of the warheads or the titanium hull of the submarine. It is very likely, however, that corrosion will destroy the shell of the weapons in a relatively short time since the torpedo compartment is reportedly open to the sea. One can therefore assume that the interior of the weapons, either is, or in a short time will be, exposed to sea water. The uranium and plutonium in the weapons will then slowly be released to the surroundings. During the expedition to the submarine in July 1994, holes in the torpedo section were sealed by nine titanium plugs in order to prevent water from flowing through [TAS94]. This should minimise the immediate corrosion of the warheads.

The exact construction of the weapons is unknown. Nevertheless, some estimates of the contents of radioactive materials in the weapons can be made. Modern nuclear warheads would be expected to contain about 10 kg of ^{235}U or about 4 kg of ^{239}Pu. Both [YAB93] and [KHL94] quote a total plutonium activity of about 16 TBq in the weapons aboard *Komsomolets*. Assuming that Soviet/Russian weapons-grade plutonium contains 94% of ^{239}Pu and 6% of ^{240}Pu [NWD93], this activity corresponds to a total of about 6.0 kg of plutonium in the two weapons altogether (5.6 kg or 13 TBq of ^{239}Pu and 0.4 kg or 3.0 TBq of ^{240}Pu). In addition, there is most likely a small quantity of tritium (^{3}H) in the weapons.

3 RELEASE OF RADIOACTIVE MATERIALS

In order to assess the radiological hazards presented by the radioactive materials on board the *Komsomolets*, one must first estimate when the radionuclides will begin to leach out, as well as the release rates once the leaching has started. One must calculate the corrosion rates taking into account the limited content of oxygen in the water caused by the lack of free-flowing sea water to the reactor and the warheads. One must further consider that the rate of release will be limited by the small size of the pinholes (pitting corrosion), and by the flow of water through the hull. To perform an accurate study, the specifications of the materials used and detailed information on the structure of the submarine, the reactor and the weapons are needed. Much of this information is unavailable. However, there do exist some studies on corrosion, and some measurements of radionuclide releases from the *Komsomolets* have been made [KHL94]. This information is presented below.

3.1 Corrosion

Corrosion is the first step in the release of any radioactive material in the submarine (except for those radionuclides that were already dissolved in the water of the primary circuit at the time of the accident). The corrosion of the construction materials is discussed separately from the corrosion of the nuclear fuel in subsequent sections below.

3.1.1 Corrosion of construction materials

Corrosion rates of steels in sea water have been extensively studied, and besides general handbooks and manuals, reports issued by both the United States Environmental Protection Agency and the Royal English Marine College are of special interest. Information from a report published by the latter was used in estimating the corrosion of the dumped reactor compartment of the nuclear icebreaker *Lenin* [CAR94] and in assessing the releases of radionuclides into the marine environment from this installation [SIV94]. These corrosion data were used as the basis for the prognosis of the releases from *Komsomolets*.

The most important factors influencing the rate of corrosion in sea water are:

- The concentration of dissolved oxygen on the metal surface;
- The temperature of the water;

- The geometry of the surface and the presence of cracks;
- The presence (or absence) of a protective coating (important for electrochemical corrosion which is caused by different electrochemical potentials of the different materials, particularly those of iron and titanium).

Other factors of potential significance include the accumulation of silt or biota on the surfaces, as well as the salinity of the water. The rate of steel corrosion is minimal at temperatures typical of the site where the *Komsomolets* sank. There has been no observed correlation between corrosion rates and the depths at which the corrosion takes place.

Over the course of time, the rate of corrosion decreases rapidly due to the reduced oxygen concentration on the surface of the metal. Therefore, corrosion rates for the first year are usually tabulated separately from the rates that apply later. It is possible for the latter set of corrosion rates to be 3–5 times smaller than the former set.

Because of the ocean currents and the damaged outer hull, the corrosion of the pressure hull of the submarine is probably occurring in flowing water. On the other hand, the corrosion of the elements of the nuclear installation is taking place in still waters. The nuclear installation itself was designed to operate at high temperatures and pressures, and no cracks in its materials have been observed. The two elements iron and titanium, which have very different electrochemical potentials are not in contact with each other anywhere on the submarine. Because of the generally large physical distances between these two elements, it is assumed that no significantly accelerated corrosion due to electrochemical processes takes place.

Under these conditions, the corrosion of the reactor and hull materials in sea water may be characterised by the following corrosion rates:

- Stainless steel: 1 μm/y;
- Carbon steel: 75 μm/y;
- Titanium alloy: << 1 μm/y.

Upon comparing these values, it appears that over time the process of corrosion will proceed in three subsequent stages:

1. Corrosion of the carbon steel of the reactor vessel;
2. Corrosion of the internal, stainless-steel cladding of the reactor vessel;
3. Corrosion of the hull and the bulkheads of the submarine.

To simplify the analysis, it is assumed that the corrosion takes place at a constant rate, and that it does not reach saturation (which is usually found in experiments with still-water corrosion).

The first stage, whereby the reactor vessel suffers damage on the one side that is in contact with sea water, will take at least 2 000 years (150 mm corroding at 0.075 mm/y). As shown in Figure 2.3, the reactor is situated within the limited space of its hold, and here the water will be still. The hold containing the reactor and the steam generator is separated from the rest of the

reactor compartment by a heavy protective shield. Even after the accident, this shield remained practically intact. The reactor volume is connected to the reactor regulation equipment room by only one or two damaged pipes, both with a small diameter. Hence, corrosion of the reactor will take place in still sea water.

During the 2 000 years mentioned above, the corrosion of the stainless-steel cladding inside the reactor vessel will be a maximum of about 2 mm (0.001 mm/y for 2 000 y). The thickness of the cladding is 5 mm. In other words, there should be no corrosional destruction of the reactor vessel and of the constructions inside the reactor for at least 1 000 years. The reactor core inside the stainless-steel basket will remain undamaged inside the intact hull of the submarine for more than 1 000 years. Any prognoses beyond this time period would be highly uncertain.

The corrosion of the biological shield should also be very low and will not lead to structural damage of the submarine. Corrosion of the bulkheads and the hull of the submarine, all of which are made of a titanium alloy, will take place at an extremely low rate. Because of this slow corrosion rate, the release of induced activation products (which are fixed inside the construction materials) will be practically absent for the first 1 000 years. By that time, most activation radionuclides will have decayed anyway, and any subsequent releases of these radionuclides will be insignificant.

The products of corrosion are metal oxides. They have smaller densities than the original materials and are therefore larger in volume (typically two to three times as large). Since corrosion products are formed on the surface of the metal, they prevent the access of oxygen to the unoxydised metal below. Within the limited volume of the reactor room, all of the dissolved oxygen will soon have been used for corrosion. Given the low water exchange between this room and the outside water, the influx of oxygen will be negligible. This causes a sharp decrease in the rate of corrosion; thus the destruction of the reactor vessel as a result of corrosion may indeed occur at a much later time than originally suggested above.

3.1.2 Corrosion of nuclear fuel

The release of fission products such as ^{137}Cs and ^{90}Sr into the sea water is determined by the composition of the fuel and the corrosion rate of the fuel rods, as well as the rate of water exchange between the reactor core and the external marine environment.

The following discussion of corrosion of nuclear fuel is based on the results of experimental observations of radionuclide releases from fuel rods into sea water [DOJ91]. These experiments were begun in 1983, and continue into the present. The experiments study the behaviour in sea water of full-sized fuel assemblies and model assemblies where different sets of rods with intact and damaged cladding are in contact with different construction materials.

In the experiments involving full-sized fuel assemblies unloaded from the reactor, conditions in the reactor were modelled as closely as possible to reality using the actual combination of

assembly materials, the actual spaces between fuel rods, the actual heights and the actual surface conditions of the materials. In this way, differences in electrochemical potential, space effects, deposition of radionuclides onto surfaces and their sedimentation into the lower parts of the assemblies could be very well accounted for. The water exchange was simulated by periodic changes of the sea water. In the modelling experiments, which used a small number of fuel rods, the test conditions (such as the temperature of the water, the contact pairs and the state of the fuel cladding) were varied.

The observed rate of increase of the specific activity of radionuclides in sea water was not very high. It was possible to directly study the most radiologically significant nuclides such as ^{137}Cs, ^{90}Sr, ^{60}Co, ^{239}Pu, ^{240}Pu and ^{241}Am.

Cesium is a monovalent and strontium a divalent metal, and they are present in sea water in a monodisperse state which forms real solutions independently of the pH level or of the presence of alien suspensions and colloidal admixtures. Geochemically, they behave similarly in sea water. Some researchers have suggested the possibility of a selective leaching of cesium. The controlled studies of fuel leaching confirm that 2–3 times more cesium than strontium is released, although both elements exist in nearly equal quantities in spent nuclear fuel. Because of this, cesium studies should lead to rather conservative assessments of the release of radiologically significant radionuclides into the marine environment.

