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# PROPOSAL FOR A NUCLEAR POWER-PLANT SHIP DECOMISSIONING

**Adalberto R. S. Junior[1], Luciano Ondir Freire[2] and Delvonei Alves de Andrade[3]**

[1] Instituto de Pesquisas Energéticas e Nucleares (IPEN / CNEN - SP)
Av. Professor Lineu Prestes 2242
05508-000 São Paulo, SP, Brazil
sobreiro@marinha.mil.br

[2] Instituto de Pesquisas Energéticas e Nucleares (IPEN / CNEN - SP)
Av. Professor Lineu Prestes 2242
05508-000 São Paulo, SP, Brazil
luciano.ondir@gmail.com

[3] Instituto de Pesquisas Energéticas e Nucleares (IPEN / CNEN - SP)
Av. Professor Lineu Prestes 2242
05508-000 São Paulo, SP, Brazil
delvonei@ipen.br

**Abstract:** The goal of this work is to review decommissioning methods for nuclear propulsion ships throughout of survey on decommissioning experience. Governmental regulation typically dictates clean-up of a decommission site. It is satisfying the stringent regulations that prove to be a primary cost driver for decommissioning and waste disposal. Reactor types and sizes, the number of reactors on an individual plant site, and labor costs are among the main factors affecting costs. Thus, it is so important to develop a good recycling policy after nuclear-power plant ship inactivation. This work found that adequate requirements identification must keep economics always in the center of design. Experience shows, except after major catastrophic accidents, nuclear industry may earn public trust by open dialogue with the population and sound engineering practices, searching for right technical solution and great planning for long time. To achieve this goal, this work proposed the following method: firstly, it presents the characteristics of nuclear-powered submarines. Secondly, an approach concerning the decommissioning process of nuclear-powered submarines adopted by the US Navy, Russian Navy, Royal Navy, French Navy and others which brings the past experience on this field, providing some information on history, architectures and hints of reasons for the success or failures of each project. Finally, this works compared the decommissioning processes of these navies under the perspective of the nuclear regulatory process.

***Keywords:*** nuclear power-plant ships, Navy, decommissioning

## 1. INTRODUCTION

Nowadays, except for Russian container ship Sevmorput (and nuclear icebreakers), there is not nuclear merchant ships. Also, except for Akademik Lomonosov nuclear barge which aims at supplying power at northern artic (and Chinese ACPRS 50 project), remote locations and islands employ oil to produce electric power. At remote places, the smaller size (than large grid generators) leads to lesser cycle efficiency; transport and maintenance raise costs. Shipping is an important player on sulfur, carbon, and nitrogen oxides emissions [1], which may lead to greenhouse gases emission regulations that make the use of fossil fuels yet more expensive.

Currently, the supply chains are global and about 95% of global commerce goes through shipping [2]. Therefore, increases in shipping costs due to fuel (fuel is the greatest cost driver) affect all economy. To keep costs reasonable, new ship powering technologies need to appear. Wind and solar power could be a choice if the average ship speed is about 10 knots (currently, container ships travel at 20 to 25 knots) and travel times may have large variance as wind and sun power depends on weather. For base load electricity in remote places, wind and solar power are not competitive because the need of energy accumulation and they need

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large land surfaces, displacing agriculture. So, nuclear power is a solution to cut greenhouse emissions which has stable output as it does not depend on the weather.

Apart the decarbonization goal, societies need also to assure energy security as lack of energy would have catastrophic impact on population capability to survive, as all basic needs (food, water) depend on energy. From this perspective, the issue is not if human activity is causing (or not) the climate changes, but how to secure access to energy given the climatic changes do occur. In past, the planet had periodic climate changes, without human influence and such changes should continue in future. Both solar and wind power have a risk factor because they depend on climate, which may change over time. Fossil fuels have risk and volatility on their prices because reserves concentrate in few countries. Nuclear fuels are present on all continents and in more countries, making its supply safer and its volatility is lower because of mining standard of long-term contracts. Anyway, for nuclear power, fuel is not a major cost driver, as it is for fossil power. With its high-power density, making nuclear fuel stocks for a long time is cheaper than compared with fossil fuels, allowing creation of intermediate buffers to support a supply cut.

However, nuclear industry faces barriers: lack of stable regulation; anti-nuclear sentiment on occidental countries; large capital cost; unpredicted costs for decommissioning; and need of expensive and complex competencies. Because long route shipping involves two or more countries, nuclear shipping needs to prove safety to authorities of all countries.

This work aims at reviewing the current methods for decommissioning nuclear ships to set the base to a proposal of method of a nuclear merchant ship. As most of current human experience on naval reactors is on military submarines, most examples are based on other countries submarine scrapping programs.

