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Estimated Inventory of Radionuclides in Former Soviet Union Naval Reactors Dumped in the Kara Sea

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Abstract

Radionuclide inventories have been estimated for the reactor cores, reactor components, and primary system corrosion products in the former Soviet Union naval reactors dumped at the Abrosimov Inlet, Tsivolka Inlet, Stepovoy Inlet, Techeniye Inlet, and Novaya Zemlya Depression sites in the Kara Sea between 1965 and 1988. For the time of disposal, the inventories are estimated at 69 to 111 kCi of actinides plus daughters and 3,053 to 7,472 kCi of fission products in the reactor cores, 917 to 1,127 kCi of activation products in the reactor components, and 1.4 to 1.6 kCi of activation products in the primary system corrosion products. At the present time, the inventories are estimated to have decreased to 23 to 38 kCi of actinides plus daughters and 674 to 708 kCi of fission products in the reactor cores, 124 to 126 kCi of activation products in the reactor components, and 0.16 to 0.17 kCi of activation products in the primary system corrosion products. Twenty years from now, the inventories are projected to be 11 to 18 kCi of actinides plus daughters and 415 to 437 kCi of fission products in the reactor cores, 63.5 to 64 kCi of activation products in the reactor components, and 0.014 to 0.015 kCi of activation products in the primary system corrosion products. All actinide activities are estimated to be within a factor of two.

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ESTIMATED INVENTORY OF RADIONUCLIDES IN FORMER SOVIET UNION NAVAL REACTORS DUMPED IN THE KARA SEA

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In the Spring of 1993, a Russian report, "Facts and Problems Related to Radioactive Waste Disposal in Seas Adjacent to the Territory of the Russian Federation,"[1] was released. The findings presented in this Russian report were the result of a scientific study commissioned by the Office of the President of the Russian Federation and headed by Dr. Alexi V. Yablokov. The Yablokov Commission, as they were later called, reported that 16 naval reactors from seven former Soviet Union submarines and the icebreaker *Lenin*, each of which suffered some form of reactor accident, were dumped at five sites in the Kara Sea. Table 1 presents a summary of their findings for time of disposal.[1] Six of the 16 naval reactors contained their spent nuclear fuel (SNF). In addition, approximately 60% of the SNF from one of the three *Lenin* naval reactors was disposed of in a reinforced concrete container and metal shell. The 100 kCi reported for Tsivolka Inlet, the *Lenin* disposal site, result primarily from the fission products ^{90}Sr and ^{137}Cs. The Yablokov Commission estimates of total radioactivity are 2,300 kCi of fission products in the SNF and 100 kCi of ^{60}Co in the reactor components. With rare exception, no other radionuclides were identified and there was no estimate provided for the current levels of radioactivity.

Table 1. Yablokov Commission findings for the former Soviet Union naval reactors dumped in the Kara Sea.[1]

Disposal Site	Disposal Date	Naval Reactors Discarded[a]	Reactors Containing SNF	Fission Product Activity (kCi)
Abrosimov Inlet	1965	2 (No. 285)	1	800
		2 (No. 901)	2	400
		2 (No. 254)	-	-
	1966	2 (No. 260)	-	-
Tsivolka Inlet	1967	3 (OK-150)	0.6[b]	100
Novaya Zemlya Depression	1972	1 (No. 421)	1	800
Stepovoy Inlet	1981	2 (No. 601)	2	200
Techeniye Inlet	1988	2 (No. 538)	-	-
Total		16	6.6	2,300

a. The entries in this column represent the number of naval reactors discarded and their associated ship or power plant identification number.
b. The SNF was not contained in the naval reactor, but in a reinforced concrete and metal shell.