Americium and curium are generally trivalent, but may also be found in the 4th, 5th or 6th valence state. All transuranic elements tend to form complexes (some of them colloidal in nature) where iron may be the condensation centre. In sea water, these complexes exist mostly in a finely dispersed state with particle sizes on the order of 10–100 nm. The sedimentation rate for such particles is on the order of 1 m per year.

Most of the corrosion products of the materials in the reactor core are either sedimented or become adsorbed by surfaces. It was found that once a fuel assembly had been in sea water for about half a year, the increase in the total specific activity of the water had practically ceased, and its alpha activity, as well as the beta and gamma activity of isotopes of iron, chromium and nickel, had decreased substantially. This observation implies that the amount of corrosion products which is released into the primary circuit of the reactor becomes balanced by their sedimentation into the lower parts of the reactor volume and into spaces between the fuel elements.

Another important point when considering the effects of corrosion on the *Komsomolets* reactor, is the fact that the decrease in heat production (cf. Figure 2.5) and the low water temperature significantly slow down the corrosion rate of the nuclear fuel. The corrosion rate of the fuel rods is reduced by a factor of two to three for every 10 °C decrease in the water temperature (at temperatures below 50 °C).

3.2 Observed releases of radionuclides

The first attempts to measure radionuclide releases from the reactor of the nuclear submarine *Komsomolets* were made in May 1989 [KHL94]. At that time, water samples in the vicinity of the submarine were collected by the deep submersible manned vehicle *Mir*. The samples were analysed in the laboratory on board R/V *Academic Mstislav Keldysh* with the use of a sodium-iodide detector measuring 63 mm in diameter and 63 mm in height. No gamma-emitting radionuclides were detected above the detection limit of about 4 kBq/m^3.

The first successful attempt to measure the release of fission products from the reactor of the submarine was made in 1991. Since that year, the release of radionuclides has been observed as described below [KHL94].

In 1991, measurements were made by a larger gamma spectrometer (known as REM–1). This consisted of a monocrystal of sodium iodide with a diameter of 200 mm and a height of 200 mm. The crystal was in turn optically connected to a photomultiplier, and the entire spectrometer assembly was placed inside a strong titanium shell which was mounted on the outside of *Mir*. This detector system collected gamma spectra from locations on the sea bottom, on the hull of the submarine and in open water near different parts of the submarine. REM–1 can detect gamma emissions with energies ranging from 0.1 MeV to 3.0 MeV.

On the first submergence, 192 spectra were recorded. These spectra included measurements of the natural background radioactivity of water (which was measured at distances of more than 1.5–2 m away from the bottom or the hull of the submarine). The background spectra indicated gamma emissions from ^{40}K and showed no traces of ^{137}Cs.

However, when spectra were recorded in the immediate vicinity of the ventilation tube from the reactor compartment (cf. Figure 2.3), a peak was detected at about 0.66 MeV (the energy of gamma radiation from decay of ^{137}Cs). The concentration of ^{137}Cs corresponding to this peak was (4.1±1.1) kBq/m^3.

No cesium signal was found in any of the 192 spectra recorded during the second submergence in 1991. However, on the third submergence, some of the 215 recorded spectra indicated cesium peaks. At the same site near the vent tube where ^{137}Cs had been detected earlier, the ^{137}Cs concentration was now (22±7) kBq/m^3. For all other locations of the detector, the concentration of radiocesium was below the detection limit (for three-minute exposures) of about 100 Bq/m^3. These results formed the initial basis of the radiation monitoring of the *Komsomolets* [NEJ93] (see Figure 3.1).

During the 1992 expedition, a total of 409 spectra were collected near the submarine using a new and smaller spectrometer (REM–2). This detector is based on a monocrystal of sodium iodide measuring 200 mm in diameter and 100 mm in height and confined in a spherical shell made of a durable aluminium alloy. Near the outlet of the ventilation tube, the radiocesium

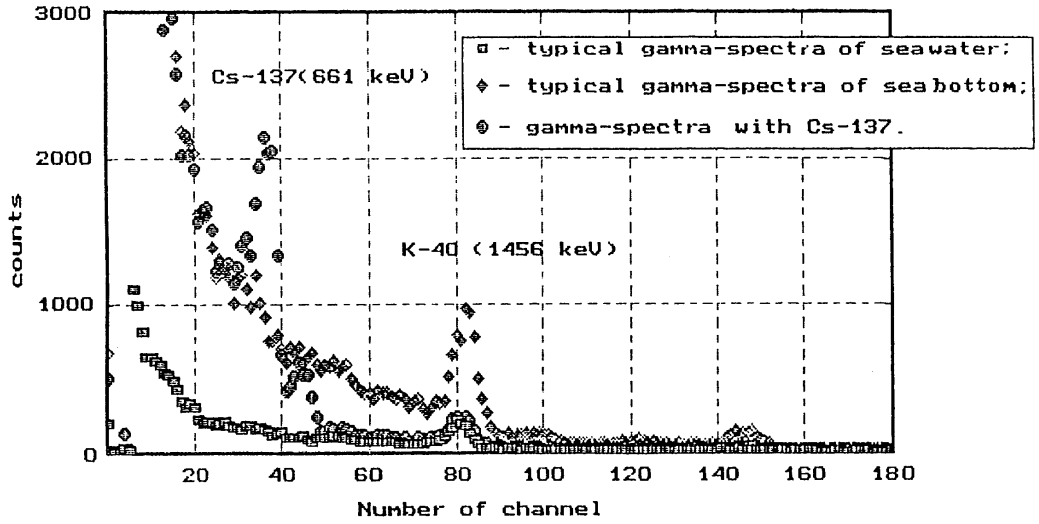

Figure 3.1. Gamma-ray spectra (three-minute exposures) obtained at three different sites in 1991 [KHL94].

concentration was measured to be (3.0±0.7) kBq/m^3. These measurements were made near the detection limit of the REM–2 spectrometer.

The 1992 expedition also made measurements several nautical miles away from the *Komsomolets* using a spectrometer (known as REM–5) with a very low detection limit of about 10 Bq/m^3 (for 30-minute exposures). The spectrometer was equipped with a unique 12.5-litre monocrystal (about twice the volume of REM–1). A total of 16 gamma-ray spectra (ten-minute exposures) were taken, some of them as far down as at 2 100 m. No radiocesium was detected above the detection limit of about 20 Bq/m^3.

The observations made during the 1993 expedition confirmed the results of the earlier expeditions. A total of 956 spectra were registered by the gamma-ray spectrometer REM–2. ^{137}Cs in concentrations of around 4 kBq/m^3 was detected in 24 spectra collected near the outlet of the reactor-room ventilation tube.

The 1994 expedition to the *Komsomolets* site included measurements with several new spectrometers. More than 400 spectra were recorded with the autonomous spectrometer REM–10, which was fitted onto the right-hand side support of *Mir*. REM–10 has a sodium iodide monocrystal similar to that in REM–1. A ^{137}Cs peak was found in 15 of the spectra with a maximum concentration of about 1.9 kBq/m^3. The detection limit was about 150 Bq/m^3.

Measurements were also made inside the reactor-compartment ventilation tube. The smaller spectrometer REM–4AM, which is capable of measuring ^{137}Cs concentrations ranging from about 40 kBq/m^3 to more than 10 MBq/m^3, was inserted 0.8 m into the ventilation tube. A number of spectra with an exposure time of 69 minutes were collected. Further measurements (with 25-minute exposure times) were made with the autonomous spectrometer REM–11

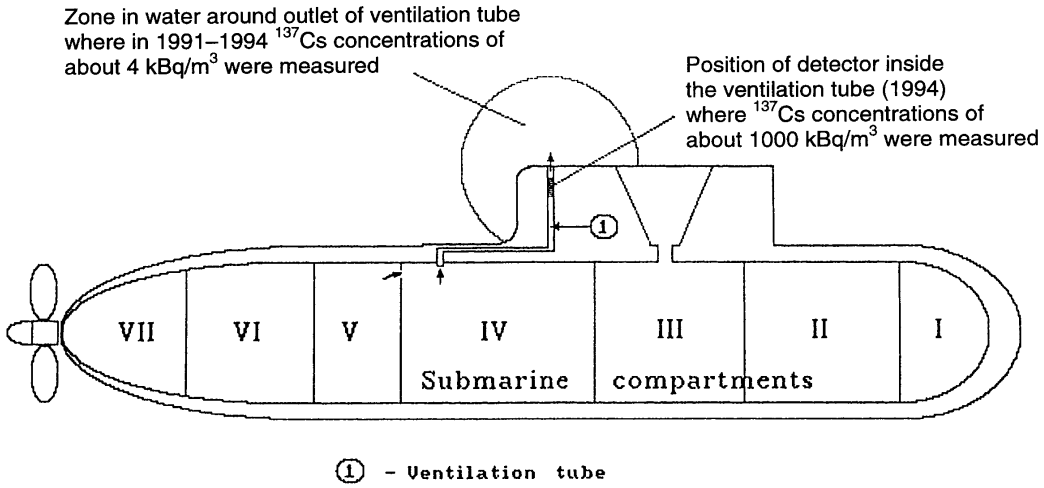

Figure 3.2. Sketch of the sunken submarine Komsomolets *indicating locations of registered ^{137}Cs contamination [KHL94].*

located 0.5 m inside the ventilation tube. All of the spectra revealed a radiocesium peak corresponding to a ^{137}Cs concentration of between 0.4 MBq/m^3 and 4 MBq/m^3.