Each submarine produces an estimated 850 tones of low and intermediate level waste (LILW). A number of problems make dismantling difficult: finding equipment for defueling, finding sites for the waste, getting enough funds, a lack of trained professionals, and disputes over access and liability (Nielsen and others 1997, Webster 2003). In the past, a nuclear submarine’s reactor was disposed off by extracting it from the vessel and sinking it in the sea (Olgaard 2006); actually, this practice nowadays is forbidden and not allowed anymore (fears have been raised over the creation of nuclear hot spots in oceans and seas).

In 1991 approximately 200 decommissioned nuclear submarines existed in Russia. By 2003, half of these had actually been dismantled. However, many of the reactors from these ships had been dumped in the sea or were still floating in buoys near the shipyards (Webster 2003). In the UK, a site for decommissioning out-of-service submarines has not yet been selected, and twenty submarines are currently awaiting dismantling or being prepared for “afloat storage” (Environment Agency UK 2011). The Submarines Dismantling Project (SDP) finally started in 2016, has the HMS Swiftsure as a pilot project and probably a guide to proof the dismantling process. The decommissioning of total 27 pressure hulls will cost at least £ 10.4 billions in 25 years and still go on up to 2040.

The costs of decommissioning and waste disposal include the possibility of risks to public health, safety and the environment when not properly managed.

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Figure 1 - Reactors cut out of nuclear submarines and stored on the Hanford reservation DOE site in Washington Sate USA (Photo by Fred Dawson www.flickr.com)

## 2. NS SAVANNAH

In 1955, President Eisenhower proposed that the US build the world's first atomic-powered merchant vessel to demonstrate America's peaceful use of the atom. It was commissioned in 1962 and decommissioned in 1972 in an effort to reduce spending by the Maritime Administration (JAMES P. TARZIA, 2009, 07 slide).

Accordingly the decommissioning status, the Nuclear Steam Supply System (NSSS) is presently in protective storage. This phase of decommissioning activities is characterized by active surveillance, monitoring and maintenance of the nuclear facilities housed onboard the ship, and custody and maintenance of the ship as the primary physical boundary and protective barrier of the licensed site. Final decommissioning of the NSSS nuclear facilities will be performed by a method which the equipment, structure and portions of the facility and site that contain radioactive contaminants are removed or decontaminated to a level that permits termination of the license after cessation of operations (Regulatory guide 1.184, Rev 1).

Regarding the status of decommissioning funds annual report, the amount of funds estimated to be required for licensed activities were approximately \$3.0 million annually (U.S. Department of Transportation, 2016, p. 9). There was a plan to dry-dock the NSSS for regular maintenance once during the protective storage period, in 2018, at an estimated cost of \$6.8 million.

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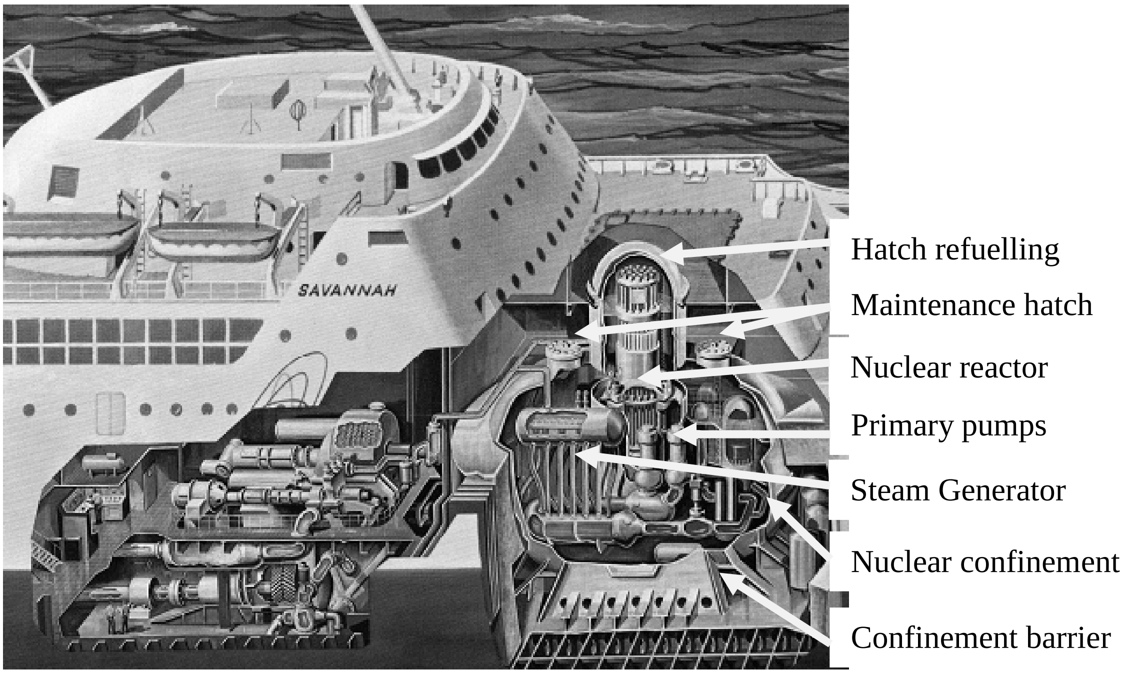


