Report

Technical and Proliferation-Related Aspects of the Dismantlement of Russian Alfa-Class Nuclear Submarines

MOHINI RAWOOL-SULLIVAN, PAUL D. MOSKOWITZ, & LUDMILA N. SHELENKOVA

Mohini Rawool-Sullivan is a technical staff member at the Los Alamos National Laboratory. Her areas of expertise include assessing nuclear threats and building radiation sensors for the nonproliferation regime. Paul D. Moskowitz is the manager of the Environmental Threat Reduction Program in the Nonproliferation and National Security Department at Brookhaven National Laboratory. He has been working on Russia submarine decommissioning and dismantlement projects for the U.S. Department of Defense, the U.S. Department of Energy and the U.S. Environmental Protection Agency since 1995. Dr. Ludmila N. Shelenkova is an assistant biophysicist at the Brookhaven National Laboratory, Nonproliferation and National Security Department. She develops, implements, and coordinates programs based on collaboration with Russian weapon scientists.

Between 1950 and 1994, the Soviet Union built a total of 245 nuclear submarines. At the end of 1994, the newly formed Russian Federation (RF) had the largest fleet of nuclear-powered submarines and surface ships in the world. At that time, the Russian Federation had a total of 140 active nuclear-powered vessels in its fleet. In addition to nuclear submarines, the nuclear fleet included four Kirov-class guided-missile cruisers, a small number of nuclear-powered scientific research, support, and space-tracking vessels, and seven civilian nuclear-powered icebreakers. According to the Bellona Foundation, a Norwegian organization which monitors naval nuclear developments in Russia, the eighth Russian nuclear-powered icebreaker, *50th Anniversary of Victory,* was fitted with two reactors in July 2001.[1] After the breakup of the Soviet Union in 1991, the financially strapped Russian Federation inherited the Soviet nuclear fleet. As a result, by 1996 only 109 nuclear submarines remained in service. Two-thirds of these submarines are assigned to the Northern Fleet and one-third are assigned to the Pacific Fleet.

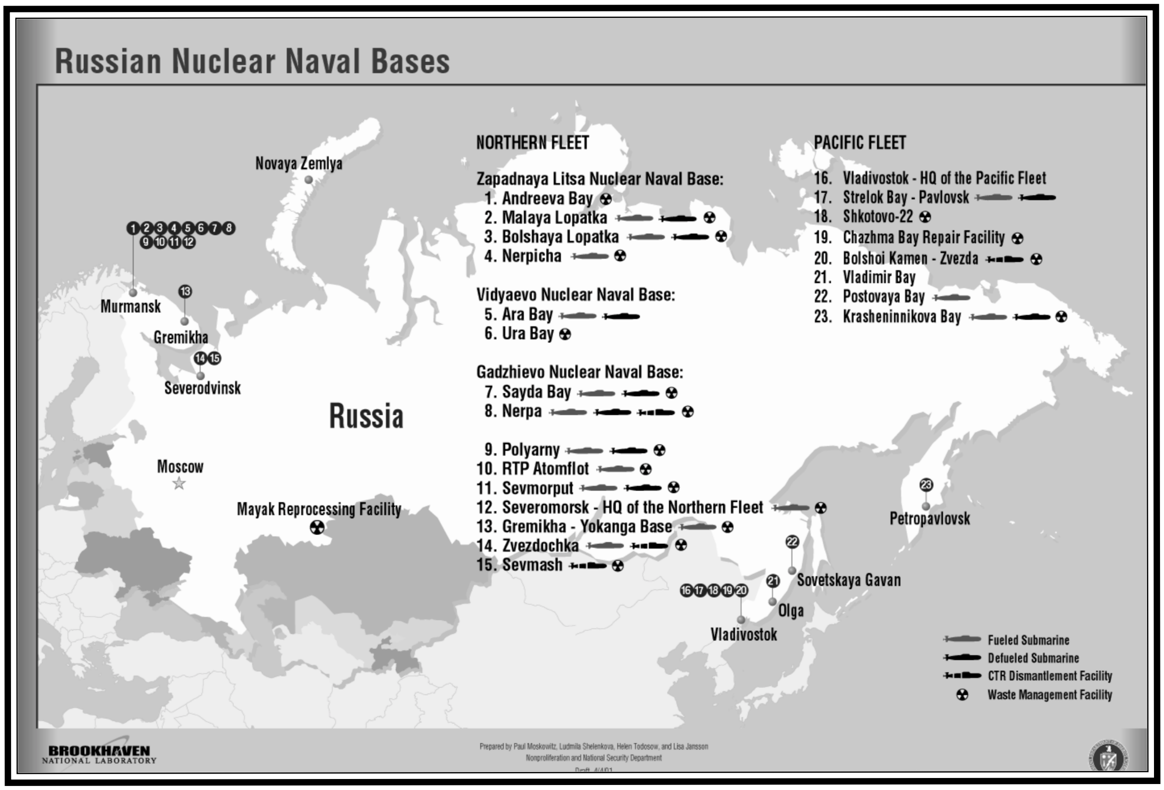
Nuclear-powered submarines have provided the Soviet and Russian navies with significant advantages over diesel submarines. Nuclear submarines can stay submerged for months at a time and hence can patrol wide underwater areas without detection. Nuclear submarines also have higher speeds than their diesel counterparts, and provide better living conditions for their crews. Since 1952, four generations of nuclear submarines and several experimental nuclear submarines have been built for the Soviet and Russian navies. From 1955 to 1964 a total of 55 first-generation (November-, Hotel-, and Echo- class) submarines were built. At the height of the Cold War, approximately five to 10 nuclear submarines were being commissioned per year from each of the four Soviet submarine yards: Sevmash in Severodvinsk; Admiralteyskiye Verfi in St. Petersburg; Krasnoye Sormovo in Nizhniy Novgorod; and Amurskiy Zavod in Komsomolsk-na-