The gamma-ray spectrometer REM–11 was left inside the ventilation tube on July 26, 1994, for the purpose of collecting spectra over the course of an entire year. One spectrum will be recorded every 12 days, and all the collected spectra will eventually be read out by the 1995 expedition.

Figure 3.2 summarises the results of the gamma-ray radiation monitoring in the vicinity of the *Komsomolets*. No ^{137}Cs peak was detected in any of the spectra that were collected on the upper deck of the reactor compartment. This important observation implies that the ^{137}Cs activity in volume V_2 of Figure 2.3 must be less than about 40 MBq/m^3.

3.3 Expected releases of radionuclides

This section co-ordinates the preceding results of calculations and existing observations in an attempt to predict future releases of radionuclides from the *Komsomolets*. The evaluations are based on [KHL94]. Transfer routes of radionuclides are simplified and sorption-desorption processes are not considered. Ignoring these processes can only lead to an overestimate of the assessed releases anyway; thus, this approach contributes to making conservative estimates.

The first step is to assess the water exchange between the reactor compartment and the marine environment. The exchange of water between volume V_1 in Figure 2.3 and the external environment is influenced by the following factors:

- Conditions of all cross-sections along the path from the reactor to the outlet of the ventilation tube;
- The presence of buffer volumes;
- Thermal stimulation of water exchange due to heat production;
- Tidal variations;

- Variations in atmospheric pressure;
- Pulsing influence of water flow due to near-bottom currents.

As already mentioned, the reactor core lies in still water which is connected to the surrounding sea through a multi-barrier system of corrosion-proof materials (stainless steel and titanium alloys). The corrosion rate for the barriers is less than 1 μm per year. With time, the area of any cross-section along the way from the reactor to the outlet can only decrease since corrosion products have larger specific volumes than the initial materials. Tidal variations and variations in the atmospheric pressure will produce a water exchange in V_1 of not more than 0.01 m^3 (10 litres) per day.

The water exchange and radionuclide releases can also be estimated from the experimental data on ^{137}Cs concentrations that were presented in Section 3.2. Figure 2.3 defines three volumes (V_1, V_2, V_3), three water fluxes (g_1, g_2, g_3) and three ^{137}Cs concentrations (a_1, a_2, a_3). It is assumed that the exchange of water occurs much more slowly in V_3 than in V_2, that is, $V_3/g_3 << V_2/g_2$. From the above-mentioned experimental observations, a_3 = 0.4–4 MBq/m^3 and $a_2 \leq 40$ MBq/m^3. The ^{137}Cs concentration a_1 inside the reactor is due to leaching from the fuel elements caused by salt water mixed with the initial bidistillate. A direct flow of water through the reactor would be incompatible with the observations. In any case, the water flow out of V_2 must be much greater than out of V_1, that is, $g_2 >> g_1$ and therefore $a_2 << a_1$. Before the accident, $a_1 \leq 400$ MBq/m^3. After 50 days of elevated temperatures, the rate of leaching decreased. Correspondingly, the volume activity a_1 of ^{137}Cs in the primary circuit must have reached an equilibrium value. A comprehensive assessment of this activity led to the conclusion that at the end of the first 50 days after the sinking, $a_1 \leq a_1^0 = 100$ GBq/m^3 of ^{137}Cs [KHL94].

The change with time of the radiocesium concentration a_1 in the primary circuit can be described by the equation

$$a_1 = a_1^0 \left(1 - e^{-\alpha t}\right) e^{-\lambda t}$$

where α is a constant of value 0.046 per day, and λ is the decay constant for ^{137}Cs ($6.3 \cdot 10^{-5}$ per day).

The time dependence of the concentration a_2 (ignoring sorption-desorption processes) can be described by

$$\frac{da_2}{dt} = \frac{a_1 g_1}{V_2} - \left(\lambda + \frac{g_2}{V_2}\right) a_2 \ .$$

As stated earlier, the maximum value of a_2 permitted by observations is about 40 MBq/m^3. The above equations permit this value for a_2 if $g_1/g_2 = 3 \cdot 10^{-4}$. From experimental observations,

g_3 is on the order of 100 m^3 per day. Assuming equilibrium, the amounts of radionuclides flowing into and out of V_2 must be equal. Thus,

$$g_2 = \frac{a_3}{a_2} g_3 \ .$$

Taking the upper limit for a_2 and using the experimentally obtained values for g_3 and the range of a_3 (as quoted above), g_2 = (1–10) m^3 per day. Consequently, the water flow out of the reactor is $g_1 = (0.3–3)\cdot 10^{-3}$ m^3 per day.

Assuming a stable equilibrium situation where the leaching of radionuclides from the submarine is determined by the maximum value of g_1 and the initial ^{137}Cs concentration a_1^0, the release of ^{137}Cs would amount to about 100 GBq per year. The solution of the above differential equation for a_2 indicates that the maximum release rate will be reached three years after the sinking. This maximum is rather extended in time, however, and does not change much from one year to ten years after the sinking.

There is yet another direct approach for estimating the release of ^{137}Cs from the ventilation tube. Videotapes made during the expeditions to the submarine show a visible flow of water from the ventilation tube with a velocity not higher than 0.1 m/s. With a tube diameter of 220 mm, the upper limit on the water exchange g_3 will be about 0.004 m^3/s. The highest experimental value for a_3 was about 4 MBq/m^3 (cf. Section 3.2). These figures yield an upper boundary on the ^{137}Cs release of about 500 GBq per year. Thus, all the evidence presented supports the notion that for the foreseeable future, the release of ^{137}Cs from the reactor installation on board the sunken submarine *Komsomolets* cannot exceed a few hundred GBq per year. The release rate of other radionuclides (most importantly ^{90}Sr) should be at least an order of magnitude lower.

4 OCEANOGRAPHIC CONDITIONS

The area of sea bottom where the *Komsomolets* rests is a part of the continental slope which in that region extends northeastwards and has a mean steepness of about 1°. The submarine lies on a terrace in this slope with a steepness no greater than 0.3–0.5°. The base of the terrace consists of hard rock covered with a layer of silt 40 m thick [KHL94].

In general, little is known about the ocean currents at various depths. Near *Komsomolets*, model studies indicate a fairly stable current flowing towards the northeast at a speed of about 0.05 m/s [ADL94]. Measurements of the currents near the *Komsomolets* site were made by the Norwegian Institute of Marine Research (IMR) at depths of 667 m, 1 567 m and 1 642 m (local bottom depth was 1 697 m) throughout May, June and July of 1993. In contrast to the model studies, however, the measurements showed a stronger and more variable current with a southwards residual [BLI94].

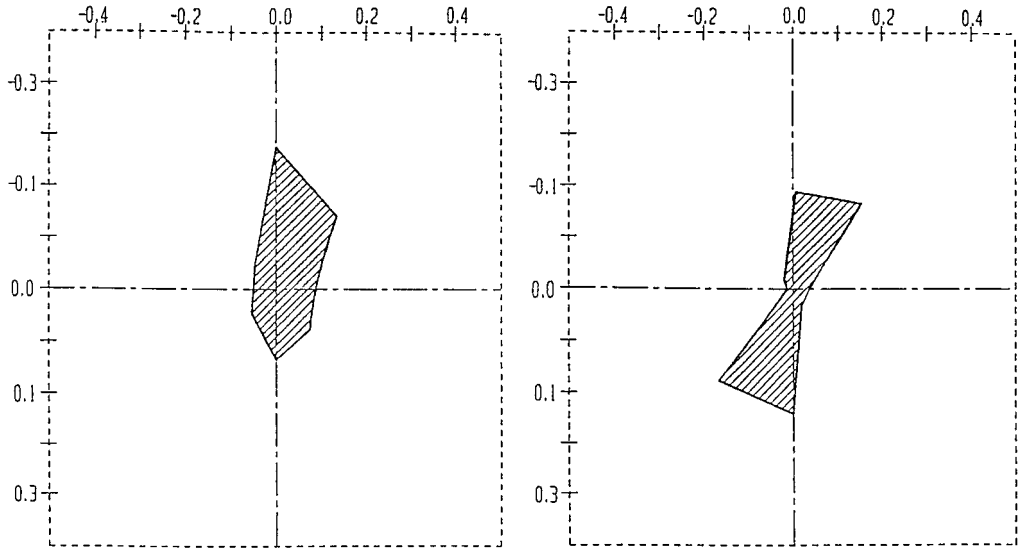

Figure 4.1. Russian measurements of the distributions of ocean currents (left-hand graph) and water mass transfers (right-hand graph) at the Komsomolets *site [KHL94]. The numbers along the axes indicate compass points.*

These latter measurements are supported by [KHL94]. Here, the distribution and other characteristics of the ocean currents at the *Komsomolets* site are based on observations from five expeditions, results of modelling and literature studies. It was found that the main directions of currents on the surface of the sea are towards the north and northeast with typical velocities of about 0.2 m/s. The maximum current velocity found in the upper 300 m was 1.8 m/s. At greater depths (1 000 m and 1 600 m), the currents are interchangeable with some preference for the northeast direction. Average velocities here are about 0.2 m/s.