Figure 2 - NS Savannah layout

## 3. NS OTTO HAHN

After 10 years of worldwide operation the nuclear research ship "Otto Hahn" was taken off duty in 1979. During the process of dismantling, 4 phases were foreseen in the schedule (*DOBSCHUETZ*, p. 8):

**Phase 1: Preparing works -** In the three nuclear compartments were taken intensive and numerous measurements, made by different types of instruments, to determine the activity concentration and the dose rates in the compartments itself, on the surface of the various installations and in the components. According to the dose rate measured there has been made a classification of working areas marked with high and low level of local dose rates which was the basis for the planning of the dismantling works.

**Phase 2: Dismantling works** - The dismantling works started parallel in the three compartments with priority of dismantling the components with the highest activity, with exception of the reactor Unit. Large and heavy components were decontaminated on the spot before being disassembled, the others at the decontamination place after disassembly. The result of the decontamination process was examined with a sampling instrument which took samples overall from the surface to be checked by electrolytic scraping. The disassembled installations were segregated according to the activity level and the size. Some of them could be released after clearance; the others were packed in containers or in drums and shipped to a waste storage facility.

**Phase 3: Dismantling of the reactor unit -** It has been decided in the dismantling concept to remove the reactor unit as a whole. At first components of big size like the reactor coolant pumps, the reactor platform and the control rod drive mechanism were disassembled in the containment and after this taken out in the above-mentioned loading room to be packed. The reactor unit was decontaminated and provided with a protection coating. The transport of the unit had the following steps: lifting it with a floating crane putting it on a pontoon, shipping it to a quay, lifting it on a heavy load-trailer pulled by four trucks and bringing it by road to storage in the research centre.

**Phase 4: Decontamination of the controlled area -** The last step of the dismantling works was to remove the remaining installations and to clean the whole controlled area from rests of contamination. The cleaning works started with the containment and ended with secondary systems which have been contaminated due to a steam generator leak. The decontamination works were done with chemical and mechanical methods and were finished when it was approved, by measuring of samples that the dose rate was below the clearance level. The decontamination of the ship to release it for further use was entailed with a considerable expenditure of time and works.

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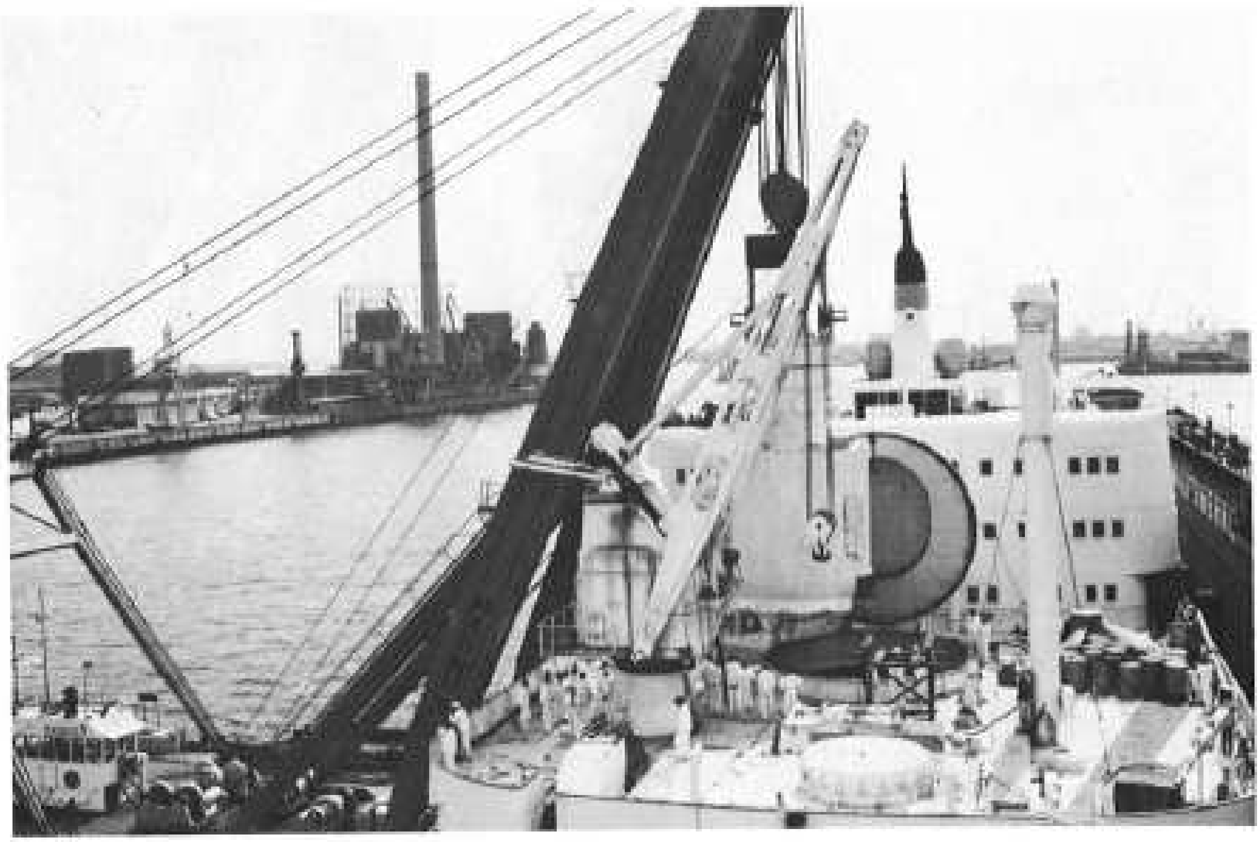