Amure (see Figure 1). Beginning in the 1980s, the Soviet Union launched several titanium-hulled submarines. The ill-fated *Komsomolets* (Mike-class), which sank with 42 crewmembers aboard in 1989, had a titanium hull. Later, two series of nuclear submarines were constructed with titanium hulls: the Project 705 (Alfa-class) and the Project 945 (Sierra-class). These titanium-hulled nuclear submarines are no longer in production. The *Kursk*, which sank on August 12, 2000, killing all of its crew, belonged to the Oscar II-class (third generation). Third generation Akula-class attack submarines and Oscar-class cruise missile submarines, fourth generation Severodvinsk-class attack submarines (which carry anti-ship cruise missiles as well as torpedoes), and fifth generation Borey-class SSBNs are still in production. However, severe funding problems have slowed the pace of completion and commissioning of these submarines.

While the proliferation challenges posed by the dismantling of Russian nuclear submarines have been addressed in a number of articles, there is one unique aspect of this problem which has received little attention. The Soviet Union, unlike the United States, built nuclear submarines powered not only by pressurized water reactors (PWRs), but also constructed submarines with liquid metal cooled (LMC) reactors. Although only eight submarines (seven Alfa-class and one prototype) were built with LMC reactors, this report analyzes the unique proliferation and safety issues the decommissioning of these submarines presents.

The report begins by discussing the development of the Russian naval propulsion program, including the origins of the liquid metal cooled reactor program. It then discusses the design, development, production, and operation of the Alfa-class submarines that were powered by LMC reactors. The LMC reactor fuel cycle and its proliferation and safety implications are also addressed. The article concludes with an examination of the unique challenges posed by the dismantling of the LMC reactors removed from the Alfa-class submarines, and urges additional international assistance to help Russian address these challenges.

Figure 1: Locations of acilities involved in the Alfa-class/LMC reactor activities



History of Russian Naval Reactors

Table 1 shows Russian naval propulsion reactor design models, their power, the uranium enrichment level of their fuel, and the class of vessels built with these models. This table is based on data obtained from the NIS Nuclear Profiles Database of the Center for Nonproliferation Studies at the Monterey Institute of International Studies, except for the information on the number of reactors on Alfa-class submarines.[2] For many years, most Western reference material suggested that the Alfa-, Sierra-, and Akula-class submarines were powered by two reactors. Recently obtained information, however, shows that these submarines were powered by just one reactor.[3]

Russian research into naval reactors began in the early 1950s. Veterans of these early programs take great pride in these efforts because of the originality of their programs, which were not copied from U.S. or other designs. Two options were considered from the early stages of development. The first approach used a water-cooled, water-moderated design (also known as a PWR) developed at the Kurchatov Institute in Moscow under the leadership of A. Alexandrov. The second approach used a lead-bismuth cooled reactor design (also known as an LMC reactor) developed at the Institute of Physics and Power Engineering in Obninsk under the leadership of A. Leipunsky. Over the next 40 years, the Soviet Union developed and produced three generations of naval PWRs. Each generation featured improved reliability, compactness, and quietness. The first generation PWRs (VM-A type) were deployed from 1957 to 1968. All of these reactors are now retired. The second generation, VM-4 type reactors were deployed from 1968-1987. As of 1995, some of these reactors were still in use. The third generation reactors (OK-650 type) entered service starting in 1987. Besides these reactor designs, several one-of-a-kind PWR designs were developed for research submarines and vessels.