The measurements of velocities and directions of bottom currents were for the most part made about 5 m above the sea floor [KHL94]. Significant changes were observed in rather short time intervals. The highest measured velocity of the bottom current was 1.5 m/s. The left-hand graph in Figure 4.1 shows the distribution of the current velocities by compass points. The prevailing directions are towards the north and east, but other directions are also possible. The right-hand graph in Figure 4.1 shows the distribution of water mass transfers (that is, the product of direction and speed of the currents). Clearly, water is preferentially transferred along a line from south-southwest to north-northeast. The transfers in the northern direction are about as large as those in the southern direction confirming the generally chaotic and diffuse nature of bottom currents.

Measurements of temperature, salinity and density show that the water masses in the upper layers are well stratified [BLI94]. Below these layers, the water masses are fairly homogeneous. Seasonal and annual variability are quite small. The stratification of the water provides a vertical stability which prevents the movement of water from the deeper layers (below 1 000 m) up to the surface.

The water temperature near the bottom of the sea during the various expeditions (July–August) was about –0.8 °C [KHL94].

The highest tidal variations of the sea surface in the area where the *Komsomolets* sank are less than 1.2 m [KHL94].

The composition of biota near the *Komsomolets* site is quite varied [KHL94]. The most prominent species is plankton which migrate daily in a vertical direction from the surface to a depth of around 500 m. During winter, about one third of the biomass of wintering plankton concentrates at depths below 1 000 m (in concentrations of up to 200–300 mg/m^3). However, during winter, the exchange between the plankton and the surrounding environment is limited to the breathing process. In spring, the plankton ascend to the surface for reproduction whereupon most of them die and a new generation of plankton appears.

Benthal organisms are generally distributed over the upper 800 m with an average surface density of up to 0.1 kg/m^2 [KHL94].

The nutritional significance of the Norwegian Sea benthos is not great. At shallower depths, the benthos biomass is formed mostly by sponges and *Brachiopoda*. These are filtrator organisms which accumulate matter brought to them by the flow of water. Fish feed neither on sponges nor on *Brachiopoda*, so these species therefore constitute a dead end on the food chain.

Industrial fisheries near Bear Island and Spitsbergen constitute the highest links of the food chain. Most of the cod and sea perch is caught at depths not greater than 300–400 m. Halibut and some other species are caught at 800–900 m. There is no industrial fishing at depths below 1 000 m [KHL94].

5 TRANSFER MECHANISMS

A model simulation for the dispersion of “passive tracers” released at the position of the *Komsomolets* has been performed [ADL94]. The study was carried out for FFI as a co-operation between IMR and the Norwegian Meteorological Institute (DNMI). As suggested by the discussion in Section 2.2.3, it was assumed that the release from the submarine was “cold”, that is, there was no hot-water plume that could transport particles quickly towards the surface of the sea. A hydrodynamic model was used to simulate the relevant ocean currents. In the transport calculations, the tracers passively followed the currents (*advection*). Spatial and temporal variability in the currents lead to a spreading of the particles. Furthermore, diffusion due to small-scale turbulence in the currents were included as “random walk”.

There is some professional disagreement over the applicability of the IMR/DNMI model simulations [HAU94], especially in its applications to technical topics such as co-ordinate models, driving forces, vertical advection and diffusion, time scales and grid sizes. Another

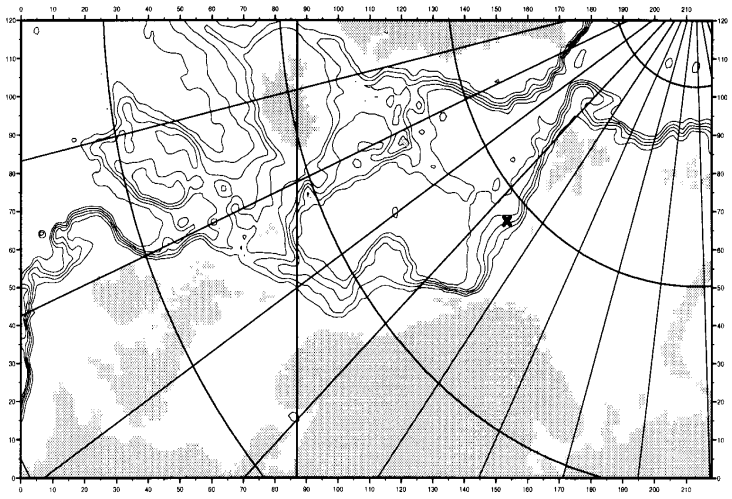

Figure 5.1. Model domain with bottom contours every 500 m [ADL94]. The position of the Komsomolets *is marked with an "x". The hydrodynamic model was run on the whole domain, while the transport model was run on the domain to the right of the vertical bar. The co-ordinates are given in grid cell units.*

problem is the modelling of the currents, which does not agree very well with the observations quoted in Chapter 4. Nevertheless, the model in question is presently the only one available for this discussion. A summary and the results of the IMR/DNMI study follow below (cf. [ADL94]).

The IMR/DNMI study utilised a hydrodynamic model known as the three-dimensional Princeton Ocean Model [BLU87]. Some modifications to the model were made at DNMI and IMR. For the study on *Komsomolets*, the hydrodynamic model was driven by density gradients and wind forcing. Tidal forcing was not taken into account. The equations for salinity and temperature were not solved; instead these fields were interpolated in time from the applied climatology [OTT93]. The model was run for the three months of May, June and July 1992.

The model area is shown in Figure 5.1. The ocean area under investigation was divided into 218×120 grid cells, each 20 km×20 km in size. In the vertical direction, 17 levels with increased resolution near the surface and bottom were used. The current velocity at all depth levels as well as the sea surface elevation were recorded once daily for each grid cell.

Figure 5.2 shows a snapshot of the model current at 98% of the bottom depth. The current at this depth, as calculated in the model, is rather weak. The most prominent feature is the current following the isobaths around the deep part of the ocean. In particular, the current flows northwards into the Arctic Ocean along the edge west of the Barents Sea and continues eastwards along the northern break of the Barents Sea.

In the model, the transport processes are driven by the stored current-velocity fields from the hydrodynamic model. These fields are used to move the particles to their next position

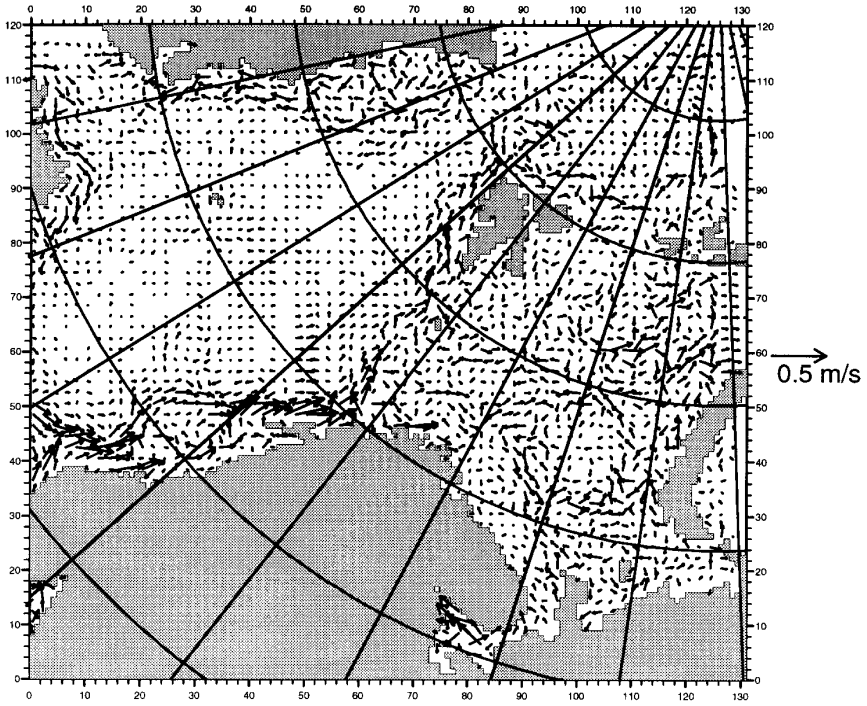

Figure 5.2. Modelled current field on May 1, 1992, at 98% of the bottom depth. For comparison, the length of an arrow indicating a speed of 0.5 m/s is shown to the right. The co-ordinates are given in grid cell units.

