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Scenarios for Potential Radionuclide Release from Marine Reactors Dumped in the Kara Sea

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Abstract

The largest inventory of radioactive materials dumped in the Kara Sea by the former Soviet Union comes from the spent nuclear fuel (SNF) of seven marine reactors, the current (1994) inventory of which makes a total of approximately 4.7×10^{15} Bq (130 kCi). In progressing its work for the International Arctic Seas Assessment Project (IASAP), under the auspices of the International Atomic Energy Agency (IAEA), the Source Term Working Group has analysed the Source Term and subsequently developed a number of model scenarios for the potential release patterns of radionuclides into the Kara Sea from the SNF and activated components dumped within the marine reactors. These models are based on the present and future conditions of the barrier materials and their configuration within the dumped objects. They account for progressive corrosion of the outer and inner steel barriers, breakdown of the organic fillers, and degradation and leaching from the SNFs. Annual release rates are predicted to four thousand years into the future.

Source Term Development[1,2,3,4]

Background

Sixteen marine reactors from seven former Soviet Union submarines and the icebreaker *Lenin* were dumped at five sites in the Kara Sea. Six of the seven nuclear submarines contained two pressurized water reactors (PWRs) each. Eleven of these PWRs were dumped into the Kara Sea between 1965 and 1988: ten within their reactor compartments, one within the hull of a barge-like pontoon and covered with concrete, and four containing their SNF. The seventh nuclear submarine contained two liquid metal reactors (LMRs) and used lead-bismuth (Pb-Bi) as coolant. This submarine, with its reactor compartment intact and SNF and Pb-Bi coolant aboard, was sunk in September 1981. The three OK-150 PWRs from the icebreaker *Lenin* were discarded within their reactor compartment in August 1967. In addition, approximately 60% of the SNF and the core barrel from the N2 PWR were dumped in a specially-prepared pontoon in Tsivolka Fjord.

Characteristics of the Steam Generating Plants

The steam generating plant (SGP), including the steam generators and circulation pumps, was located in an isolated reactor compartment. Each PWR consisted of a cylindrical carbon steel RPV. Nuclear submarine cores were loaded with U-Al alloy fuel containing 50 kg of ^{235}U enriched to 7.5% or 20%. *Lenin* cores were loaded with varying quantities of UO_2 sintered ceramic fuel enriched to 5.0% ^{235}U and clad in Zr-Nb alloy or stainless steel (SS). Each LMR consisted of a cylindrical SS RPV. LMR cores were loaded with U-Be sintered ceramic fuel containing 90 kg of ^{235}U enriched to 90% and clad in SS. To reduce heat and radiation effects on each RPV and subsequently extend their operating lives, SS thermal shields were employed.

Reactor Operating Histories & Radionuclide Inventories

Current available information on the operating histories of the nuclear submarine SGPs is limited to the years of startup and shutdown and the fuel burn-up. The longest and shortest periods of SGP operation were of the order of five years and one year, respectively. Fuel burn-up for the PWRs varied from a low of 12.5 GWd to a high of 38.8 GWd. In the case of the LMRs, fuel burn-up for the second core load was only 875 MWd. Current available information on the operating history of the icebreaker *Lenin* SGP is much more extensive. There were two fuel loads associated with the first SGP: the first lasted from 1959 to 1962 and the second lasted from 1963 to 1965. The total integrated power productions for the first SGP were equal to 40.3 GWd for the N1 PWR, 32.2 GWd for the N2 PWR, and 35.5 GWd for the N3 PWR.

Radionuclide inventories associated with the nuclear submarine LMRs and the icebreaker *Lenin* PWRs were based on their detailed core operating histories and calculated neutron spectra. For the nuclear submarine PWRs, lack of information necessitated basing the inventories on the model for the *Lenin* SGP. Details of the dumped SGPs are given in Table 1.

Disposal Operations

With the exception of the one PWR from submarine factory number 421, all nuclear submarine PWRs were dumped in their separated reactor compartments. The four RPVs containing SNF were filled with a hardening compound based on furfural. SNF remained in the two LMRs; before disposal, a number of actions were taken to secure the reactors and reactor compartment for disposal including the use of some 2 m^3 of the furfural based compound and 250 m^3 of bitumen. The three PWRs of the icebreaker *Lenin* were discarded within their reactor compartment. Approximately 60% of the SNF and the core barrel from the N2 PWR were placed in a specially-prepared pontoon, later dumped close to the *Lenin* reactor compartment. At the time of disposal, the reactor compartments were allowed to flood thereby exposing any unprotected external surface of each RPV and the cavities and internal constructions of those RPVs without SNF or the furfural based compound to sea water.

Modelling Strategy

Radionuclide release from the dumped SGPs was assumed to be driven by seawater corrosion of the materials forming the plants. Using the best available predictions for corrosion rates in an Arctic environment, models were then developed to predict the release rates of the fission product, activation product and actinide inventories in the reactors. Using the inventory and construction data, corrosion rates were applied to computer models of the reactors to produce radionuclide release rates for scenarios ranging from no effective containment (Case 1)[5] to all containment barriers being fully effective (Case 4)[5]. Results have so far been obtained for all dumped reactors with the exception of the LMRs of submarine factory number 601, which are more complex to model owing to their unique construction.

