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ABSTRACT

Between 1965 and 1988, 16 marine reactors from seven Russian submarines and the icebreaker *Lenin*, each of which suffered some form of reactor accident, were dumped in a variety of containments, using a number of sealing methods, at five sites in the Kara Sea. All reactors were dumped at sites that varied in depth from 12 to 300 m and six contained their spent nuclear fuel (SNF).

This paper examines the breakdown of the reactor pressure vessel (RPV) barriers due to corrosion, with specific emphasis on those RPVs containing SNF. Included are discussions of the structural aspects of the steam generating installations and their associated RPVs, a summary of the disposal operations, assumptions on corrosion rates of structural and filler materials, and an estimate of the structural integrity of the RPVs at the present time (1996) and in the year 2015.

INTRODUCTION

In 1991, the first reports began to appear on Russia's long-running high-level radioactive waste disposal operations in the Arctic region. In the Spring of 1993, Russia released a summary of the liquid and solid radioactive waste disposal operations, *Facts and Problems Related to Radioactive Waste Disposal in Seas Adjacent to the Territory of the Russian Federation* (Office of the President of the Russian Federation, 1993). The *White Book*, as this report was later called, revealed that 16 marine reactors from seven Russian submarines and the icebreaker *Lenin* were dumped at five sites in the Kara Sea, an arm of the Arctic Ocean located east of Novaya Zemlya. Six of the submarine RPVs still contained their spent nuclear fuel (SNF). Fig. 1 shows a map of Novaya Zemlya with the approximate locations of the five disposal sites. Table 1 presents a summary of pertinent disposal information for all marine reactors dumped in the Kara Sea.

The focus of the work reported here is the breakdown of the reactor pressure vessel (RPV) barriers due to corrosion, with specific emphasis on those RPVs containing SNF, i.e., submarine factory numbers 901, 285, 421, and 601. A complete discussion of the marine reactor disposal operations and their impact on radionuclide release to the shallow waters of the Kara Sea may be found in Mount et al. (March 1997).

In all cases the dumped reactors, generally known as steam generating installations (SGIs), were taken out of service owing to possible or actual core damage after an accident. The *White Book* referred to each SGI solely by the hull factory number used during construction. Nilsen et al. (1996) correlated factory number with submarine type, allowing identification of the submarine and the accident resulting in reactor disposal. For background—and to understand the severity of the accidents associated with those RPVs containing SNF—Table 2 describes the dumped units and accidents.

CHARACTERISTICS OF THE PRESSURIZED WATER REACTOR STEAM GENERATING INSTALLATIONS (SIVINTSEV, 1994, 1995b, 1995c)

Each nuclear submarine contained two reactors. Four of the six reactors containing SNF were of the pressurized water reactor (PWR) type and were from submarine factory numbers 901, 285, and 421. Specific information about the SGIs associated with the four discarded PWRs remains classified. Generally, the entire SGI, including the steam generators (SGs) and circulation pumps, was located aft of the submarine sail in an isolated reactor compartment (RC). The two PWRs were aligned vertically, either in a plane perpendicular to the keel or along the keel, and were surrounded by a water-filled steel shield tank. Biological shields were located above the shield tank and around each PWR; however, the specifics of their construction materials are unavailable.

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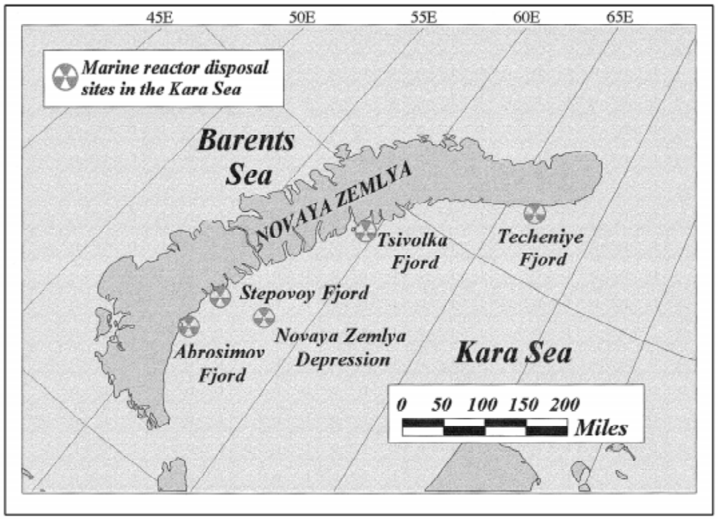

FIGURE 1. APPROXIMATE LOCATIONS OF THE MARINE REACTOR DISPOSAL SITES IN THE KARA SEA.