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

This report presents the results of an independent effort to provide a time-dependent inventory of selected actinides and fission products in the SNF and activation products in the reactor components and primary system corrosion products of the 16 former Soviet Union naval reactors. Each reactor type, fuel load, power, operating history, and associated accident date were required for this estimate. In the case of the icebreaker *Lenin*, the reactor type (pressurized water reactor (PWR)), the ^{235}U enrichment range (4.6 - 6.4%) and fuel load (80, 76, and 129 kg), the average full power (65 MW), the operations period (560,000, 550,000, and 660,000 MW hours), and the number of effective full-power hours (8,600, 8,500, and 10,000 hours) for the three reactors was directly available from Russian sources.[2,3]

Unfortunately, for national security assets such as nuclear powered submarines, core history information like that published on the *Lenin* is virtually impossible to obtain. As such, a method for estimating the necessary reactor core histories had to be developed. Assuming one knows the NATO classification of each submarine whose discarded naval reactors contained SNF, one may use Western estimates of their operating characteristics to derive the required core history information. Among the information required for each submarine is the shaft horsepower; the average and maximum speeds; the propulsion efficiency, which includes both thermal and mechanical conversion; the "hotel" load or total thermal power requirement of the submarine for all electric power and steam loads; the number of reactors; the at-sea time; the core life; and the ^{235}U enrichment.

Based upon Western estimates of the four submarines whose discarded naval reactors contained SNF,[4,5,6] two are believed to be first-generation November and Hotel class submarines with two PWR each, one is believed to be a converted first-generation November class submarine with two liquid metal type reactors, and one is believed to be a second-generation Yankee II class submarine with two PWR. For these November, Hotel, and Yankee II class submarines, the assumed shaft horsepower (32,500, 29,750, and 37,250 hp) and maximum speed (29, 24.5, and 26.75 knots) are the average of the literature values.[7,8,9,10] The average speed at which each submarine was assumed to operate was arbitrarily set at 11 knots. In the case of the propulsion efficiency (15%),[11] "hotel" load (15 MW), at-sea time (120 days/year), and core life (7 years), the values assumed were the range limits or values that would maximize the minimum quantity of U in the reactor fuel load. The value limits on ^{235}U enrichment (10-36%)[12] are a best estimate from the available data. While the lower range limit is considered nominal for first-generation submarines of the November and Hotel class, the inclusion of a Yankee II class submarine requires the assumption of a range in enrichment.

The radionuclide inventory in the SNF was calculated with ORIGEN2,[13] a point (no spatial dependence) depletion personal computer code that has been used extensively to characterize spent nuclear fuel and high level waste. The ORIGEN2 fixed data library used in these estimates is that for a generic PWR fueled with UO_2 enriched to 4.2% in ^{235}U at a burnup of 50,000 MW days per metric tonne of U. A number of factors were considered in the selection of this particular library. First, 14 of the 16 discarded naval reactors are believed to be of the PWR type. Second, since the *Lenin* fuel matrix was described in the Yablokov Commission report as UO_2, it follows that the fuel matrix in first-generation submarine naval reactors built during the same period of time was also very likely UO_2. Third, the lowest ^{235}U enrichment in the *Lenin* reactors was quite close to 4.2%.

The highest ^{235}U enrichment considered for the submarines is substantially greater than 4.2%. One might expect that as the ^{235}U enrichment is increased, there will be a proportional decrease in the production of actinides. This is not the case; as the ^{235}U enrichment is increased, the neutron energy spectrum can be expected to harden or shift toward higher energies. With this shift in neutron spectrum, more resonance absorptions are expected to occur, which, in turn, will lead to a relative increase in the production of actinides. For a ^{235}U enrichment of 36%, the use of ORIGEN2 may result in an underestimate of the actinides by as much as a factor of two. The effect of a ^{235}U enrichment of 36% on the ORIGEN2 fission product estimate is believed to be significantly less. A more accurate estimate of the actinides in the higher enrichment fuels may be calculated with the computer code ORIGEN-S.[14] However, to perform this calculation, one must know either the relative shape and magnitude of the neutron energy spectrum or the composition and dimensions of a reactor fuel assembly or unit cell. With such information not readily available, the limitation in the prediction of the actinide inventory associated with the use of ORIGEN2 was considered acceptable.

To estimate the time-dependent inventory of activation products in the reactor components and primary system corrosion products of the discarded naval reactors, the results of a British calculation for a generic nuclear powered submarine one year after shutdown were used.[15,16]

The maxima and minima in the estimated inventory of radionuclides presented herein were developed through an assessment of the variability of two key parameters: ^{235}U enrichment and time between reactor shutdown and disposal of the SNF. The effect of ^{235}U enrichment on the estimated inventory of radionuclides was evaluated for the *Lenin* and submarine naval reactors in the following way. In the case of the SNF from the *Lenin* naval reactor, the reported range in ^{235}U enrichment was assumed to be associated with a single three-reactor core load. Under a further assumption that the three *Lenin* reactors were loaded with approximately equal quantities of U, the ^{235}U enrichments of 4.6% and 6.4% were associated with the two reactors loaded with 76 and 80 kg of ^{235}U and the one reactor loaded with 129 kg of ^{235}U, respectively. In the case of the six submarine naval reactors containing SNF, the assumed minimum and maximum in ^{235}U enrichment were associated with separate reactor core loads.