Figure 3 - Lifting of the reactor unit out of the NS Otto Hahn (Photo by von_Doubschutz-eng Federal Ministry of Environment, Germany)


Figure 4 - Putting down of the reactor unit on heavy load-trailer (Photo by von_Doubschutz-eng Federal Ministry of Environment, Germany)

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## 4. THE US NAVY SCRAPPING AND RECYCLING PROGRAM FOR NUCLEAR-POWERED SUBMARINES

Under the Nuclear-Powered Ship and Submarine Recycling Program, all decommissioned Nuclear-powered Attack Submarines and Nuclear-powered Ballistic Submarines (SSNs/SSBNs) and cruisers (CGNs) are dismantled at the Puget Sound Naval Shipyard in Bremerton, Washington. This shipyard is the only one which participates in the recycling program (Loring-Morison, 1995, p.47). To dispose of the more than 100 nuclear submarines, US dollars 2.7 billion had been provided for the program (Handler, 1993a, p.9). The estimated cost of inactivating and scrapping nuclear-powered submarines is as follows:

Table 1 – Estimated cost of inactivating and scrapping (Source: MacKinnon III and Burrit, 1995, p.1)

| **Type** | **Inactivation cost** | **Scrapping cost** |
|---|---|---|
| SSBN | US $ 29.6 million | US $ 9.2 million |
| SSN | US $ 29.6 million | US $ 6.9 million |

For the inactivation process-the first step in the program-the submarine is placed in a dry dock. Inactivation involves defueling the submarine, removing classified and sensitive military equipment, and generally preparing the submarine for extended waterborne storage or scrapping. Upon completion, the bare hull is formally decommissioned and struck off the Naval Vessel Register. After the removal of the reactor compartments, the hull is cut into large sections for removal from the dry dock. Removable scrap is segregated into recyclable and waste material with further segregation of the waste material into hazardous and non-hazardous waste. The toxic wastes have to be treated very carefully during the scrapping process and removal requires protective measures for the workers (e.g.: certain hazardous materials such as polychlorinated biphenyls (PCBs) or asbestos). Most of the toxic wastes are various types of insulating material. But there are oil and oil-related products. One significant type of toxic waste is the sulfuric acid from the vessel's lead batteries which could amount to more than 20 tons. Some of these materials, and where they might be found on board ship, are listed in the following table:

Table 2 – Toxic Wastes produced during dismantling (Source: MacKinnon III and Burrit, 1995, p.1)

| Hazard | Source on submarine |
|---|---|
| Polychlorinated biphenyls (PCBs) | Electrical cables; ventilation gaskets; transformers; foam and other insulation; hydraulic oils; greases; machinery mounts and other rubber products |
| Asbestos | Pipe and ventilation lagging; valve packing; electrical cable coverings; heat shields; sound dampening; deck tiles |
| Lead | Ballast; paint; batteries; cable; plumbing systems |
| Mercury | Instruments; fluorescent light tubes |
| Cadmium | Plated fasteners |
| Ethylene glycol | Antifreeze; air conditioning and refrigeration systems |
| Halogenated fluorocarbons | Refrigeration and air conditioning systems; aerosol cans |

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## 5. THE FRENCH STRATEGY FOR DISPOSAL OF NUCLEAR-POWERED SUBMARINES

The French Navy had decommissioned your first nuclear propulsion submarine (Le Redoutable) in 1991 (Jane’s Defence Weekly, 29 May 1996, p.10). Meanwhile for the first one was transformed it into a museum, in 2010 on Cherbourg shipyard, *Le Foudroyant* (the last one of *Le Redoutable* class) still was waiting her dismantling the rest of the ship, just after removal of the reactor.