TABLE 1. PERTINENT DISPOSAL INFORMATION FOR THE MARINE REACTORS DUMPED IN THE KARA SEA.

Disposal site	Year of disposal	Factory number	Dumped unit	Disposal coordinates[1]	Disposal depth[2] (m)	Number of reactors	
						Without spent nuclear fuel	With spent nuclear fuel
Abrosimov Fjord	1965	901	Reactor compartment	71° 56.03' N 55° 18.15' E	20 (10-15)	-	2
		285	Reactor compartment	71° 56.03' N 55° 18.08' E	20 (10-15)	1	1
		254	Reactor compartment	71° 55.22' N 55° 32.54' E	20	2	-
	1966	260	Reactor compartment	71° 56.03' N 55° 18.08' E	20	2	-
Tsivolka Fjord	1967	OK-150	Reactor compartment	74° 26.10' N 58° 36.15' E	50	3	-
Novaya Zemlya Depression	1972	421	Reactor	72° 40' N 58° 10' E	300	-	1
Stepovoy Fjord	1981	601	Submarine	72° 31.25' N 55° 30.25' E	50 (30)	-	2
Techeniye Fjord	1988	538	Reactors	73° 59' N 66° 18' E	35-40	2	-
Total						10	6

1 Disposal site coordinates for all units except those from factory number OK-150 are from the *White Book* (Office of the President of the Russian Federation, 1993). Disposal site coordinates for the OK-150 units are from Sivintsev (September 1995).

2 The disposal depths were provided in May 1993 by the Russian Federation; those in parenthesis were obtained during joint Norwegian-Russian scientific cruises in 1993 and 1994.

TABLE 2. SUMMARY OF REACTOR ACCIDENTS LEADING TO DISPOSAL OF REACTOR CORES CONTAINING SPENT NUCLEAR FUEL (GILTSOV et al., 1992; OLGAARD, 1993; NILSEN et al., 1996)

Factory number	NATO classification and hull number	Remarks
901	Hotel K-19	The submarine was on patrol in the North Atlantic in June 1961. Primary pipework ruptured, leading to a loss of primary coolant and core damage. The crew prevented further core damage and probable meltdown by assembling a core cooling system from the drinking water supply. The RC[1] was subsequently removed.
285	November K-11	An accident occurred during refueling in February 1965 which led to an uncontrolled chain reaction and fire. The RC was badly damaged and was cut out of the submarine.
421	Yankee II K-140	An accident occurred in August 1968 which led to overpressurization of the primary circuit. Core damage was suspected, so the RC was cut out and the right board RPV[2] removed for disposal.
601	Mod November K-27	This was an experimental LMR[3] powered vessel. A secondary to primary leak in the left board reactor led to fuel channel blockage and core damage, following which an estimated 20% of the fuel pins were transported to the SGs[4].

1 Reactor compartment (RC).
2 Reactor pressure vessel (RPV).
3 Liquid metal reactor (LMR).
4 Steam generators (SGs)

Each nuclear submarine PWR consisted of a cylindrical steel RPV, a reactor core and its associated support structure, and a series of radial and bottom thermal shields, the latter being employed to reduce heat and radiation effects on the RPV and subsequently extend its operating life. For submarine factory numbers 901 and 285, the RPVs were made from type 15Х2МФА carbon steel, with approximate dimensions:

(1) 1.4-m diameter,

(2) 3.7-m height,

(3) 120-mm thick walls with a 6-mm thick internal cladding of type 1Х18Н9Т stainless steel (SS),

(4) 310-mm thick bottom with a 5-mm thick internal cladding of type 1Х18Н9Т SS, and

(5) 400-mm thick lid.

Figure 2 shows the cross section of an RPV of the type used in submarine factory numbers 901 and 285 (Sivintsev, August 1994).