The effect of time between reactor shutdown and disposal, or decay time, on the estimated inventory of radionuclides was evaluated by assuming a minimum decay time and a best estimate decay time for each naval reactor and disposal site. With the exception of the two naval reactors that were discarded in Stepovoy Inlet in 1981, the minimum decay times were based on the Yablokov Commission finding of a minimum period of one year between reactor shutdown and disposal. The two naval reactors discarded in Stepovoy Inlet were identified with a November class submarine that suffered a reactor accident in 1968. As such, their minimum decay times were established at 13 years.

The best estimate decay time for those discarded naval reactors with SNF was assumed to be the time period, in whole years, between the reactor accident date, deduced from Western estimates,[4,5,6] and its associated disposal date. For those discarded naval reactors without SNF, the best estimate decay time was arbitrarily established at one year. In the case of the *Lenin*, whose reactor accident was reported to have occurred either early or late in 1966, the best estimate decay time was established at two years.

For the time of disposal, the inventories are estimated at 17 to 66 kCi of actinides plus daughters and 1,695 to 4,782 kCi of fission products in the SNF, 917 to 1,127 kCi of activation products in the reactor components, and 1.4 to 1.6 kCi of activation products in the primary system corrosion products. Our estimate of 1,695 to 4,782 kCi of fission products compares favorably with the Yablokov Commission finding of 2,300 kCi of fission products. Of the 917 to 1,127 kCi of activation products in the reactor components, 161 to 184 kCi are associated with the ^{60}Co inventory in the 16 discarded naval reactors. On a per-reactor basis, the estimated ^{60}Co inventory in the reactor components is in excellent agreement with the Yablokov Commission finding of 100 kCi in the reactor components of ten naval reactors. With respect to the selected actinides and fission products, the disposal sites in order of greatest total activity are Tsivolka Inlet, the location of the *Lenin* remnants, and Abrosimov Inlet. For the activation product inventories in the reactor component and primary system corrosion products, the disposal sites in order of greatest total activity are Abrosimov Inlet and Tsivolka Inlet. Since the radioactivity in the reactor components and primary system corrosion products at a given disposal site is simply a function of the number of reactors discarded, it follows that Abrosimov Inlet should be the site of greatest activity.

Table 2 presents a summary of the estimated radioactivity in the SNF at the present time (1993). Summarized for each of the selected actinides and fission products are the minimum and maximum in radioactivity associated with the five disposal sites. With respect to the selected actinides, the radionuclide and disposal site with the greatest activity remain ^{241}Pu and Tsivolka Inlet, respectively. With respect to the selected fission products, the radionuclides in order of greatest activity are now ^{137}Cs and ^{90}Sr. The disposal sites in order of greatest total activity are now Abrosimov Inlet and Stepovoy Inlet. Overall, the inventories are estimated at 6 to 24 kCi of actinides plus daughters and 492 to 540 kCi of fission products.

Table 3 presents a summary of the estimated radioactivity for selected activation products in reactor components and primary system corrosion products at the present time (1993). Summarized for each of the selected activation products are the minimum and maximum in radioactivity associated with the five disposal sites. With respect to the reactor components, the radionuclides with greatest activity are ^{63}Ni at Abrosimov Inlet and ^{55}Fe at Techeniye Inlet, while the disposal site of greatest activity is now Techeniye Inlet. With respect to the primary system corrosion products, the radionuclide and disposal site with greatest activity are ^{60}Co and Techeniye Inlet, respectively. That Abrosimov Inlet is no longer the site of greatest activity is not surprising. While the radioactivity in the reactor components and primary system corrosion products at a given disposal site remains a simple function of the number of reactors discarded, when radioactive decay of the activation products is considered, Techeniye Inlet becomes the expected site of greatest activity. Overall, the inventories are estimated at 125 to 126 kCi of activation products in the reactor components and 0.16 to 0.17 kCi of activation products in the primary system corrosion products.