The long-term storage of all radioactive waste is handled by the National Radioactive Waste Agency (ANDRA) which is also responsible for civilian nuclear waste. The process of dismantlement is in many steps similar to US Navy. After unloading the fuel, the reactor compartment, forming a section of the ship, is isolated and separated from the rest. The compartment is emptied of all removable equipment and sealed off. After that, the section is dry-stored at Cherbourg for 15-20 years. A location protected from inclement water and large enough to store other submarine sections, as dismantling progresses, has been provided at the Cherbourg arsenal (Masurel, 1995, p.3).

The reactor is dismantled separately and resulting waste is stored on the surface by ANDRA. After 15-20 years of interim storage, the circuits and components of the reactor can be dismantled and cut into transportable packages. This is necessary once France does not have a long-term storage site able of accepting a “package” with the volume and mass of a reactor compartment.

The fuel disposal strategy plans have two phases of interim storage: firstly, for 5 to 20 years in a pool until the radioactivity level has decreased sufficiently to allow dry storage. And then, secondly, dry storage for another 10 to 50 years before reprocessing or terminal storage by ANDRA. For this last step no decisions have been made so far. Problems with this strategy based mainly on medium-term storage will increase as more nuclear submarines are taken out of service.

## 6. THE UNITED KINGDOM’S PLANS FOR DISPOSAL OF NUCLEAR-POWERED SUBMARINES

Last years, in Devonport shipyard has been working in the De-fuel, De-equipment and Lay-up Preparation project (DDLP). Almost all the submarines which belong to British Navy were moored and are still waiting final disposition. From these submarines, only the spent nuclear fuel has been removed. All the remaining reactor compartments are still inside the hulls and have been sealed in after removal of the fuel elements. The entire hulls are currently being kept afloat in the naval dockyards at Devonport and Rosyth.

At least until the end of the 1980s, the British Navy had recommended the sealing of the submarine hulls and their sinking in the mid-Atlantic as by far the safest and least disruptive means of long-term disposal (House of Commons, 1989). However, since this option does not seem available any longer due to the latest revisions of the London Dumping Convention, UK submarines will probably be disposed of by deep land burial. The reason for choosing this quite expensive option is that, in the United Kingdom, a deep repository is already being planned at Sellafield in northern England while a suitable, shallow repository will not be available.

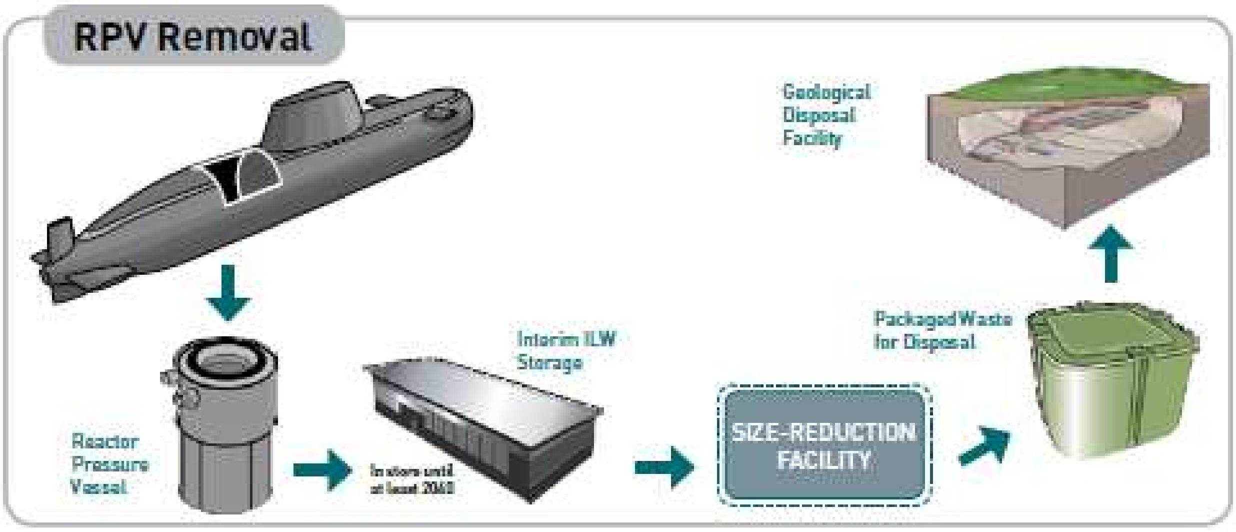


Figure 5 – UK Submarine Dismantling Project, Submarine Dismantling Consultation, MoD. (2011).

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## 7. DISMANTLING RUSSIAN SUBMARINES AND DISPOSAL OF REACTOR COMPARTMENTS

The dismantlement process of titanium-hulled submarines is much more time-consuming and requires advanced equipment. After defueling submarine reactors, the ship systems are shut down and reusable equipment is removed from Russian submarines. Besides that, missile compartments of strategic submarines are dismantled according to the provisions of the strategic Arms Reductions Treaty.