For submarine factory number 421, the RPVs were made from a variety of carbon steels, with approximate dimensions:

(1) 2-m diameter,

(2) 3.4-m height,

(3) 120-mm thick walls of type 15Х2МФА−А carbon steel with a 7.5-mm thick internal cladding of SS,

(4) 110-mm thick bottom of type 12Х2МФА−А carbon steel with a 7.5-mm thick cladding of SS, and

(5) 390-mm thick lid of 25Х2МФА carbon steel.

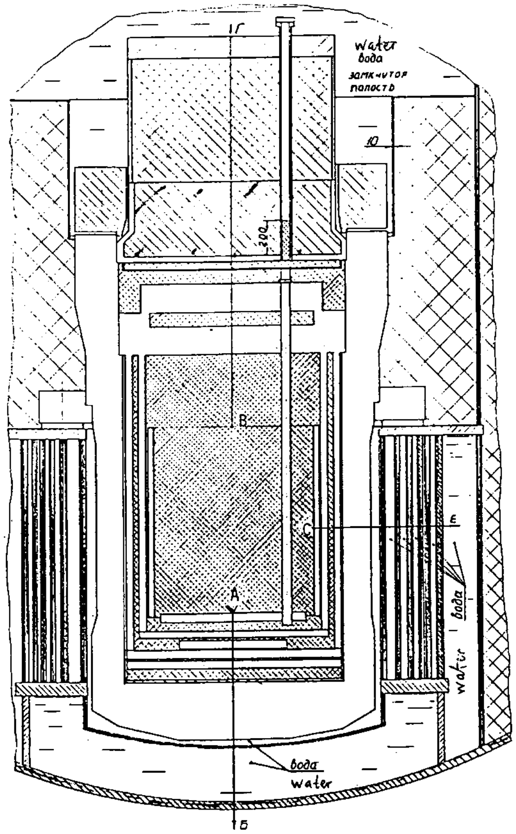

FIGURE 2. CROSS SECTION OF A REACTOR PRESSURE VESSEL OF THE TYPE USED IN SUBMARINE FACTORY NUMBERS 901 AND 285.

Figure 3 shows the cross section of an RPV of the type used in submarine factory number 421 (Sivintsev, August 1994).

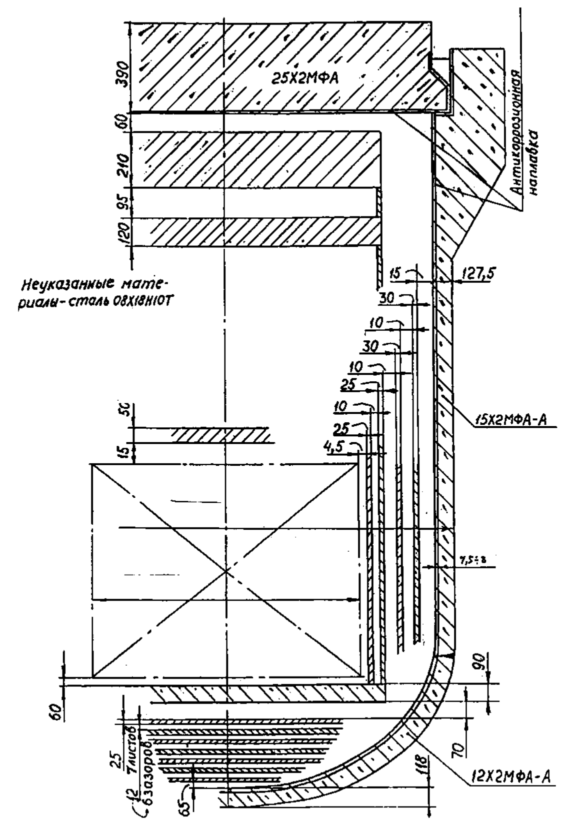

FIGURE 3. CROSS SECTION OF A REACTOR PRESSURE VESSEL OF THE TYPE USED IN SUBMARINE FACTORY NUMBER 421.