Despite certain advantages gained by using heavy metal-coolant in a submarine reactor, the LMC reactor design was ultimately abandoned in favor of the PWR designs. This decision was motived by safety considerations, maintenance problems, accidents, and advances in PWR designs. The main difficulty with LMC reactors arose from the need to keep these reactors sufficiently hot while the submarine was in port. If the reactor temperature fell below about 123 degrees Celsius (°C), the liquid-bismuth coolant would congeal, causing the reactor to seize up and essentially "freeze" itself.

Russian Nuclear-Powered Submarines with LMC reactors

Immediately following the successful launch of the first Soviet nuclear-powered submarine, Project 645 was initiated in 1957. The objective of this project was to build a 1,500-ton "interceptor" submarine that could get to a target location before the target information was obsolete. To meet this requirement, the submarine had to have underwater speed of about 40 knots. The speed of a submarine is largely a function of its wetted hull area and the power of its engines. Thus, to obtain high speeds, a design with a smaller volume hull and high-powered engines is required. A. B. Petrov of the Malakhit Design Bureau (SKB-143) in Leningrad came up with an innovative design for such a submarine.[4] A LMC reactor design was selected to provide high power using a compact reactor. The LMC reactor shielding consisted of a single wall inside the submarine, although normally single-wall shielding would be considered inadequate. The engine plant was completely automated and expected to run unmanned. The crew in this first design was expected to be 15 to 17 personnel. The complexity of this design required that all crewmembers be officers. If this design were built with a steel hull, however, the weight of the submarine would not allow it to meet the required performance specifications. This problem was resolved by using a titanium alloy hull. The use of titanium alloy allowed the hull walls to be thinner and reduced overall weight. Around 1963, after many delays, Petrov was dismissed from the project, and under the direction of M. G. Rusanov, the design of

Figure 2: Alfa-class submarine

Source: Federation of American Scientists the interceptor submarine was altered. The new design increased the displacement to 2,300 tons and doubled the number of internal compartments.[5]

This design was ready for construction in 1965. The first submarine to have LMC reactors was designated K-27, and used a Project 627 ZhTS-class hull. This vessel was designed by Special Design Bureau Number 143 (SKB-143) in Leningrad and was constructed at the Severodvinsk shipyard. The hull was divided into seven compartments: (1) torpedo room; (2) accumulators and living accommodation; (3) control room; (4) reactor compartment; (5) turbo and diesel generators, cooling and auxiliary machinery; (6) turbines; and (7) generator. The main purpose of K-27 was to test the functioning of LMC reactors on a submarine. The main electrical system was designed to operate at a frequency of 400 Hertz, which in turn permitted a reduction in size of some of the reactor equipment. For example, the capacity of the batteries in

Table 1: Naval Propulsion Reactor Design

MODEL	POWER	FUEL ENRICHMENT (% Uranium-235)	VESSELS
2 PWR*/VM-A	70 MWt	20%	Hotel, Echo, November
1 PWR/VM-4	70-90 MWt	20%	Charlie
2 PWR/VM-4	70-90 MWt	20%	Victor II and III, Delta, Yankee
2 PWR/OK-650	190 MWt	20-45%	Typhoon, Oscar
1 PWR/OK-650	190 MWt	20-45%	Akula, Sierra, Mike
2 PWR/VM-5 m	177 MWt	unknown	Papa
2 LMR**/VT-1	73 MWt	weapons-grade	November 645
2 LMR/OK-550 or BM-40A	155 MWt	weapons-grade	Alfa
1 PWR/type unknown	10 (X-Ray)	unknown	X-Ray, Uniform, AS-12
2 PWR/KN-3	300 MWt	unknown	Kirov (battle cruiser)
2 PWR/type unknown	171 MWt	unknown	Kapusta (auxiliary ship)
2-3 PWR/OK-150 and OK-900	90 MWt	5%	Lenin (icebreaker)
2 PWR/KLT-40	135 MWt	up to 90%	Arktika (icebreaker)
1 PWR/KLT-40	135 MWt	up to 90%	Sevmorput (auxiliary ship), Taymyr (icebreaker)

Source: “Russia: Naval Nuclear Reactors,” Center for Nonproliferation Studies, NIS Nuclear Profiles Database
*PWR is pressurized water reactor. **LMR is liquid metal reactor. In this report, “weapons-grade uranium” refers to uranium enriched to 90 percent or more U-235.

K-27 was only one-fourth that in submarines equipped with PWRs. The submarine was also equipped with automatic turbo generators.