However, differences exist in sequences of further operations of submarine disposal. The most of defueled Russian submarines have to be kept afloat at least for 15-20 years until dismantling; they are rarely undergone appropriate operations for waterborne storage. As a result, personnel have to be kept aboard the submarine, in order to prevent sinking the ship near its pier. The threat of an environmental disaster resulting from the failure to take steps to salvage these vessels is growing every year. Lacking permanent land-based storage sites, the Pacific Fleet has had to develop provisional solutions. The submarine’s outer shell is stripped away; the reactor compartment and the two adjoining compartments are hermetically sealed as a single unit. The sealed compartments are towed to a remote base or bay for temporary-but indefinite-floating storage (once sealed compartments are also less likely to sink than a whole submarine).

So far, there is no equipped long term storage facilities to place removed reactor compartments and keep them under control. Disposal of submarines with accidental reactors represents a specific problem in Russia. There are three or two accidental submarines correspondingly with the Pacific and the Northern Fleets. According to experts, the fuel of some of theses submarines can not be removed by existing technical means. Managing reactor compartments of the accidental submarines needs specific technologies as well.

Table 3 - Core and fuel data for KLT-40 of NS Sevmorput (source: Bellona Foundation Report nr 2:96 and Jane´s Fighting Ships 2012-2013

| Parameter | Value |
|---|---|
| Reactor power | 135 MWth |
| Core height | 1 m |
| Core diameter | 1.21 m |
| Mass of U-235 in core | 150.7 kg |
| U-enrichment | 90% |
| Number of fuel elements | 241 |
| Fuel element lattice type | triangular |
| Fuel element lattice pitch | 72 mm |
| Shroud, outer diameter | 60 mm |
| Number of fuel pins | 53 |
| Fuel pin lattice pitch | 7.2 mm |
| Fuel pin diameter | 5.8 mm |
| Cladding material | Zr-alloy |
| Fuel material | U-Zr-alloy |

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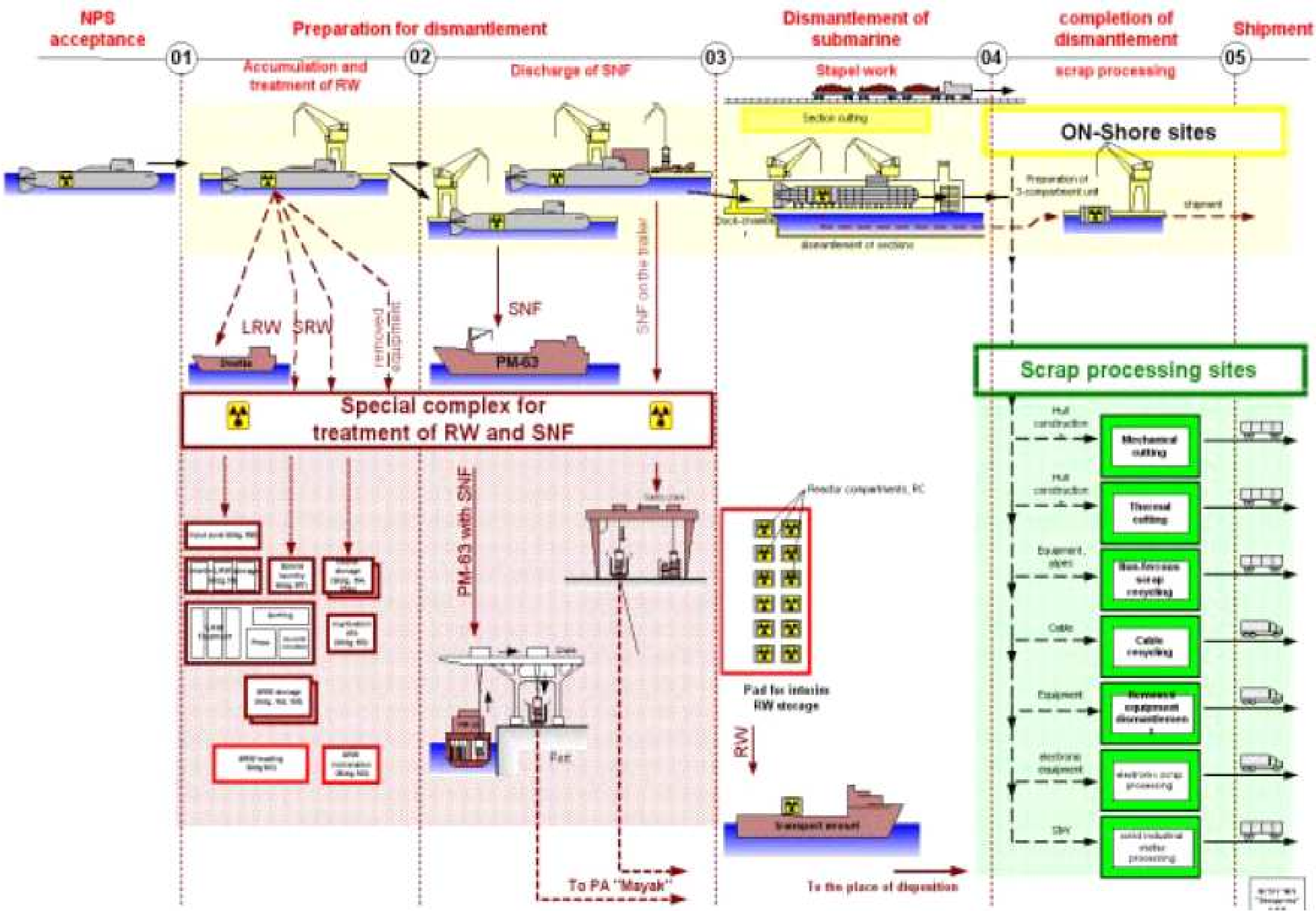