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Table 2. Estimated radioactivity in the SNF at the present time (1993) for the former Soviet Union naval reactors dumped in the Kara Sea.

Nuclide	Disposal site activity range (Ci)											
	Abrosimov Inlet		Tsivolka Inlet		Novaya Zemlya Depression		Stepovoy Inlet		Techeniye Inlet		All sites	
Actinides												
$^{239+240}Pu$	94	474	343	374	33	167	55	280	--	--	526	1,295
^{241}Am	14	605	412	688	5	204	6	277	--	--	436	1,774
^{238}Pu	18	258	102	148	7	105	9	123	--	--	136	634
^{241}Pu	117	5,710	4,450	7,690	61	2,990	79	3,510	--	--	4,707	19,900
Subtotal	243	7,047	5,307	8,900	106	3,466	149	4,190	--	--	5,805	23,603
All	247	7,050	5,310	8,900	108	3,466	152	4,190	--	--	5,817	23,606
Fission Products												
^{129}I	0.02	0.03	0.01	0.01	0.009	0.009	0.01	0.02	--	--	0.06	0.06
^{90}Sr	46,200	51,400	18,500	23,700	19,000	21,400	32,100	33,400	--	--	115,800	129,900
^{134}Cs	0.3	3	2	3	1	12	2	6	--	--	5	23
^{137}Cs	51,300	54,600	21,900	26,800	21,100	22,600	35,400	35,400	--	--	129,700	139,400
^{154}Eu	152	190	87	116	98	125	132	132	--	--	469	563
^{125}Sb	2	6	5	6	4	12	7	9	--	--	18	33
^{147}Pm	63	155	72	119	128	345	225	365	--	--	488	984
^{155}Eu	31	49	27	33	28	45	47	51	--	--	133	178
^{99}Tc	15	15	6	7	5	5	9	9	--	--	34	36
^{151}Sm	686	1,360	271	380	244	496	468	866	--	--	1,669	3,102
Subtotal	98,449	107,777	40,869	51,164	40,608	45,040	68,389	70,238	--	--	248,316	274,220
All	195,000	213,000	80,900	101,000	80,500	86,700	136,000	139,000	--	--	492,400	539,700

Table 3. **Estimated radioactivity of selected activation products in the reactor components and primary system corrosion products at the present time (1993) for the former Soviet Union naval reactors dumped in the Kara Sea.**

Nuclide	Disposal site activity range (Ci)											
	Abrosimov Inlet		Tsivolka Inlet		Novaya Zemlya Depression		Stepovoy Inlet		Techeniye Inlet		All sites	
Reactor Components												
^{60}Co	2,297	2,654	1,100	1,250	542	804	1,080	1,080	13,200	13,200	18,219	18,988
^{14}C	91	91	34	34	11	11	23	23	23	23	182	182
^{63}Ni	34,140	34,420	13,000	13,100	4,420	4,510	8,480	8,480	10,100	10,100	70,140	70,610
^{55}Fe	336	429	193	249	138	296	276	276	34,300	34,300	35,243	35,550
^{59}Ni	374	374	140	140	47	47	94	94	94	94	749	749
All	37,238	37,968	14,467	14,773	5,158	5,668	9,953	9,953	57,717	57,717	124,533	126,079
Primary System Corrosion Products												
^{60}Co	20	23	9	11	5	7	9	9	113	113	156	162
^{14}C	0.0001	0.0001	0.00005	0.00005	0.00002	0.00002	0.00003	0.00003	0.00003	0.00003	0.0002	0.0002
^{63}Ni	1.7	1.7	0.6	0.7	0.2	0.2	0.4	0.4	0.5	0.5	3.5	3.5
^{55}Fe	0.01	0.01	0.006	0.008	0.004	0.009	0.009	0.009	1.1	1.1	1.1	1.1
^{59}Ni	0.01	0.01	0.004	0.004	0.001	0.001	0.003	0.003	0.003	0.003	0.02	0.02
All	21	24	10	11	5	7	10	10	115	115	161	167

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Yablokov Commission Findings[1]

Nuclear remnants of seven submarines and the icebreaker Lenin have been dumped in the Kara Sea