CHARACTERISTICS OF THE LIQUID METAL REACTOR STEAM GENERATING INSTALLATIONS (YEFIMOV, 1994, 1995)

The two remaining reactors containing SNF were of the liquid metal reactor (LMR) type and were within submarine factory number 601. The entire SGI, including the SGs, circulation pumps, and primary circuit volume compensators, was located aft of the submarine sail in an isolated RC. The two LMRs were aligned vertically in a plane perpendicular to the keel and were surrounded by a lead-water tank shield. The SGs, circulation pumps, and primary circuit volume compensators were enclosed in lead-lined structures. A lead-bismuth (Pb-Bi) eutectic served as the heat transfer medium (coolant).

Each LMR also consisted of a cylindrical RPV, a reactor core and its associated support structure, and a series of radial and bottom thermal shields. The RPV was made from SS, with approximate dimensions:

(1) 1.8-m diameter,
(2) 3.7-m height, and
(3) 30-mm thick walls.

External to the outer surface of the RPV were two cylindrical channel regions of 30 mm each that were formed through the addition of two concentric cylindrical SS shells of 10 mm and 20 mm, respectively. Figure 4 shows the cross section of an RPV of the type used in submarine factory number 601 (Yefimov, 1994). Cross sections for control or compensation rod (CCR) and emergency protection rod (EPR) channels of the type used in submarine factory number 601 are shown in Fig. 5 (Yefimov, 1994).

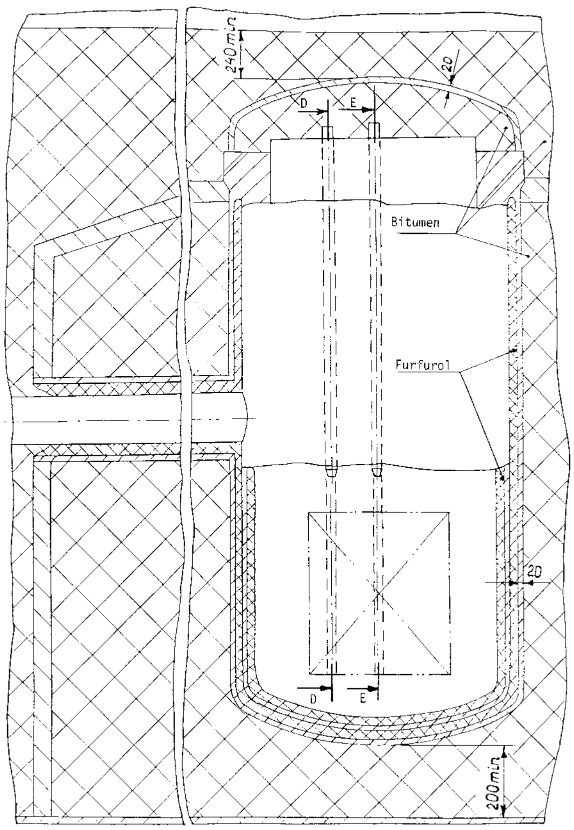

FIGURE 4. CROSS SECTION OF A REACTOR PRESSURE VESSEL OF THE TYPE USED IN SUBMARINE FACTORY NUMBER 601.

PRESSURIZED WATER REACTOR DISPOSAL OPERATIONS (SIVINTSEV, 1994, 1995a, 1995b, 1995c)

With the exception of the right board RPV from submarine factory number 421, all PWRs containing SNF were dumped in their separated RCs. The SNF was removed from the left board RPV of submarine factory number 285. The SNF remained in the right board RPV of submarine factory number 285, the right board RPV of submarine factory number 421, and both RPVs of submarine factory number 901.

Before disposal, the primary circuit loops and equipment of all PWRs were washed, dried, and sealed. However, there is no indication that the seals were hermetic. Those RPVs containing SNF were filled with Furfurol(F), an organic hardening compound based on furfural, prior to disposal. Before filling each RPV with Furfurol(F), the 30 CCR guide tubes were sealed and a 10-mm diameter breather hole was drilled through the upper wall of two. During filling, the RPV was heated, one breather hole was used as the inlet, and one breather hole was used as the outlet. Once the process was completed, each 10-mm diameter breather hole was capped with a 2.5-mm thick weld.

The shallow waters of Abrosimov Fjord were used for four separate disposal operations. Of those four, two were separated RCs from submarine factory numbers 901 and 285 which were dumped in 1965 at estimated depths of 50 m (Sivintsev, September 1995) and 20 m (Office of the President of the Russian Federation, 1993; Sivintsev, September 1995), respectively.