Figure 6 – Russian decommissioning for Long term waterborne storage (Source: Kalistratov. (2011))

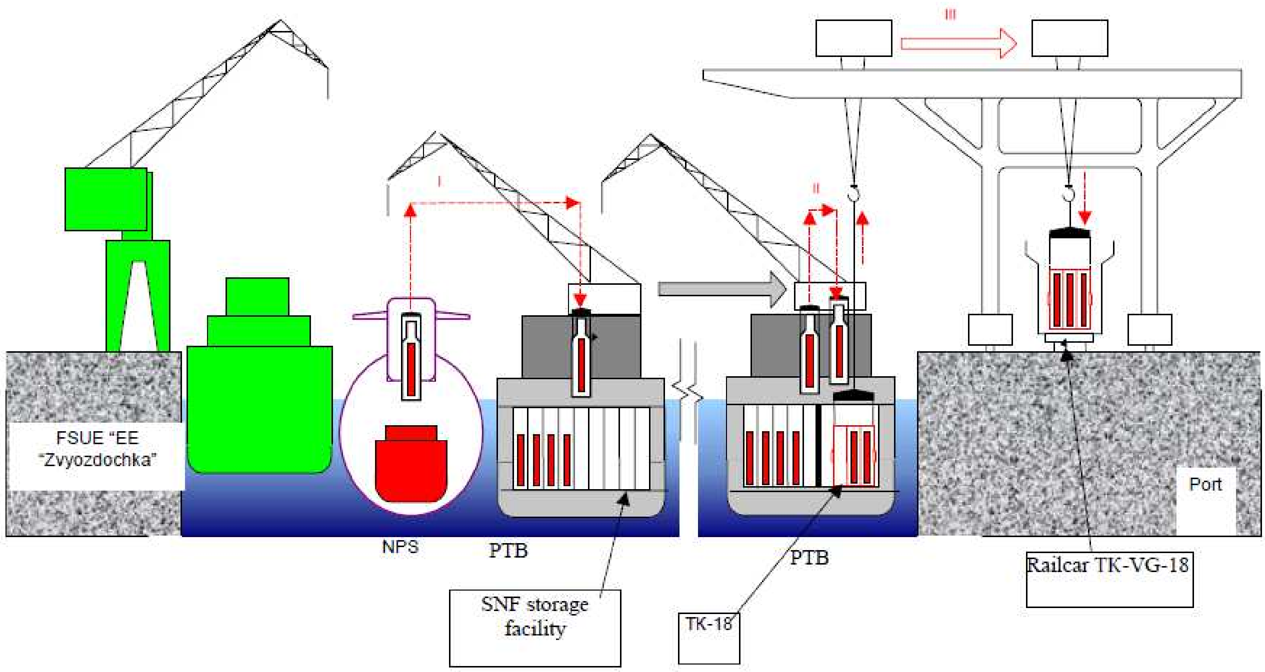


Figure 7 – Russian schematic for nuclear fuel removal (Source: Kalistratov. (2011))

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## 8. TECHNICAL ISSUES

Decommissioning of nuclear submarines may cause costs to grow continuously and will cause environmental problems for the years to come. The magnitude of the problem is not really known to the broader public. The time horizon of radioactive decay is far beyond the human ability to plan. Today no one can forecast the ecological risks of land burial on ground water – and it is only a weak hope that the consequences of past Russian dumping will not greatly affect the ecological stability of whole Sea areas.

In the United States, France and Great Britain, the decommissioning process seems to be progressing less chaotically. But in these countries as well the problems of long-term storage of military and civilian nuclear waste still have any problems. This is all the more pressing, as the build-up of nuclear-powered submarines enters the next round. New generations of submarines have been ordered or planned in several nations; in fact, nuclear submarines are becoming increasingly important in future nuclear deterrence strategies. However, there now exists a unique chance to stop a new arm build-up in this field of military technology.