K-27 was equipped with two VT-1 type LMC reactors. But the submarine suffered a major accident with one of its reactors in 1968, and nine members of the crew died. In this accident, one of the reactors of the submarine was severely damaged after a pipe in the reactor compartment was contaminated by corrosion particles from the liquid metal coolant. After the accident, the core was removed from the undamaged reactor. All empty spaces in the damaged reactor compartment including the empty cavities in the reactor itself were filled with furfural and bitumen developed by the Kurchatov Institute. In 1981, the entire vessel was scuttled in the Kara Sea, near Novaya Zemlya.

Despite this accident, the experience gained with Project 645 led to the design and construction of seven Project 705 and 705 K-class or Alfa-class submarines. All of these submarines were equipped with LMC reactors. The Alfa-class submarines were built for speed (40+ knots); hence it was of small consequence that they were noisy, as it was assumed they could escape from any torpedoes fired at them. Since Alfa submarines were designed to be “interceptor” submarines, their operational endurance was relatively short—approximately 50 days. The first Alfa-class submarine experienced numerous problems, and the last Alfa-class submarine, K-123, was decommissioned around 1995. All of the Alfa submarines were lightly armed. Equipment in these submarines was unique, and thus hard to maintain.

Liquid Metal Cooled Reactors

In 1953, the Soviet Union began construction of a land-based full-scale prototype of a LMC reactor and associated propulsion unit, called a 27/VT. This facility was commissioned at Obninsk in January 1959.[6] It became the research and development base and training facility for naval LMC reactors. The facility operated for two run periods lasting a total of 17 years. Two different cores were used for these runs. After the second run, researchers noticed a high content of slag in the reactor core.[7] In these tests they also noticed the coolant freezing problems in some sections of lead-bismuth circuits due to either emergency situations or personnel errors.

Yet another problem arose when the primary coolant circuit sprung leaks in the course of scheduled repairs. In this situation, the hazard came from radioactive aerosols and gaseous polonium compounds (combined with lead and in some cases with hydroxide). Polonium-210, which is an alpha emitter with a lifetime of 13.8 days, is generated by the interaction of neutrons (generated in the reactor core) with bismuth-209 from the lead-bismuth coolant (about 44 percent lead and 56 percent bismuth).[8] This reaction generates bismuth-210, which decays into Po-210. After emission of an alpha particle, polonium-210 decays into stable lead-206. These problems were analyzed and technical measures were developed to prevent their recurrence.[9] The main technical parameters of the land prototype LMC reactor are listed in Appendix A, Table A-1. Table A-2 lists the characteristics of the core of the land prototype LMC reactor of facility 27/VT. In 1978, another full-scale prototype of the LMC reactor was put into operation at the KM-1 facility at the A.P. Aleksandrov Scientific Research Technological Institute (NITI), in Sosnovy Bor.[10]

The reactors of the Alfa-class submarines were never refueled, for it was simply not technically possible to remove the fuel assemblies without the metal coolant solidifying in the process. It is true that a team led by B. Gromov published an article in which they report that they froze the undamaged core of K-27, kept it in this state for two years, and then thawed the reactor core and brought it up to high power.[11] However, this success must have been achieved under controlled experimental conditions, and the procedure could not be used for routine operational refueling. As a result, Alfa-class submarines were never refueled once the coolant in their reactors was frozen.

Since the mixture of lead and bismuth utilized in the LMC reactor has a high boiling point (1670°C) and a melting point of 123°C, it is unnecessary to keep LMC reactors under pressure as is the case for the pressurized water-cooled reactors.[12] Conversely, it is important to keep LMC reactors constantly heated above 123°C so that the metal solution does not solidify. Once the solution hardened, it was impossible to restart these reactors, as the fuel assemblies were then frozen in the solidified coolant. A special land-based facility was constructed at Zapadnaya Litsa, the base of the Project 705–705 K- or Alfa-class submarines, to deliver superheated steam to the LMC reactors of the moored vessels. In addition, a smaller ship and floating barracks were also stationed at the pier to deliver steam from their own boilers to the Alfa submarines at the piers. This method of providing external heating proved to be unreliable, suffering breakdowns in the 1980s. After this failure, the reactors of all operational Alfa-class submarines were kept running continuously until they were decommissioned in the 1990s. Consequently, while the reactors were running, the vessels needed to be manned.

In theory, the following factors were expected to make the LMC reactor design safer overall than the PWR design:[13]

- The high boiling point of the metal coolant mixture (approximately 1680°C) means that there is no possibility of over-pressurization of the primary circuit in the event of accidental overheating of the coolant.
- Since it is impossible to overheat the coolant, heat removal from the core is more reliable, increasing safety.
- Reactor power decreases in the event of both emergency overheating and the simultaneous failure of the emergency protection system.
- In the core and within the coolant there is no release of hydrogen from irradiation or chemical reactions. The coolant itself also reacts only very slightly with air or water. As a result, there is no danger of an explosion in the event of a coolant leak.
- If a leak did take place, the coolant would rapidly solidify. The melting point of the coolant mixture is 123°C, thereby removing the possibility of reactor damage and loss of coolant.