Site	Disposal Date	Naval Reactors	Reactor Cores	Activity* (kCi)
Abrosimov Inlet	1965	2 (No. 285)	1.0	800
		2 (No. 901)	2.0	400
		2 (No. 254)	-	-
	1966	2 (No. 260)	-	-
Tsivolka Inlet	1967	3 (OK-150)	0.6	100
Novaya Zemlya Depression	1972	1 (No. 421)	1.0	800
Stepovoy Inlet	1981	2 (No. 601	2.0	200
Techeniye Inlet	1988	2 (No. 538)	-	-
TOTAL		16	6.6	2,300

*Fission products only

Submarine Identification[2,3]

The seven submarines whose nuclear remnants were dumped in the Kara Sea have been identified.

Submarine	Class	Accident Date
K-3	November	June 1962
		September 8, 1967
K-5	Hotel/November	Mid 1960's
K-11	November	Feb 12, 1965
K-19	November	July 4, 1961
K-22	Hotel	
K-27	November	May 24, 1968
K-140	Yankee II	Aug 23, 1968

Association of the Dumped Reactor Cores with Submarine Class

Based upon information currently available, a specific submarine and submarine class has been assigned to each nuclear submarine core that was dumped in the Kara Sea.

Disposal Date	Reactor Cores	Submarine	Class
1965	1 (No. 285)	K-3	November
	2 (No. 901)	K-19	Hotel
1972	1 (No. 421)	K-140	Yankee II
1981	2 (No. 601)	K-27	November

Reactor Core Information for the Icebreaker Lenin[4,5]

The Lenin had three reactors and was last refueled in 1963.

No. of Assemblies per Reactor: 219 ^{235}U Enrichment: 4.6% to 6.4%

Core Histories

^{235}U Loading (kg)	Operation (MW hours)	Effective Full Power Hours
80	560,000	8,600
76	550,000	8,500
129	660,000	10,000

Reactor Core Information for the Submarines

Open literature information on the core histories of FSU submarines is difficult to obtain.

Estimates of the reactor fuel load can be made from the power requirements of the submarine. For a submarine to operate at a given speed, S_i, the power requirement, P_i, in MWs, is given by:

$$P_i = SHP\left(CF_1\right)\left(\frac{S_i}{S_{max}}\right)^3$$

where,

SHP = shaft horsepower, hp, and

$CF_1 = 0.7457 \times 10^{-3}$ MW/hp.

Reactor Core Information for the Submarines (cont'd)

The overall power requirement of the reactor, P_R, in MWs, is given by:

$$P_R = \frac{\left(\frac{P_i}{PE}\right) + HL}{N_R}$$

where,

PE = propulsion efficiency,

HL = "hotel" load requirements, MW, and

N_R = numbers of reactors.

Reactor Core Information for the Submarines (cont'd)

The minimum quantity of ^{235}U required to power the submarine for a specific duration, $^{235}UL_{min}$, in grams, is given by:

$$^{235}UL_{min} = CF_2(P_R)(AST)(CL)$$

where,

CF_2 = 1.24 grams ^{235}U/MWd,

AST = at sea time, d/y, and

CL = core life, y.

Reactor Core Information for the Submarines (cont'd)

The minimum quantity of U in the submarine reactor fuel load, UL_{min}, in grams, is given by:

$$UL_{min} = \left(\frac{{}^{235}UL_{min}}{E_U} \right)$$

where,

E_U = enrichment of ^{235}U

Basic Data Used to Estimate the Submarine Minimum Reactor Fuel Load

Parameter	Range	Value Assumed
November Class SHP (10^3hp)[6,7]	30.0 - 35.0	32.5
Hotel Class SHP (10^3hp)[7,8]	29.5 - 30.0	29.75
Yankee II Class SHP (10^3hp)[6,7,9]	29.5 - 45.0	37.25
November Class S_{max} (kt)[6,7]	28 - 30	29
Hotel Class S_{max} (kt)[7,8]	23 - 26	24.5
Yankee II Class S_{max} (kt)[6,7,9]	26.5 - 27	26.75
Propulsion efficiency, PE, (%)[10]	15 - 20	15
"Hotel" load, HL, (MW)	12 - 15	15
Number of reactors, N_R[7,8,9]	2	2
At sea time, AST, (d/y)	120	120
Core life, CL, (y)	5 - 7	7
^{235}U enrichment, E_U, (%)[11]	10 - 36	10 - 36

Reactor Core Radionuclide Inventory Prediction

Radionuclide inventories in the reactor cores were calculated with ORIGEN2,[12] a point (no spatial dependence) depletion personal computer code that has been used extensively to characterize spent reactor fuel and high-level waste.