At the time of disposal, the RCs were allowed to flood, thereby exposing a significant portion of the external surface of each RPV and the cavities and internal constructions of those RPVs without SNF to sea water. As such, sea water is assumed to have been within the left board RPV of submarine factory number 285 for more than 30 years.

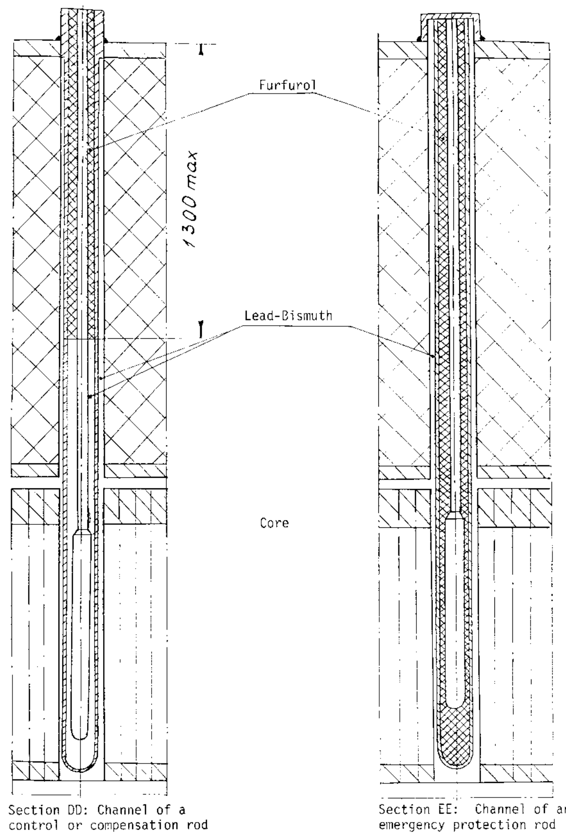

FIGURE 5. CROSS SECTION FOR CONTROL OR COMPENSATION ROD AND EMERGENCY PROTECTION ROD CHANNELS OF THE TYPE USED IN SUBMARINE FACTORY NUMBER 601.

The right board RPV, with its SNF, was removed from the RC of submarine factory number 421, placed into a steel collar-like support structure within the hull of a barge, and covered with concrete. The concrete layer above the RPV lid was about 200-mm thick. The concrete between the outer surface of the RPV wall and the inner surface of the barge hull was no less than 800-m thick.

In 1972, the barge containing the right board RPV of submarine factory number 421 was dumped in the Novaya Zemlya Depression at an estimated depth of 300 m (Office of the President of the Russian Federation, 1993; Sivintsev, September 1995).

LIQUID METAL REACTOR DISPOSAL OPERATIONS (SIVINTSEV, DECEMBER 1995; YEFIMOV, 1994, 1995)

The SNF remained in the two LMRs of submarine factory number 601. Before disposal, a number of actions were taken. The following is a summary of those actions:

(1) solidified Pb-Bi was removed from all sections of the undamaged right board reactor primary circuit except the RPV;
(2) solidified Pb-Bi remained in all sections of the damaged left board reactor primary circuit;
(3) control rods were permanently fixed in the cores, their drive mechanisms were removed, and the upper ends above the reactor lids were cut away;
(4) channels containing the CCRs were filled with Furfurol(F) in the regions above the Pb-Bi;
(5) channels containing the EPRs were filled with Furfurol(F) in their entirety and sealed by welding steel covers to the upper surface of the reactor lids;
(6) cylindrical channel regions external to the RPV that were formed through the addition of two concentric cylindrical steel shells were filled with Furfurol(F);
(7) SGs of the damaged left board reactor were filled with Furfurol(F) via the secondary circuit;
(8) 20-mm thick elliptic covers were welded to the top of each reactor lid and the volumes between the covers and lids, a maximum of 490-mm thick, filled with bitumen; and
(9) the volumes of the structures containing the SGs, circulation pumps, and volume compensators, the tank of the lead-water shield, and the RC to a level of 240 mm above the elliptic covers were filled with bitumen.

Overall, some 2m^3 of Furfurol(F) and 250m^3 of bitumen were used to prepare the RC for disposal.