Detailed information on the LMC reactors installed on the Alfa-class submarines is hard to find. In their two papers, "Possible Criticality of the Marine Reactors Dumped in Kara Sea,"[14] and "Potential Radionuclide Release Rates from Marine Reactors Dumped in the Kara Sea,"[15] J. M. Warden and his colleagues describe the LMC reactors. According to these papers, the LMC reactor of the sunken November class submarine (K-27) consisted of a cylindrical stainless steel (SS) reactor pressure vessel with the following dimensions: 1.8 meters (m) in diameter, 3.7 m in height, and 30 millimeter (mm) thick walls. These LMC reactor cores were loaded with 90 kg of uranium-235 enriched to 90 percent and clad in SS. The core was made up of a triangular lattice of ceramic fuel pins composed of highly enriched uranium alloyed with beryllium and sintered with beryllium oxide. The pins were surrounded by lead-bismuth coolant. The core radius was 390 mm and was surrounded by a stainless steel (SS) layer and a beryllium oxide reflector, with more lead-bismuth coolant and SS situated above and below the core. The core was penetrated by 10 control and compensation rods (CCRs) and 3 emergency protection rods.

Another source of information on LMC reactor fuel is data collected during Project Sapphire.[16] Project Sapphire, carried out in 1994, involved the packaging and transfer of 581 kg (1,278 lbs) of highly enriched uranium (HEU) from the Ulba Metallurgical Plant near Ust'-Kamenogorsk in Kazakhstan to the Y-12 Plant at the Oak Ridge National Laboratory in Tennessee.[17] The project was initiated by President Nursultan Nazarbayev of Kazakhstan, in consultation with Russia, in order to prevent the possible theft of this material by terrorists or proliferants states. The HEU involved was reportedly left over from the Soviet Alfa submarine program, and had been stored at Ulba in unsecured and unsafeguarded facilities, without electronic means of accounting.[18] Instead, material inventories were simply recorded by hand into books. The material was in seven forms: HEU metal (168.7 kg); HEU oxides (29.7 kg); beryllium-HEU alloy fuel rods (148.6 kg); beryllium-HEU alloy machining scrap and powder (231.5 kg); beryllium oxide-uranium dioxide fuel rods (1.6 kg); graphite with trace HEU (0.7 kg); and laboratory salvage (0.2 kg).[19] The average enrichment of the material was 89-90 percent U-235.[20] The LMC reactor of each Alfa class submarine is believed to have contained approximately 200 kg of HEU.[21]

Two different models of LMC reactors were developed. The four submarines built at the Admiralty Shipyard used the BM-40A reactor with two separate steam loops and circulating pumps. The submarines built at Severodvinsk (project 705K) used the OK-550 with branched first-loop lines and triple circulating loops and pumps. Both models were equally susceptible to leaks and meltdowns.

The LMC Reactor Fuel Cycle and Proliferation Implications

Initially, the HEU-beryllium alloy fuel for the LMC reactors was produced at the Ulba Metallurgical Plant. Production of this fuel at Ulba ended in the 1970s and the production of all naval reactor fuel was consolidated at the Machine Building Plant in Elektrostal near Moscow.[22] From Elektrostal, fuel was delivered to the Navy, which conducted most refueling. Fresh fuel was also delivered to submarine construction shipyards for fuelling newly-built submarines and for refueling submarines undergoing major overhauls. The spent fuel from these submarines was to be transported to the Mayak Production Association in Chelyabinsk Oblast, Russia, for reprocessing.

LMC reactor cores are loaded or unloaded in the form of a removable unit referred to as removable reactor core unit (RRCU).[23] Each RRCU includes the core with fully inserted neutron-absorbing emergency protection rods (EPRs), reflector, and some shielding material.[24] The removal of the RRCU can be performed either with or without coolant in the reactor vessel. When a spent RRCU is removed from a reactor vessel, its EPRs are left in fully inserted positions. The driving mechanisms of these EPRs are then dismantled and SS caps are welded onto the EPR inserts.[25] This procedure aims to prevent any accidental removal of the EPRs from a spent RRCU. These spent RRCUs are put into a steel container with non-irradiated lead-bismuth eutectic at a temperature ranging from about 150°C to 160°C. After the spent RRCU has been placed in the steel storage container the temperature of the lead-bismuth eutectic is allowed to fall below its melting point. As a result, spent RRCUs are stored in the frozen lead-bismuth eutectic. The steel containers holding the spent RRCUs are then sealed and a layer of bitumen applied to prevent moisture penetration. The maximum estimated heat release in loaded or unloaded RRCUs is 3 kW.[26] All of the spent RRCUs from Alfa-class submarines are stored at the Gremikha naval base in Murmansk Oblast, Russia.[27] The rest of the Alfa-class submarines have fuel onboard with frozen coolant. The procedures described above for the storage of LMC RRCUs were intended for short-term storage (three to five years) and not for long-term storage. Some of the LMC RRCUs have been at Gremikha for over 10 years.[28] It is possible that storing RRCUs over long period of time in short-term storage could cause safety and/or security problems as a result of the impact of physical and chemical processes (galvanic and chemical corrosion, phase conversion). RRCUs in short-term storage may also be vulnerable to possible theft, terrorist attack (sabotage), earthquakes, and fires.