The fixed data library used in these estimates is that for generic PWR fueled with UO_2 enriched to 4.2% in ^{235}U at a burnup of 50,000 MWd/MTU.

Use of this library for fuels enriched to 36% in ^{235}U may cause the transuranics to be underestimated by as much as a factor of two.

More accurate calculations may be performed with ORIGEN-S[13] when definitive information on the reactor neutron energy spectrum or materials of construction and geometry of a fuel assembly or unit cell becomes available.

Reactor Component and Primary System Corrosion Product Radionuclide Inventory Prediction[14]

Activation of reactor components such as the core support structure, pressure vessel, and shielding and in the primary system corrosion products are estimated from results of a British calculation for a generic submarine one year after shutdown.[15]

Nuclide	Half-life (y)	Reactor Components (Ci)	Primary System Corrosion (Ci)
^{60}Co	5.27	1.27×10^{4}	1.09×10^{2}
^{14}C	5,730	1.14×10^{1}	1.57×10^{-5}
^{63}Ni	100.1	5.22×10^{3}	2.61×10^{-1}
^{55}Fe	2.73	6.11×10^{4}	1.94×10^{0}
^{59}Ni	75,000	4.68×10^{1}	1.37×10^{-3}
TOTAL		7.91×10^{4}	1.11×10^{2}

Variability of Radionuclide Inventory with Respect to ^{235}U Enrichment in the Submarine Fuel and Decay Time at Disposal

To assess the variability of the radionuclide inventory with respect to ^{235}U enrichment in the submarine fuel, 10% and 36% enrichments in ^{235}U were assumed.

To assess the variability of the radionuclide inventory with respect to decay time at disposal, a minimum decay time and best estimate decay time was assumed for each site. The following summarizes the assumed periods of decay.

Site	Disposal Date	Naval Reactors	Minimum Decay (y)	Best Decay (y)
Abrosimov Inlet	1965	2 (No. 285)	1.0	3.0
		2 (No. 901)	1.0	4.0
		2 (No. 254)	1.0	1.0
	1966	2 (No. 260)	1.0	1.0
Tsivolka Inlet	1967	3 (OK-150)	1.0	2.0
Novaya Zemlya Depression	1972	1 (No. 421)	1.0	4.0
Stepovoy Inlet	1981	2 (No. 601)	13.0	13.0
Techeniye Inlet	1988	2 (No. 538)	1.0	1.0

Estimated Total Activity (Ci)

Reference time: Time of Disposal

SITE	Reactor Cores Actinides	Reactor Cores Fission Products	Reactor Components	Primary System Corrosion Products
Abrosimov Inlet	573 - 23,100	663,000 - 2,300,000	503,966 - 632,066	762 - 886
Tsivolka Inlet	16,100 - 27,800	632,000 - 1,480,000	191,174 - 236,974	291 - 333
Novaya Żemlya Depression	212 - 8,640	213,000 - 811,000	42,248 - 79,078	74 - 111
Stepovoy Inlet	212 - 6,860	187,000 - 191,000	20,777	45
Techeniye Inlet			158,017	221
TOTAL	17,097 - 66,400	1,695,000 - 4,782,000	916,182 - 1,126,912	1,394 - 1,596
Yablokov Commission		2,300,000	1,000,000	

Estimated Activity (Ci) for Selected Actinides

Reference time: Present (1993)

SITE	NUCLIDE			
	$^{239+240}Pu$	^{241}Am	^{238}Pu	^{241}Pu
Abrosimov Inlet	94 - 474	14 - 605	18 - 258	117 - 5,710
Tsivolka Inlet	343 - 374	412 - 688	102 - 148	4,450 - 7,690
Novaya Zemlya Depression	33 - 167	5 - 204	7 - 105	61 - 2,990
Stepovoy Inlet	55 - 280	6 - 277	9 - 123	79 - 3,510
Techeniye Inlet				
TOTAL	526 - 1,295	436 - 1,774	136 - 634	4,707 - 19,900