(advection) in time increments of six hours. Furthermore, diffusion is included by allotting each particle a random-walk velocity at every time step (that is, every six hours). This velocity depends on the diffusion coefficient, which in this study was set at 100 m^2/s horizontally and $2 \cdot 10^{-4}$ m^2/s vertically. If the computed advection velocity caused the particle to hit the ground, the velocity was halved repeatedly until the particle ended up inside the sea. Similarly, if the random-walk diffusion step would put the particle on ground, a new random step of lower velocity was tried until the new position was at sea.

The transport model was run on the ocean area to the right of the vertical bar in Figure 5.1. In the calculations, ten particles were released daily near the *Komsomolets*. To obtain a longer running time than the three-month period described above, the input was repeated cyclically for a total running time of 600 days.

The calculated current at the centre of the particle-release cell for the model period (May, June and July 1992) was found to be quite stable towards the northeast, with a speed of about 0.05 m/s. However, as mentioned in Chapter 4, actual current measurements indicate a stronger and more variable current.

A concentration field (as a function of time) was computed from the distribution of the released particles. Horizontally, this was achieved by assigning a bell-shaped distribution function to each particle. The width of the bell was set at $R = \sqrt{1 + 0.09 \cdot T}$, where the age T of the particle is measured in days and R is given in grid units. Since the width of the bell

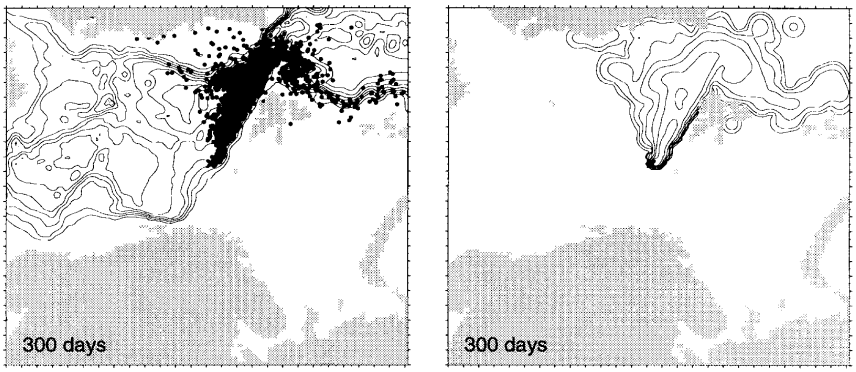

Figure 5.3. The left-hand panel shows the distribution of the 3 010 released particles after 300 days, as well as bottom contours for every 500 m. The right-hand panel shows the derived depth-integrated concentration field. The outermost isoline is at 0.01 particle weight per cubic meter. For each succeeding isoline, the concentration is multiplied by a factor of $\sqrt{10}$.

increases with the age of the particle, an old particle is spread out over a larger area than a young one. This method therefore affords another way of parametrising diffusion. The width of the bell-shaped function selected here corresponds to an additional horizontal diffusion coefficient of 100 m^2/s. To obtain the concentration of particles, the distribution functions were summed and averaged over the pertinent depth interval.

The left panel in Figure 5.3 presents a horizontal view of the 3 010 particles that were released during the first 300 days. The right panel shows the derived depth-integrated concentration field. In general, the particles have been transported northwards. A major fraction of them has entered the Arctic Ocean and turned east along the northern break of the Barents Sea. The particles are spread out and cover the deep area between the Barents and East Greenland shelves. On the Greenland side, some of the particles have moved southwards and some have entered the shelf. Furthermore, a few particles have entered the Barents shelf from the north. The concentration panel in Figure 5.3 shows peak concentrations in the submarine grid cell and an elongated high-concentration plume west of Spitsbergen.

Depth is recorded for each particle. The vertical distribution of the particles in 100-m intervals after 300 days is shown in Figure 5.4 (left). The peak of the distribution appears in the release interval 1 700–1 800 m, but the distribution is spread out over the entire water column with a secondary maximum in the top 100 m. The large number of particles appearing in the upper layer is unrealistic, for observed salinity and temperature structures indicate that only a very limited exchange of water takes place between the bottom and the surface. The particle height above the sea bed is also recorded and shown in Figure 5.4 (right). Nearly 50% of the particles are found less than 500 m above the bottom with peak concentrations in the lowest 100 m.

Figure 5.5 shows the concentration fields for the depth intervals 0–100 m (left) and 1 700–1 800 m (right) after 300 days. These are the levels containing the most particles (cf. Figure 5.4). In the top layer, the concentration is essentially zero at the position of the submarine.

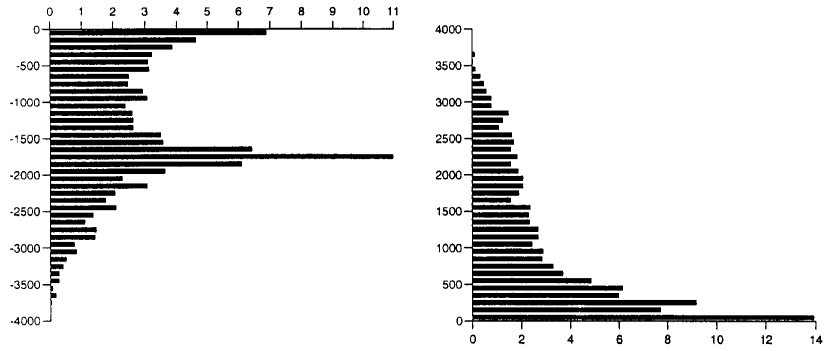

Figure 5.4. Vertical distribution of the particles after 300 days (percentage of the total) as a function of depth below the surface (left) and height above the bottom (right). The depths are measured in meters.

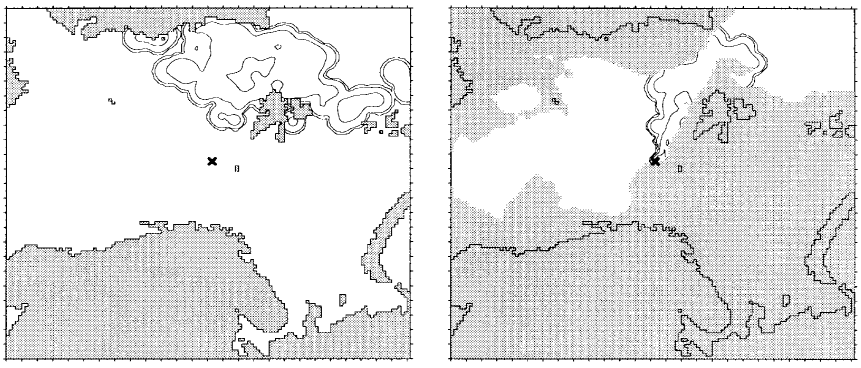

Figure 5.5. Concentration field (particles/m^3) in the depth intervals 0–100 m (left) and 1 700–1 800 m (right) after 300 days. The outermost isoline is at 10^{-14} particles/m^3, and for each succeeding isoline, the concentration is multiplied by 10.

The maximum concentration ($1.6 \cdot 10^{-11}$ particles/m^3 based on a release of 3 010 particles) is found to the north of the vessel and west of Spitsbergen (in grid cell (84, 100)). The extent of the concentration field is similar to the depth-averaged picture (Figure 5.3), but the concentrations are higher near the boundary of the field. In the release interval (1 700–1 800 m), the direction of the transport is the same as near the surface, but the speed is lower. In this interval, the peak concentration is $9.5 \cdot 10^{-10}$ particles/m^3 in the release cell. (Note that the model cannot be applied to this cell. It averages the concentrations over the entire volume of the cell (20 km×20 km×100 m), while the release comes from a very small source inside this volume. The concentrations near the submarine are therefore expected to be considerably higher than those estimated by the model. This is demonstrated with a simple example in Chapter 6.)

The time evolution over 600 days of the vertically integrated concentration field (that is, the total number of particles per grid cell) is depicted in Figure 5.6. After 200 days, the particles have progressed northwards and are entering the Arctic Ocean. This trend continues during the rest of the 600-day period, but the spreading of the particles and the southwards transport near East Greenland become more prominent with time. In the last panels, the field has