The predicted Case 4 release rate from all the units dumped in Abrosimov Bay, summed over all radioactive isotopes, is given in Figure 1. The initial release, dominated by the rapidly decreasing ^{60}Co inventory, comes off the outer surfaces of the RPVs; when they are first penetrated through the primary circuit stubs and control rod channels, the fuel is exposed to sea water and the release rate rises to 1.5×10^{13} Bq yr^{-1} (400 Ci yr^{-1}) around the year 2005. This release rate falls rapidly as the fuel disappears, leaving the thermal shields and the RPV as the last of the components to corrode. The release rate falls to 7.4×10^{9} Bq yr^{-1} (0.2 Ci yr^{-1}) by 2400, and by the year 2660, all the units have corroded away.

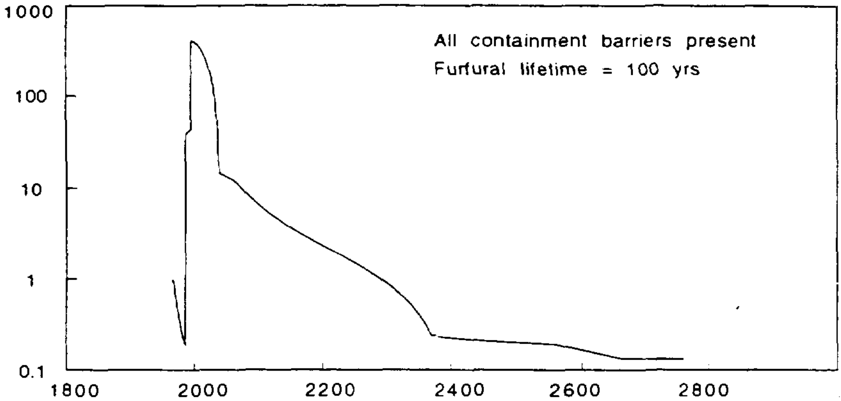

Figure 1- Total predicted radionuclide release rates in Ci yr^{-1} in Abrosimov Fjord to the year 3000

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Table 1. Current available information for the steam generating plants of the marine reactors dumped in the Kara Sea.

Characteristic	Marine factory number													
	901		285		254		260		OK-150			421	601		538	
Reactor																
Type	PWR[1]		PWR		PWR		PWR		PWR			PWR	LMR[2]		PWR	
Position	LB[3]	RB[4]	LB	RB	LB	RB	LB	RB	LB	CL[5]	RB	RB	LB	RB	LB	RB
^{235}U initial conditions																
Load (kg)	50		50		50		50		129[6]	75[6]	75[6]	50	90		50	
Enrichment (%)	20		7.5		20		20		5			20	90		20	
Steam generating plant																
Startup date	1961		1961		1958		1959		Aug 1959			1968	Dec 1962		1961	
Shutdown date	1961		1964		1962		1962		Oct 1965	Feb 1965	Oct 1965	1968	May 1968	Jun 1968	1963	
Burn-up (GWd)	1.71	1.67	2.78	2.73	3.08	3.88	1.72	1.94	40.3	32.2[7]	35.5	1.25	0.88[6]		1.68	1.44
Disposal date	May 1965		Oct 1965		1965		1966		Aug 1967			1972	Sep 1981		1988	
RPV[8] disposal condition																
With SNF[9]	Yes	Yes	-	Yes	-	-	-	-	-	-	-	Yes	Yes	Yes	-	-
Without SNF[10]	-	-	Yes	-	Yes	Yes	Yes	Yes	Yes[11]	Yes[12]	Yes[11]	-	-	-	Yes	Yes
Activity (10^{14} Bq) in 1994																
Fission products	7.2		6.3		-		-		18[13]			2.9	6.0		-	
Activation products	0.060		0.13		0.095		0.051		2.3[14]			0.03	2.3		0.045	
Actinides	0.034		0.081		-		-		0.83[13]			0.03	0.013		-	
Total	7.2		6.5		0.095		0.051		22			2.9	8.4		0.045	

1 Pressurized water reactor (PWR).
2 Liquid metal reactor (LMR).
3 Left board (LB).
4 Right board (RB).
5 Center line (CL).
6 For the second fuel load.
7 Burnup for the second fuel load was 14.2 GWd.
8 Reactor pressure vessel (RPV).
9 With thermal shields, hardware, spent nuclear fuel (SNF), and furfural.
10 With thermal shields and hardware and without SNF.
11 With thermal shields, hardware ,and furfural and without SNF.
12 With furfural and without SNF. Thermal shields, hardware, and approximately 60% of SNF discarded in a special container.
13 Activity discarded in special container.
14 Twenty-seven percent of activity discarded in special container.