In September 1981, over 13 years after the reactor accident, submarine factory number 601 was sunk in the shallow waters of Stepovoy Fjord at an estimated depth of 50 m (Office of the President of the Russian Federation, 1993). At the time of her sinking, the hatches of the RC were open. As such, sea water has been in the compartment above the bitumen filler for over 15 years.

CORROSION RATES OF STRUCTURAL MATERIALS AND EFFECTIVE LIFETIMES OF FILLER MATERIALS

Estimates of the structural integrity of the RPVs containing SNF rely heavily upon corrosion rates of the containment and effective lifetimes of the barrier materials in the dumped SGIs. Such materials include the metals used in their original fabrication, and fillers applied prior to dumping to inhibit metallic corrosion and provide additional barriers to activity release into the sea.

Factors affecting the lifetime of materials exposed to sea water include dissolved oxygen, temperature, pH, salinity, sulfates, pressure, marine life (biofouling), and water flow. Heiser and Soo (July 1995) provide a detailed review of the influence of these factors on a range of materials, with data derived from analysis of dump sites in the Atlantic and Pacific. However, little data is available on the behavior of materials in relatively shallow Arctic waters. To derive corrosion rates, comprehensive reviews of available source references were made, with notable contributions from Carter (May 1994) and Heiser and Soo (July 1995).

In all cases, realistic but conservative values of material corrosion rates were determined; their values are summarized in Table 3. The rates lie towards the high end of recorded data in order to err towards the pessimistic side of the spectrum. For estimating purposes, corrosion rates established in this way are designated best corrosion rates (BCRs) and filler lifetimes.

Not surprisingly, much greater data is available on the performance of steels in sea water than any other material. The range of values, however, is wide, and related to the factors cited earlier. Applying the BCR principle detailed above, realistic but conservative corrosion rates were determined for long-term immersion in sea water under two distinct mechanisms: bulk corrosion and pitting corrosion, with the latter applied under conditions of high stress in the heat-affected zones of welded areas. As can be seen from Table 3, two types of steel were assumed for simplicity: SS for specific SGI components and mild steel (low alloy and/or carbon steels) for RPVs and the submarine structure. To account for the possible accelerating effect of biofouling, corrosion rates were doubled for steels with outside surfaces fully exposed to the sea.

Little information is available about the long-term behavior of the filler substances when immersed in sea water and under irradiation. Bitumen is known to become brittle and crack below room temperature. As Furfurol(F) is a patented Russian material, information about its composition and behavior was not readily available, and long-term behavior is, in any case, difficult to predict. It is known to be a mixture of the following constituents: epoxy resin, amine type solidifier, mineral filler, shale distillate and furfuryl alcohol (Alexandrov and Sivintsev, 1995). An effective lifetime of 500 years is quoted in the *White Book* (Office of the President of the Russian Federation, 1993) for this material.

In the absence of reliable data on the performance of Furfurol(F) and bitumen in such environmental conditions, a conservative lifetime of 100 years in the radiation environment is assumed in the estimates and this was supported for Furfurol(F) by a preliminary evaluation (Alexandrov and Sivintsev, 1996). Hence for the estimation of structural integrity, it was assumed that at the time of disposal, the fillers were fully effective as barriers to water ingress, but quickly began to degrade through shrinkage, embrittlement, and cracking and became ineffective after the 100 year lifetime.

Concrete was used to encase the RPV from submarine factory number 421. It is known that concrete is, in almost all conditions, porous to water. However, with little information on the type of concrete or its behavior in sea water, a similar effective lifetime to that of the other fillers is assumed in the estimates.

STRUCTURAL INTEGRITY OF THE REACTOR PRESSURE VESSELS CONTAINING SPENT NUCLEAR FUEL

Table 4 provides an estimate of the structural integrity of the RPVs containing SNF, at the present time (1996) and in the year 2015, and implications for recovery purposes. This represents a theoretical assessment only, and should therefore not suggest remedial action without confirmation of the actual condition of the SNF containers through site survey.

TABLE 3. CORROSION RATES AND FILLER LIFETIMES USED FOR ESTIMATING THE STRUCTURAL INTEGRITY OF THE REACTOR PRESSURE VESSELS CONTAINING SPENT NUCLEAR FUEL.