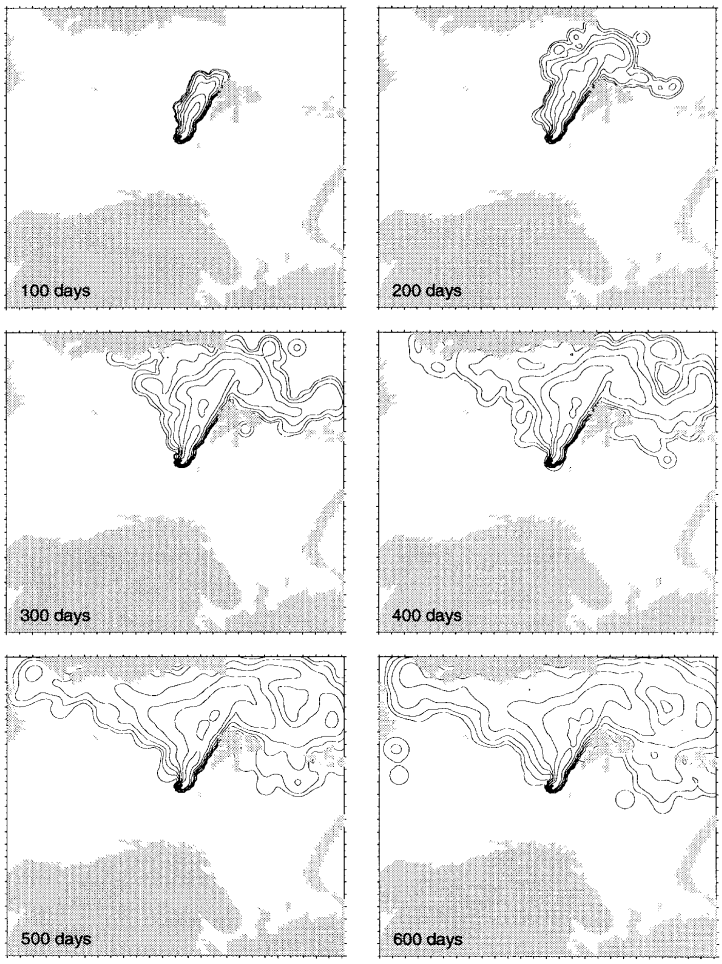

Figure 5.6. Time evolution of the vertically integrated concentration of particles released at the Komsomolets *site. The outermost isoline is at 0.01 particles per grid cell. For each succeeding isoline, the concentration is multiplied by a factor of* $\sqrt{10}$.

reached Iceland. After 400 days, a few particles enter the Barents shelf from the north. Towards the end of the period, the extent of the area with the highest concentration levels appear to have approached a stationary state.

The vertical advection in the model leads very rapidly to relatively high concentrations near the surface. As mentioned above, such vertical transport of water from a depth of more than 1 600 m to the surface is inconsistent with the observed salinity and temperature structure of the Arctic seas. However, regardless of vertical advection, this model study is consistent with the common opinion that most of the water-soluble radioactive contamination from *Komsomolets* will be transported into the Arctic Ocean.

As noted earlier, not all radioactive materials in the submarine are equally soluble in water. In particular, the actinides are not very soluble at all, and they will for the most part be deposited in the sediments near the vessel. Obviously, the model applied in this study cannot adequately

describe their movement. On the other hand, important nuclides such as cesium and strontium are highly water soluble. Thus, their movement should be well described by the model.

6 DOSE ASSESSMENT

The concentration of radionuclides in sea water as a result of their release from *Komsomolets* may be estimated from the results of the transport model described in Chapter 5. The highest concentration of particles anywhere in the top 100 m of the ocean has been calculated for every 10 days up to 600 days after the beginning of the release [ADL94A]. These calculations indicate that the concentration reaches a steady state after about 450 days. During the period from 450 days to 600 days after the beginning of the release, the particle concentration in the most contaminated grid cell varies between $2.1 \cdot 10^{-11}$ m^{-3} and $2.7 \cdot 10^{-11}$ m^{-3}. The following calculations therefore assume a steady-state maximum concentration of $3 \cdot 10^{-11}$ particles per m^3. These calculations will necessarily overestimate the concentration of radionuclides which are not completely water soluble. Since the radionuclides deposited in sediments at great depths are less accessible to man than those dissolved in sea water, the calculations will therefore also overestimate the effective doses received by man.

The inventory of radionuclides on board the *Komsomolets* is discussed in Chapter 2. The values used for the calculations are listed in Table 6.1. The table also lists the decay-corrected activities at three later times, namely on January 1, 1991 (which is approximately when a steady state may first have occurred), January 1, 1995, and April 7, 2089 (100 years after the accident). As presented in the table, the total radionuclide inventory on board the *Komsomolets* at the time of its sinking was about 30 PBq, and after 100 years, this will be reduced to about 0.6 PBq. Calculations have been performed in order to estimate the effects of the releases from *Komsomolets* at the above-mentioned times. The results are presented below. (Because ^{95}Kr is a noble gas and therefore not very likely to be taken up in the food chain, it was ignored in these calculations.)

As already mentioned, the model used here is not suitable for estimating the concentration of radionuclides in the immediate vicinity of the *Komsomolets*. Since the model averages the concentrations over an entire cell, the radionuclide concentrations near the submarine are expected to be considerably higher than those estimated by the model. For example, as maintained in Section 3.2, the ^{137}Cs concentration right near the outlet of the ventilation tube is measured to be several thousand Bq/m^3. However, as also verified by the reported observations, such concentration levels will only be found in the very near vicinity of the submarine.

Section 3.3 presents an upper boundary of 500 GBq per year on the release of ^{137}Cs from the submarine. No other radionuclides are mentioned. In order to establish model values for the complete release of radionuclides from the submarine, assumptions must be made for the releases of other important radionuclides. The given release rate of 500 GBq/y for ^{137}Cs corresponds to a certain fraction of the total inventory of this radionuclide. In the calculations,

Table 6.1. Radionuclide inventory on board the Komsomolets *at the time of its sinking. The list includes the most important radionuclides and is assembled based on information from [KHL94] presented in Chapter 2. The inventories given for later times include both the released radionuclides and those remaining on board the submarine.*

Nuclide	Half-life	Activity (Bq)			
		Apr. 7, 1989	Jan. 1, 1991	Jan. 1, 1995	Apr. 7, 2089
Reactor:					
^{55}Fe	2.73 y	$1.3\cdot10^{14}$	$8.4\cdot10^{13}$	$3.0\cdot10^{13}$	$1.2\cdot10^{3}$
^{60}Co	5.272 y	$5.9\cdot10^{13}$	$4.7\cdot10^{13}$	$2.8\cdot10^{13}$	$1.1\cdot10^{8}$
^{63}Ni	99.6 y	$4.4\cdot10^{12}$	$4.4\cdot10^{12}$	$4.2\cdot10^{12}$	$2.2\cdot10^{12}$
^{85}Kr	10.72 y	$4.8\cdot10^{14}$	$4.3\cdot10^{14}$	$3.3\cdot10^{14}$	$7.5\cdot10^{11}$
^{90}Sr	28.78 y	$2.8\cdot10^{15}$	$2.7\cdot10^{15}$	$2.4\cdot10^{15}$	$2.5\cdot10^{14}$
^{106}Ru	1.020 y	$8.9\cdot10^{14}$	$2.7\cdot10^{14}$	$1.8\cdot10^{13}$	—
^{134}Cs	2.062 y	$3.5\cdot10^{15}$	$2.0\cdot10^{15}$	$5.1\cdot10^{14}$	$8.6\cdot10^{0}$
^{137}Cs	30.254 y	$3.1\cdot10^{15}$	$3.0\cdot10^{15}$	$2.7\cdot10^{15}$	$3.1\cdot10^{14}$
^{144}Ce	284.893 d	$9.8\cdot10^{15}$	$2.1\cdot10^{15}$	$6.0\cdot10^{13}$	—
^{147}Pm	2.6234 y	$7.5\cdot10^{15}$	$4.7\cdot10^{15}$	$1.7\cdot10^{15}$	$2.5\cdot10^{4}$
^{239}Pu	24204 y	$4.4\cdot10^{12}$	$4.4\cdot10^{12}$	$4.4\cdot10^{12}$	$4.4\cdot10^{12}$
^{240}Pu	6555 y	$1.7\cdot10^{12}$	$1.7\cdot10^{12}$	$1.7\cdot10^{12}$	$1.7\cdot10^{12}$
^{241}Pu	14.353 y	$3.1\cdot10^{14}$	$2.9\cdot10^{14}$	$2.4\cdot10^{14}$	$2.5\cdot10^{12}$
^{242}Pu	373000 y	$1.0\cdot10^{9}$	$1.0\cdot10^{9}$	$1.0\cdot10^{9}$	$1.0\cdot10^{9}$
^{241}Am	432.1 y	$4.4\cdot10^{10}$	$4.4\cdot10^{10}$	$4.4\cdot10^{10}$	$3.8\cdot10^{10}$
^{242m}Am	142 y	$1.5\cdot10^{9}$	$1.5\cdot10^{9}$	$1.5\cdot10^{9}$	$9.2\cdot10^{8}$
^{243}Am	7362 y	$1.7\cdot10^{9}$	$1.7\cdot10^{9}$	$1.7\cdot10^{9}$	$1.7\cdot10^{9}$
^{242}Cm	162.8 d	$5.6\cdot10^{12}$	$3.8\cdot10^{11}$	$7.5\cdot10^{8}$	—
^{243}Cm	28.5 y	$4.8\cdot10^{8}$	$4.6\cdot10^{8}$	$4.2\cdot10^{8}$	$4.2\cdot10^{7}$
^{244}Cm	18.077 y	$3.1\cdot10^{10}$	$2.9\cdot10^{10}$	$2.5\cdot10^{10}$	$6.7\cdot10^{8}$
Weapons:					
^{239}Pu	24204 y	$1.3\cdot10^{13}$	$1.3\cdot10^{13}$	$1.3\cdot10^{13}$	$1.3\cdot10^{13}$
^{240}Pu	6555 y	$3.0\cdot10^{12}$	$3.0\cdot10^{12}$	$3.0\cdot10^{12}$	$3.0\cdot10^{12}$
Long-lived decay products:					
^{237}Np	2140000 y	—	$2.6\cdot10^{5}$	$2.5\cdot10^{6}$	$2.5\cdot10^{8}$
^{241}Am	432.1 y	—	$8.3\cdot10^{11}$	$2.5\cdot10^{12}$	$9.0\cdot10^{12}$
Total:		$2.9\cdot10^{16}$	$1.6\cdot10^{16}$	$8.0\cdot10^{15}$	$6.0\cdot10^{14}$

it is assumed that the same fraction of the inventory of all other radionuclides is released annually. It is also assumed that the upper boundary of 500 GBq per year applies to the releases based on the January 1, 1991, inventory. Assuming that the corrosion rates are constant, the release of ^{137}Cs at later times is reduced corresponding to its natural decay rate.