Physical protection of fresh or spent naval propulsion reactor fuel is remains a matter of serious concern owing to inadequate safety and security measures at many Russian storage facilities. The spent fuel from Alfa-class submarines still contains a large amount of (HEU). It is worth noting that separation of HEU from low-irradiated spent fuel is much easier than chemical reprocessing required for plutonium separation and can be done at smaller facilities. As a result, spent naval fuel would be attractive to terrorist groups or proliferants states seeking a relatively easy route to obtaining the necessary fissile material to fabricate a nuclear weapon. In addition, workers at Russian naval bases have frequently failed to receive their wages for months, increasing the risk of sabotage or theft.[29]

There have been several documented cases involving the theft of naval propulsion reactor fuel. A sailor and a guard were arrested in July 1993 while attempting to steal two fuel rods containing 1.8 kg of HEU (enriched to 36 percent U-235) from a storage site at the Zapadnaya Litsa naval base. In another case, two naval officers diverted 4.5 kg of HEU (20 percent U-235) from Sevmorput shipyard in November 1993. Although these and other documented cases have not involved fuel from Alfa-class submarines, the threat of theft remains high for the LMC RRCUs. It is notable that most of the cases of naval propulsion reactor fuel theft have involved insiders. In addition, there are also reports of arrests of Chinese and North Korean nationals on Russian submarine bases.[30]

Decommissioning and Dismantling of the Alfa-Class Submarines

Decommissioning (removal from active service) and dismantling (physical breakdown) of Alfa-class submarines is carried out in several stages. First, all weapons and explosives are removed, along with classified and sensitive equipment. Next the submarine is taken to a facility equipped to dismantle it. At this facility, the submarine's reactors are shut down so that defuelling can take place. At this time, additional equipment is removed from the submarine, such as loose furnishings, expendable materials, tools, and spare parts. Before defuelling begins the submarine is dry-docked. The hull above the reactor plant is opened. Special equipment necessary for the removal of the reactor core is installed. Removal and recovery of reusable materials from the reactor takes place. Then the fuel is then removed and stored in short-term storage area or transported to an appropriate facility for reprocessing. Defuelling removes over 99 percent of the radioactivity associated with the reactor. Once the fuel has been removed, most residual radioactivity (about 99 percent) in the reactor compartment is concentrated in the reactor vessel structures and the primary circuit pipelines. This residual radioactivity is caused by neutron activation of the reactor steel structure and radioactive deposits of coolant residue on the inner surfaces of the primary circuit pipes. After defuelling is completed, the reactor compartment is cut away from the rest of the hull. The reactor compartment and the remaining reactor parts are then packaged for long-term storage. The remainder of the submarine is scrapped. Decommissioning a submarine is a labor-intensive task, and requires involvement of the submarine crew for maintenance, reactor monitoring and defuelling purposes.

Alfa-class submarines are dismantled at the Sevmash shipyard in Severodvinsk, located in Arkhangelsk Oblast. Officially, the decommissioning of nuclear submarines is supposed to be self-financing. The profits from the sale of scrap material are deemed adequate to fund the entire decommissioning process.[31] In reality, however, the shipyards that carry out submarine dismantlement suffer major financial losses. These financial losses are even greater when the titanium-hulled submarines—such as Alfa-class submarines—are dismantled.[32] Greater losses are incurred in dismantling these submarines because dealing with the titanium hull requires more time and advanced equipment. The management of Sevmash estimates that the shipyard lost one billion rubles (about $2.5 M) on the decommissioning of 705 - Alfa class submarines K-463.[33]

Current Status of Alfa-class submarines

The current status of the seven Project 705 and 705 K–class or Alfa-class submarines is summarized below:[34]