Material		Best corrosion rates (mm a^{-1})	Lifetimes(a)
Stainless steel	Bulk	0.02[1]	
	Pitting	0.50	
Mild steel	Bulk	0.075[1]	
	Pitting	0.166	
Bitumen[2]			100[3]
Furfurol(F)[2]			100
Concrete[2]			100
Biofouling factor			2[1]

1 For steels, bulk corrosion rates on outer surfaces were increased by a factor of 2 to account for biofouling.
2 Filler materials were given a lifetime in preference to a corrosion rate.
3 Lifetime is the period after which the filler no longer provides a physical barrier.

TABLE 4. ESTIMATES OF THE CONDITION OF DISPOSED REACTOR PRESSURE VESSELS CONTAINING SPENT NUCLEAR FUEL CONTAINERS FOR REMEDIAL ACTION CONSIDERATIONS.

Factory number and reactors	Disposal date	Disposal site	Containment structures	Condition		Conclusions
				1996	2015	
901 2 PWR[1]	1965	Abrosimov Fjord	a. RC[2] - hull b. Mild steel bulkheads c. RPV[3]	a. 25% corroded - sound b. Unsound c. Little corroded - sound	a. 40% -weakened b. Unsound c. 5% corroded - sound	RC bulkheads now (1996) believed ineffective as containment barrier. It may not be possible to use hull for recovery purposes. RPV remains intact.
285 1 PWR[4]	1965	Abrosimov Fjord	a. RC - hull b. Mild steel bulkheads c. RPV	a. 25% corroded - sound b. Unsound c. Little corroded - sound	a. 40% -weakened b. Unsound c. 5% corroded - sound	RC bulkheads now (1996) believed ineffective as containment barrier. It may not be possible to use hull for recovery purposes. RPV remains intact.
421 1 PWR	1972	Novaya Zemlya Depression	a. Barge b. Concrete enclosure bulkheads c. RPV	a. Unsound[5] b. 25% degraded c. Little corroded - sound	a. Unsound[5] b. 45% degraded c. 5% corroded - sound	Barge may not be used for recovery purposes. Effectiveness of concrete corrosion barrier likely to be severely degraded. RPV remains intact.
601 2 LMR[6]	1981	Stepovoy Fjord	a. Submarine hull b. Bitumen inside reactor compartment c. RPVs and SGs[7]	a. 10% corroded - sound b. 15% degraded - sound c. Sound	a. 25% corroded - sound b. 35% degraded - cracked c. Sound	RC and RPV remain intact. Effectiveness of bitumen barrier considered severely degraded. Otherwise no structural constraints on remedial actions.

1 Pressurized water reactor (PWR).
2 Reactor compartment (RC).
3 Reactor pressure vessel (RPV).
4 A defueled PWR is also included in this RC.
5 Judged unsound on the basis that the pontoon and barge are known not to have been built for this specific purpose and are believed to have been old and at the end of serviceable life.
Assumptions:
a. The concrete and bitumen have effective lifetimes of 100 years, with a linear decrease in effectiveness over this period.
b. Best corrosion rates (BCRs).
c. A survey of the dump sites will be necessary to assess the actual condition of the discarded objects prior to any decisions on remedial actions.
6 Liquid metal reactor (LMR).
7 Steam generators (SGs)

CONCLUSIONS

The following can be drawn from the work reported herein:

(1) Corrosion rates and filler lifetimes were best estimates from the literature but still leave some uncertainties.
(2) Any future studies should attempt to obtain and use actual corrosion rates and onsite observations of barrier material effectiveness, from samples of the actual objects themselves, providing such investigation does not breach the containment barriers.
(3) With regard to the availability of design information for the submarine SGIs, a great deal is still unknown about the support structures for the reactor cores, thermal shields, and RPVs. The lack of this information is most significant for remedial action evaluation of the submarine RPVs that contained SNF.
(4) Overall, the RPVs containing SNF are judged to be sound and only minimally corroded by the year 2015. In the interim, the containment capability of the RPVs seems assured. However, future work should also include regular onsite investigation of the integrity of the objects, looking for any leaks which have opened earlier than anticipated by the estimates. Firstly, the condition of the welds which seal important leakage paths should be investigated. These would include the CCR cap welds on the top of the PWRs and the state of the concrete capping over unit 421.

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