Table 6.2. Estimated effects of the releases of radionuclides from Komsomolets *in 1995. The concentration factors and committed effective doses per unit intake are from [MAR90]. The doses include radiation from short-lived decay products. By "dose" in the last column is meant the committed effective dose for an individual who each day for one year has consumed 0.6 kg of fish from the most heavily contaminated waters.*

Nuclide	Concent. factor (m^3/t)	Dose per intake (nSv/Bq)	Release (Bq/y)	Activity in water (Bq/m^3)	Activity in fish (Bq/kg)	Dose (Sv)
Reactor:						
^{55}Fe	3000	0.162	$5.1\cdot10^{9}$	$4.2\cdot10^{-5}$	$1.3\cdot10^{-4}$	$4.4\cdot10^{-12}$
^{60}Co	1000	7.04	$4.7\cdot10^{9}$	$3.8\cdot10^{-5}$	$3.8\cdot10^{-5}$	$5.9\cdot10^{-11}$
^{63}Ni	1000	0.146	$7.1\cdot10^{8}$	$5.8\cdot10^{-6}$	$5.8\cdot10^{-6}$	$1.9\cdot10^{-13}$
^{90}Sr	2	35.5	$4.1\cdot10^{11}$	$3.4\cdot10^{-3}$	$6.7\cdot10^{-6}$	$5.2\cdot10^{-11}$
^{106}Ru	2	5.77	$3.0\cdot10^{9}$	$2.5\cdot10^{-5}$	$5.0\cdot10^{-8}$	$6.3\cdot10^{-14}$
^{134}Cs	100	17.5	$8.5\cdot10^{10}$	$7.0\cdot10^{-4}$	$7.0\cdot10^{-5}$	$2.7\cdot10^{-10}$
^{137}Cs	100	12.0	$4.6\cdot10^{11}$	$3.7\cdot10^{-3}$	$3.7\cdot10^{-4}$	$9.9\cdot10^{-10}$
^{144}Ce	50	5.37	$1.0\cdot10^{10}$	$8.3\cdot10^{-5}$	$4.1\cdot10^{-6}$	$4.9\cdot10^{-12}$
^{147}Pm	500	0.255	$2.8\cdot10^{11}$	$2.2\cdot10^{-3}$	$1.1\cdot10^{-3}$	$6.3\cdot10^{-11}$
^{239}Pu	40	952	$7.4\cdot10^{8}$	$6.1\cdot10^{-6}$	$2.4\cdot10^{-7}$	$5.1\cdot10^{-11}$
^{240}Pu	40	953	$2.9\cdot10^{8}$	$2.3\cdot10^{-6}$	$9.4\cdot10^{-8}$	$2.0\cdot10^{-11}$
^{241}Pu	40	18.5	$3.9\cdot10^{10}$	$3.2\cdot10^{-4}$	$1.3\cdot10^{-5}$	$5.3\cdot10^{-11}$
^{242}Pu	40	905	$1.7\cdot10^{5}$	$1.4\cdot10^{-9}$	$5.5\cdot10^{-11}$	$1.1\cdot10^{-14}$
^{241}Am	50	980	$7.3\cdot10^{6}$	$6.0\cdot10^{-8}$	$3.0\cdot10^{-9}$	$6.5\cdot10^{-13}$
^{242m}Am	50	950	$2.4\cdot10^{5}$	$2.0\cdot10^{-9}$	$1.0\cdot10^{-10}$	$2.1\cdot10^{-14}$
^{243}Am	50	976	$2.9\cdot10^{5}$	$2.3\cdot10^{-9}$	$1.2\cdot10^{-10}$	$2.5\cdot10^{-14}$
^{242}Cm	50	29.5	$1.3\cdot10^{5}$	$1.0\cdot10^{-9}$	$5.2\cdot10^{-11}$	$3.3\cdot10^{-16}$
^{243}Cm	50	674	$7.0\cdot10^{4}$	$5.8\cdot10^{-10}$	$2.9\cdot10^{-11}$	$4.3\cdot10^{-15}$
^{244}Cm	50	541	$4.2\cdot10^{6}$	$3.4\cdot10^{-8}$	$1.7\cdot10^{-9}$	$2.0\cdot10^{-13}$
Weapons:						
^{239}Pu	40	952	$2.2\cdot10^{9}$	$1.8\cdot10^{-5}$	$7.2\cdot10^{-7}$	$1.5\cdot10^{-10}$
^{240}Pu	40	953	$5.0\cdot10^{8}$	$4.1\cdot10^{-6}$	$1.7\cdot10^{-7}$	$3.5\cdot10^{-11}$
Long-lived decay products:						
^{237}Np	10	1080	$4.2\cdot10^{2}$	$3.4\cdot10^{-12}$	$3.4\cdot10^{-14}$	$8.2\cdot10^{-18}$
^{241}Am	50	980	$4.2\cdot10^{8}$	$3.4\cdot10^{-6}$	$1.7\cdot10^{-7}$	$3.7\cdot10^{-11}$
Total:			$1.3\cdot10^{12}$	$1.1\cdot10^{-2}$	$1.7\cdot10^{-3}$	$1.8\cdot10^{-9}$

The radionuclide releases estimated for 1995 are listed in Table 6.2. The total release of all radionuclides that year amounts to about 1.3 TBq, and it is dominated by ^{137}Cs (0.46 TBq), ^{90}Sr (0.41 TBq) and ^{147}Pm (0.28 TBq). For comparison, the total release of all radionuclides in the year 2089 is estimated to be about 0.1 TBq.

The upper layers of the sea are the most important for the fishing industry. Most fish caught for human consumption live in the upper 500 m of the sea and they are extremely rare below a depth of 800 m [GJO94]. Therefore, it is the concentration of radionuclides near the surface that is examined most closely here.

Table 6.2 also lists the activity in the upper 100 m of the water of the most contaminated area. In 1995, the contribution from *Komsomolets* to the radionuclide contamination of the Arctic seas is estimated to be no more than 0.01 Bq/m^3, of which 0.004 Bq/m^3 is ascribed to ^{137}Cs. (The total contribution was calculated to have been about 0.02 Bq/m^3 in 1991 decreasing to about 0.0008 Bq/m^3 in 2089). The water in the Barents Sea reportedly contains a few Bq/m^3 of ^{137}Cs [JRN93] (which in itself is quite low), so the *Komsomolets* does not cause a significant increase in this contamination level.

As described in Chapter 4, the concentrations of the various radionuclides in fish are assumed to be proportional to the concentrations found in the surrounding water. The ratio between the concentration of a given radionuclide in water to that in fish is known as the concentration factor C_f. Concentration factors for the relevant radionuclides, as well as the resulting radionuclide contamination of fish in the most contaminated waters, are presented in Table 6.2. In 1995, releases from the *Komsomolets* are expected to increase the radioactivity in such fish by a total of about 0.002 Bq/kg. This is a reduction from an estimated 0.005 Bq/kg in 1991. By the year 2089, the expected contamination will be further reduced to about 0.00005 Bq/kg. The dominating radionuclides in 1995 are ^{147}Pm (0.001 Bq/kg), ^{137}Cs (0.0004 Bq/kg) and ^{55}Fe (0.0001 Bq/kg). For comparison, fish presently caught in the Arctic seas typically contain on the order of 1–10 Bq/kg of ^{137}Cs (cf. Section 3.1.3).

The above considerations of the effects of the releases from *Komsomolets* may be further expanded to make estimates of human exposure to ionising radiation. For this purpose, a critical group was defined consisting of people who consume 0.6 kg of the most contaminated fish daily. The individual committed effective dose rates due to ingestion of this fish was then estimated by applying the formula

$$d(i) = w(i) \cdot C_f(i) \cdot c_r \cdot d_u(i)$$

where d is the committed effective dose rate, w is the radionuclide concentration in the sea water, C_f is the concentration factor, c_r is the consumption rate (0.6 kg per day), d_u is the committed effective dose per unit radioactivity ingested, and i labels the nuclide under consideration. The applied values for C_f and d_u are listed in Table 6.2.