- K-377, (formerly K-47): (Commanding Officer: A.S. Pushkin) This was the first Alfa class submarine. It suffered a reactor accident in 1972 during its sea trials. The metal coolant “froze” and it became impossible to remove the reactor fuel. After this accident, the submarine was dismantled and the whole reactor compartment (with the LMC reactor inside) was filled with furfural and bitumen.[35] This reactor compartment was then placed on a barge for transport to the Kara Sea where it was to be dumped. However, the signature by the Soviet Union of the 1972 London Convention prevented the implementation of this plan. Subsequently, the barge was towed to the island Yagry outside the Zvezdochka shipyard in Severodvinsk, where it was stored. Sometime in late 1994 or early 1995 the reactor compartment was moved to Gremikha for storage on shore.
- K-123: Built at Severodvinsk (Project 705K).[36] Launched on December 26, 1977. The original reactor compartment was removed in 1982 following an accident, and a new one installed. Liquid metal from the primary cooling circuit leaked out and contaminated the entire reactor compartment. The contaminated reactor compartment was cut out and, after welding the additional sections to its stern and nose ends for buoyancy support, was shipped to the sediment stop. Probably, in the future the fuel can be unloaded from the removed reactor. It took 8-9 years to change the reactor compartment and the submarine was finally launched again in 1990 (renumbered B-123). Recommissioned in 1991, it remained in operation till 1993. It was scheduled for decommissioning during 1995. At the start of the decommissioning the coolant was frozen in the reactor and NS was shipped afloat to the sediment stop.
- K-432: (Project 705K) This submarine is in the process of being dismantled at the Sevmash shipyard. In a freak accident, the submarine hit a whale during its sea trials, necessitating major repairs that were completed in 1988.[37] However, the submarine was never re-commissioned. The LMC RRCU from this submarine was removed in Gremikha and is being stored there. Its reactor compartment was towed to Sayda Bay on the Kola Peninsula for storage in 1998.[38]
- K-463: This submarine had unspecified reactor accident. It was decommissioned at Sevmash sometime after 1986. The LMC RRCU has been removed from the reactor and is being stored at Gremikha. This submarine was later re-engineered with standard VM-4 reactor (Project 671B) and served as a trials ship. In 1994, the reactor compartment was towed to Sayda Bay, and remains moored there today. The remainder of the submarine was scrapped.
- K-493:[39] (Project 705K) The LMC RRCU was removed from this submarine at Gremikha sometime before 1995 and is now stored there. The submarine was then reengineered with VM-4 (project 671B) and served as a training vessel. Subsequently, the submarine was stationed at the Zapadnaya Litsa (Bolshaya Lopatka) naval base on the Kola Peninsula untill 1996. It was then towed to the Sevmash shipyard for dismantling, which was completed in November 1997.
- K-373: This submarine is laid up at Zapadnaya Litsa and has not yet been defuelled. At the start of its decommissioning a problem occurred at the reactor lid due to destruction of the EPR. Some radioactive dust penetrated into the upper space of the EPR inserts (in the reactor lid area), resulting in the deterioration of the radiation situation in the reactor compartment. At present the coolant in the reactor is frozen
- K-316: Dismantling of this submarine began in the autumn of 1994 at the Sevmash shipyard. The LMC RRCU was removed at Gremikha and is currently stored there. The reactor compartment was towed to

Sayda Bay in 1995. The rest of the submarine was scrapped.

In addition to the RRCUs noted in the above list, there are also two spent RRCUs from the first run of the Project 645 nuclear submarine stored at the Gremikha storage facility. Fuel elements from the two cores of the Obninsk 27/VT prototype facility have been removed from the RRCUs there, and both the fuel elements and the remaining RRCU parts are currently stored on-site at Obninsk.

Future Challenges

Storage of the RRCUs of Alfa-class submarines raises a number of difficult issues. Owing to the high enrichment level and large quantity of fuel used in LMC reactors, there is a significant proliferation threat if the RRCUs are not adequately secured. The spent fuel from LMC reactors could be attractive to terrorists and proliferant states seeking fissile material for nuclear weapons. At greatest risk of theft are spent and partially spent fuel elements separated from the RRCUs. By contrast, fuel elements that have not yet been removed from the frozen RRCUs are less vulnerable to theft, because substantial specialized equipment is required to move a whole RRCU. The risk of theft is very low for RRCUs that are still frozen in lead-bismuth coolant. However, if at some point these fuel elements are unloaded from their RRCUs, then adequate physical protection must be provided.