Estimated Activity (Ci) for Selected Long-Lived Fission Products

Reference time: Present (1993)

SITE	NUCLIDE		
	^{129}I	^{90}Sr	^{134}Cs
Abrosimov Inlet	<0.02 - <0.03	46,200 - 51,400	<0.3 - 3
Tsivolka Inlet	<0.01 - <0.01	18,500 - 23,700	2 - 3
Novaya Zemlya Depression	<0.009 - <0.009	19,000 - 21,400	1 - 12
Stepovoy Inlet	<0.01 - <0.02	32,100 - 33,400	2 - 6
Techeniye Inlet			
TOTAL	<0.06 - <0.06	115,800 - 129,900	5 - 23

Estimated Activity (Ci) for Selected Long-Lived Fission Products

Reference time: Present (1993)

SITE	NUCLIDE		
	^{137}Cs	^{154}Eu	^{125}Sb
Abrosimov Inlet	51,300 - 54,600	152 - 190	2 - 6
Tsivolka Inlet	21,900 - 26,800	87 - 116	5 - 6
Novaya Zemlya Depression	21,100 - 22,600	98 - 125	4 - 12
Stepovoy Inlet	35,400	132	7 - 9
Techeniye Inlet			
TOTAL	129,700 - 139,400	469 - 563	18 - 33

Estimated Activity (Ci) for Selected Long-Lived Fission Products

Reference time: Present (1993)

SITE	NUCLIDE			
	^{147}Pm	^{155}Eu	^{99}Tc	^{151}Sm
Abrosimov Inlet	63 - 155	31 - 49	15	686 - 1,360
Tsivolka Inlet	72 - 119	27 - 33	6 - 7	271 - 380
Novaya Zemlya Depression	128 - 345	28 - 45	5	244 - 496
Stepovoy Inlet	225 - 365	47 - 51	9	468 - 866
Techeniye Inlet				
TOTAL	488 - 984	133 - 178	34 - 36	1,669 - 3,102

Estimated Activity (Ci) for Selected Activation Products in Reactor Components

Reference time: Present (1993)

SITE	NUCLIDE		
	^{60}Co	^{14}C	^{63}Ni
Abrosimov Inlet	2,297 - 2,654	91	34,140 - 34,420
Tsivolka Inlet	1,100 - 1,250	34	13,000 - 13,100
Novaya Zemlya Depression	542 - 804	11	4,420 - 4,510
Stepovoy Inlet	1,080	23	8,480
Techeniye Inlet	13,200	23	10,100
TOTAL	18,219 - 18,988	182	70,140 - 70,610

Estimated Activity (Ci) for Selected Activation Products in Reactor Components

Reference time: Present (1993)

SITE	NUCLIDE	
	^{55}Fe	^{59}Ni
Abrosimov Inlet	336 - 429	374
Tsivolka Inlet	193 - 249	140
Novaya Zemlya Depression	138 - 296	47
Stepovoy Inlet	276	94
Techeniye Inlet	34,300	94
TOTAL	35,243 - 35,550	749

Estimated Total Activity (Ci)

Reference time: Present (1993)

SITE	Reactor Cores		Reactor Components	Primary System Corrosion Products
	Actinides	Fission Products		
Abrosimov Inlet	247 - 7,050	195,000 - 213,000	37,238 - 37,968	21 - 24
Tsivolka Inlet	5,310 - 8,900	80,900 - 101,000	14,467 - 14,773	10 - 11
Novaya Zemlya Depression	108 - 3,466	80,500 - 86,700	5,158 - 5,668	5 - 7
Stepovoy Inlet	152 - 4,190	136,000 - 139,000	9,953	10
Techeniye Inlet			57,717	115
TOTAL	5,817 - 23,606	492,400 - 539,700	124,533 - 126,079	161 - 167

To Refine the Predictions

The decay period between the shutdown of each reactor and the time of its disposal needs to be better defined.

Activation of the materials in the cladding and fuel assembly hardware need to be included. Quantities and elemental compositions are required.

The neutron energy spectra for the reactors need to be defined.

The assumed submarine reactor core history information needs to be validated.

The radionuclide inventories need to be recalculated with ORIGEN-S[13] to decrease the uncertainties associated with the underestimate of the transuranics by ORIGEN2[12] for highly enriched fuel.

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