The resulting individual committed effective doses obtained by each member of the critical group of people eating fish contaminated by releases from the *Komsomolets* in 1995 are also listed in Table 6.2. This amounts to less than 2 nSv or about one one-millionth of the natural background radiation that most people receive yearly. The most important radionuclides here are the two cesium isotopes ^{137}Cs (1.0 nSv or 55%) and ^{134}Cs (0.3 nSv or 15%) followed by

^{239}Pu (11.2%), ^{147}Pm (3.6%), ^{60}Co (3.3%), ^{240}Pu (3.0%), ^{241}Pu (2.9%), ^{90}Sr (2.9%) and ^{241}Am (2.1%).

It is important to note that when a radionuclide decays, it does not disappear, but is transformed into a new nuclide. This nuclide is often radioactive as well. Therefore, after the reactor shut-down, radionuclides will not only decay, but will also be produced. The decay chain $^{241}\text{Pu} \rightarrow {}^{241}\text{Am} \rightarrow {}^{237}\text{Np}$ may be particularly important for dose assessments. The contributions from these radionuclides in the case of the *Komsomolets* are listed in Table 6.1 and Table 6.2. It is seen that in 1995, the produced ^{241}Am contributes 0.04 nSv (or about 2% of the total) to the individual committed effective dose. However, the contribution from ^{241}Am peaks about 73 years after shut-down of the reactor. By the year 2089, its expected contribution will be about 0.13 nSv or about 25% of the total individual committed effective dose. In comparison, the dosage received due to the production of ^{237}Np will remain insignificant (its maximum activity will occur after about 5315 years). However, the half-life of ^{237}Np is 2.14 million years. ^{237}Np can therefore accumulate in the oceans from different sources for millions of years.

7 PLUTONIUM TRANSPORT AND THE THULE EXPERIENCE

As already mentioned, the IMR/DNMI transport model assumes that no sedimentation of radionuclides takes place. This is definitely not the case for the actinides. The Thule accident[3] has provided useful information on the behaviour of plutonium in an Arctic marine environment [AAR94]. Some of this information may also be applied to a possible release of plutonium from the *Komsomolets*. It should, however, be emphasised that not only do the two accidents differ substantially, but that also the two accident sites themselves are rather dissimilar. Any analogous conclusions should thus be drawn with caution. A comparison between the similarities and the differences between the two cases follows below.

The remaining plutonium inventory from the Thule accident was about 1 TBq finely dispersed in the upper layers of the marine sediments. The *Komsomolets* contains 6.1 TBq of Pu in the nuclear reactor (excluding ^{241}Pu) and about 16 TBq in the two nuclear warheads onboard [KHL94]. Very little, if any, of this activity has been released to the marine environment so far.

The plutonium from the Thule accident is located 11 km from the Greenland coastline at about 200 m depth, whereas the *Komsomolets* is positioned between the Norwegian Sea and the Barents Sea at a depth of almost 1.7 km where it is embedded 2.5–3 m into the clay.

There is no commercial fishery at Thule, while the Norwegian Sea and the Barents Sea are important fishing areas. No significant catch of fish or shellfish takes place at a depth of 1.7 km, however.

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[3] In 1968, a B-52 bomber crashed on the ice near Thule on Greenland. Three nuclear bombs disintegrated and released about 6 kg of plutonium.

When the plutonium in the nuclear warheads from *Komsomolets* becomes exposed to sea water, it will oxidise to PuO_2, which is almost insoluble in sea water. Most of the activity released will thus most likely be retained in the sediments where bioturbation will burrow it in the course of a few years. In the Thule accident, the plutonium was dispersed as small particles sinking through the water column, and it was thus more readily available than the plutonium from the *Komsomolets*, which is probably concentrated in relatively large lumps.

A conservative assumption would be that the amount of plutonium from *Komsomolets* available in a momentary release is an order of magnitude higher than that of the Thule contamination. The water column above *Komsomolets* is an order of magnitude higher than that over the Thule site. In the first year after the release, one would then (conservatively) expect mean concentrations of Pu in the water over *Komsomolets* similar to those observed at Thule in 1968, that is, about 0.1 Bq/m^3 of $^{239+240}$Pu (the present fallout background of Pu in the North Atlantic is about 0.01 Bq/m^3). From the concentration factor for fish, the mean concentration of $^{239+240}$Pu in any fish living in this water may then be estimated to be about 0.004 Bq/kg. The water concentration would be expected to decrease rapidly, and in a few years, it would not differ significantly from the fallout background. In the long run, perhaps 5% of the total plutonium inventory, that is, about 1 TBq, would be in solution and dispersed in the water masses of the North Atlantic. This represents about 0.04% of the total Pu inventory from global fallout in the North Atlantic north of 30° N. A good 95% of the Pu in *Komsomolets* will most likely remain in the sediments.

For added perspective, one may also compare the total amount of plutonium in *Komsomolets* with the amounts of Pu discharged from Sellafield throughout the years. The plutonium in the *Komsomolets* corresponds to about 3% of the Sellafield discharge. Neither the global fallout nor the Sellafield discharge presents any significant radiological hazard. Hence it is unlikely that the *Komsomolets* plutonium will do so either.

Some Russian estimates of the consequences of the *Komsomolets* plutonium are more pessimistic [LIS93]. Here it has been calculated that if the entire plutonium inventory is released (to the water phase?) from the weapons, it is possible that fish with plutonium contents of more than 74 Bq/kg may be found at a distance of 60 km to 100 km from the *Komsomolets*. How this calculation was made is not stated. However, if a person eats 1 kg of a fish containing 74 Bq/kg of $^{239+240}$Pu, he will receive a lifetime dose of about 70 μSv. This corresponds to about 2 weeks of extra background radiation and is an insignificant dose. If the fish within a distance of 80 km from *Komsomolets* were to have a mean activity of 74 Bq/kg, one can calculate that the water mass within this distance (about 40 000 km^3), if it was in equilibrium with the fish, should contain about 80 PBq of plutonium. This is almost 4000 times more than the estimated inventory in *Komsomolets*. Furthermore, as has already been mentioned, due to its high K_d value, the plutonium will go to the sediments rather than to the water phase.

8 SUMMARY AND CONCLUSION

After an extensive discussion of the inventory of radionuclides on board the sunken submarine *Komsomolets*, as well as a comprehensive discussion of possible releases of these radionuclides, it was concluded that no more than 500 GBq of ^{137}Cs are released yearly [KHL94].

A model simulation for dispersion of passive tracers was then used to calculate the concentrations in the Arctic seas of radionuclides from the *Komsomolets*. This model is suitable for completely water-soluble radionuclides only and will overestimate the concentrations of other radionuclides. Since the radionuclides deposited in the sediments at great depths (for example, near the submarine) are less accessible to man than radionuclides dissolved in water, the model overestimates the received effective doses. For largely insoluble radionuclides such as the plutonium isotopes, the major part of the releases will remain in the sediments quite near the submarine.

Spreading of radionuclides due to movement of biota was not taken into account in the model simulations. No such movements in the vicinity of *Komsomolets* are expected to contribute significantly to the received effective doses [FOY94].

In addition to the estimated inventory of radionuclides in the reactor and nuclear weapons at the time of shut-down, the decay chains $^{241}\text{Pu} \rightarrow {}^{241}\text{Am} \rightarrow {}^{237}\text{Np}$ and $^{241}\text{Am} \rightarrow {}^{237}\text{Np}$ were taken into account in the dose assessments. After a few decades, the former decay chain contributes significantly to the calculated received effective doses.

The model simulation was run for 600 days. It predicts a northwards transport of the radionuclides. A major fraction of the released radionuclides will enter the Arctic Ocean and then turn east along the northern break of the Barents Sea, and some radionuclides will eventually enter the Barents shelf from the north. The model does not lead to high surface concentrations of radionuclides. The transport modelling is rather uncertain. Measurements of currents near *Komsomolets* suggest a more complicated current picture than that predicted by the present model.

Given the radionuclide concentrations in the water, a simple model was used to estimate the effective dose rate to a critical group. The members of this group were each assumed to daily consume 0.6 kg of fish originating from surface waters in the most contaminated area, and the model predicted that they will nevertheless receive only a negligible effective dose of radiation due to radionuclides released from the *Komsomolets*.

Among the fission products, ^{137}Cs is the nuclide contributing the most to the effective dose rate. Among the activation products, ^{60}Co is the nuclide contributing the most to the effective dose rate. Due to its shorter half-life, ^{60}Co is not as hazardous as ^{137}Cs. Among the actinides, ^{239}Pu and ^{241}Am (produced from ^{241}Pu) are the most hazardous nuclides. The actinides are not very soluble in water and will therefore not contribute as much as ^{137}Cs to the received

effective doses (on the time scales considered here, anyway). However, due to their long half-lives, these actinides will be present in the environment for a long time.

There are large uncertainties in the estimates, particularly in the dispersion model. Nevertheless, this study, which does not pretend to completely answer all relevant questions, clearly indicates that the sunken nuclear submarine *Komsomolets* represents no significant hazard to man, today or in the future.

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