As noted above, spent fuel elements from the prototype facilities are currently stored at the Institute of Physics and Power Engineering in Obninsk. It is logical to assume that there are also stocks of fresh fuel stored somewhere in Russia. A careful evaluation of the physical security of all spent and fresh fuel elements for LMC reactors is needed. The reactors of all Alfa-class submarines with fuel on board are apparently frozen as a result of various accidents and technical problems. These reactors are not operable, and as a result, it would be virtually impossible for a terrorist group of proliferants state to attempt to steal one of these Alfa-class submarines. Still, c urrent political and economical conditions in Russia make it clear that in order to further reduce proliferation risks, the international community should provide technical assistance and funding to ensure adequate security of the spent and fresh fuel elements from the LMC reactors and the dismantlement of those Alfa-class submarines that still await defuelling. Meeting this challenge may require new legislation and new thinking in donor countries, such as the United States. Although the U.S. Department of Defense Cooperative Threat Reduction (CTR) program is financing the dismantlement of Russian ballistic missile submarines, as well as the storage or reprocessing of naval propulsion reactor fuel removed from them, the mandate of this program does not extend to non-strategic weapons systems, including attack submarines like the Alfa class.

Beyond the proliferation threat, it is also important to consider the criticality safety of RRCUs removed from the Alfa-class submarines. Current storage, both land-based storage and on board submarines awaiting defuelling, was intended to be short-term. Safe long-term storage procedures for the Alfa-class RRCUs need to be developed and analyzed. At this point it is hard to evaluate the criticality safety issues related to the stored RRCUs in any depth because of inadequate technical data and analysis. To understand the criticality issues posed by using short-term storage facilities for long-term storage, the physical and chemical properties of lead-bismuth coolant over a long period of time while in a frozen state must be better understood. The corrosive and other effects of frozen coolant (if any) on SS and other materials used to store the RRCUs must also be studied. A better knowledge of these processes and the details of LMC reactor design would facilitate an accurate evaluation of the risks of a criticality incident arising under in various scenarios, such as the leakage of water into stored RRCUs.

At the moment, important details about the LMC RRCUs used on the Alfa-class submarines are unavailable, and remain classified. These details are needed to calculate criticality risks. Other issues such as fires at the storage facilities or on submarines must be studied. The effects of possible earthquakes on stored RRCUs should also be evaluated. Given a criticality accident, a consequence analysis may be performed to determine the environmental impact. This would include an analysis of the accident transient to determine the physical state of the fuel after the accident and the additional fission product inventory generated. The results of this analysis may be applied to a dispersion analysis to track the release of radioactive materials into the environment. The international community should provide technical assistance and monetary support for such studies. For its part, if it wants to see both the security and safety issues associated with the dismantling of the Alfa-class submarines adequately addressed, Russia must be willing to increase cooperation in this area and share design-specific knowledge with international partners.

In summary, both the proliferation threat and safety issues posed by the dismantling of Alfa-class submarines and the storage of their spent and fresh fuel should be regarded as global issues, and not just solely as a Russian concern. In our view, the ideal scenario would be international cooperation that ensured that the Alfa-class submarines are dismantled and spent fuel is either stored in safe and secure storage or is reprocessed. To achieve this ideal scenario, negotiations between Russian and the international community must hammer out a basis for expanded cooperation. Negotiations are currently underway to establish international cooperation in the dismantling of Russian attack submarines. These talks are both bilateral (e.g., Norway-Russia and Japan-Russia) and multilateral (e.g., the International Atomic Energy Agency Contact Expert Group for International Spent Nuclear Fuel and Radioactive Waste Management). The success of these negotiations will depend, in addition to those issues noted above, on Russia agreeing to sign international nuclear liability indemnification agreements.

TECHNICAL APPENDIX A

Table A-1: Technical parameters of the ground prototype LMC reactor at the 27/VT facility

Parameter	**Value**
Reactor Thermal Power, kW	70,000
Coolant Flow Rate, m^3/h	850
Eutectic Temperature at the Reactor Inlet, ^oC	235
Eutectic Temperature at the Reactor Outlet, ^oC	440
Steam Generation (SG) Capacity, t/h	90
Pressure of superheated steam at the SG outlet, kg/cm^3	38
Temperature of the Superheated Steam, ^oC	385

Table A-2: Core parameters of the ground prototype LMC reactor at the 27/VT facility

Parameter	**Value**
Core Diameter	769 mm
Core Height	853 mm
Content of U in U-Be alloy	7-16 %
Diameter of U-Be core	11 mm
Triangular Lattice Pitch	13.6 mm
Number of rod fuel elements	2735
The number of control and safety system (CSS) rods (absorber is natural boron carbide)	16

Sources: Suvorov, et al., "Experience of 27/VT facility construction and operation," *Proceedings of the International Conference on Heavy Liquid Metal Coolants in Nuclear Technology*, Vol. 1 (Obninsk, Russia: State Science Center of the Russian Federation-Institute of Physics and Power Engineering, 1999), p. 67.

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