## 9. SOCIAL ISSUES

The licensing methodology has been growing in recent years as complex socio-technical systems become more common. In addition to complexity, the size and financial investments of these tasks on the end of life cycle for each vessel, amplifies the importance to have acceptance from public opinion. Thus, it is important to develop a specification and design methodology in order to avoid waste of time and money due to a complex decommissioning whose functions are known a priori, managing the risk on parallel.

Moreover, to facilitate the exchange of information and national experiences relating to training, competency and human resource development considerations for decommissioning of nuclear power-plant ship; however, due to reserved data for each nation policy does not allowed to share this information, keeping in secret whatever the evolution, discover and advanced experience.

A military vessel seems to have more acceptance rather than civilian merchant ships (for instance, NS Otto Hahn, Mutsu and Sevmorput had some problems during them commissioning). Furthermore, a slightly increasing in the number of requirements applicable to US Navy has been arisen problems directly with costs.

Education may help the public to understand and accept nuclear power, as reference [1] during a simple presentation to Korean students about nuclear power, nuclear safety and radiological protection.

## 10. LESSONS LEARNED

Successful decommissioning of nuclear facilities depends on the availability of competent, qualified and capable staff, and rigorous demands are placed on such staff owing to the complexity of the technology used and the need for high standards of performance and conduct. Ensuring the availability and competence of personnel involved in decommissioning activities is a key requirement for organizations leading and managing decommissioning programs and human resource development, including specialized organizations and companies that supply services related to decommissioning. Current approaches to human resource development in the nuclear industry typically involve an increasingly integrated approach to workforce planning, education, training and nuclear knowledge management. This evolution towards a knowledge-centered integrated approach was possible because of the increasing interest in the use of digital technologies to support the planning and implementation of decommissioning projects.

Lack of planning tends to raise costs. For instance, in the British Navy, there is no any public announcement so far about how the submarines will be dismantled, once all dangerous components have been removed. Probably the pressure hull must be opened in some spots in order to remove the nuclear steam raising plant (NSRP) and whether the pressure hull will moved on to another place, how much harder workload will be employed to make again the ship stable and floating (the major ex-military British vessels are dismantling in Turkey, thus all the pressure hull should be dismantled in Devonport and Rosyth and after that, all waste steel must be sent to Turkey by sea).

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There is just one specific place in Devonport to remove the nuclear fuel from submarines responsible to perform the dismantling and its facilities now follows the recent standards from Office of Nuclear Regulation (ONR). According to UK government, it is still missing specialized knowledge to Submarine Dismantling Project.

The problem of submarine disposal has become the one to be considered of the highest priority in Russia. However, there is an impression that Russia's government continues to ignore this fact by providing scarce financing. The analysis of the US program shows, that significant resources are needed for rehabilitating the environment and population from the consequences of nuclear powered submarines exploitation. Russia will probably have to pay much more compared to the US, taking into account the fact, that it does not have an adequately developed infrastructure to solve these problems. In addition, Russia has to deal with the effects of careless and insufficiently considered actions in maintenance of nuclear powered submarine fleet in the past.

It is satisfying the stringent regulations that prove to be a primary cost driver for decommissioning and waste disposal. Reactor types and sizes, the number of reactors on an individual plant site, and labor costs are among the main factors affecting costs. Thus, it is so important to develop a good recycling policy after nuclear-power plant ship inactivation.

The experiences made by the dismantlement of the ship were the following:

- A precise knowledge of the structural arrangement and the radiological state of the installations is an important condition for a successful work. That implies that the works are done continuously by the same staff of well-trained workers with knowledge of the design of the nuclear part of the ship and exact knowledge of the existing dose rates at the working places. The latter implies an overall dose measurement before and during the works as well to arrange optimal radiation protection precautions.
- In addition, the knowledge of the radiological state of the installations gives the possibility to choose the optimal decontamination method both under radiation protection and effectiveness aspects.
- The use of mechanical methods for the disassembling of the installations has shown two advantages, the exposure of the workers can be reduced and the cleaning works after the removal of the installations can be simplified. The experience shows that the optimum can be reached with shearing or cutting tools. Some mechanical methods however have turned out to be unsuitable by the disassembling of load shielded components because tools like saws and milling machines were blocked by the load shavings; in this case methods for melting the load are more proper before disassembly.
- When using mobile shields, it has turned out that the use of shields which can be fitted and taken apart in a quick way is desirable. To use methods like screwing instead of welding when assembling them is a more effective radiation protection concept.
- When using buffer tanks for collecting wastewater and other contaminated liquids it is shown as necessary that design supplies a technical system to remove the charges the deposited sludge. The accumulated sludge in the buffer tank has created a source of remarkable dose rate of the works.

## 11. CONCLUSIONS

Given that the decommissioning process may take several decades, it is important that plans are defined in advance. Greater funding and international cooperation are required to share information and expertise on the decommissioning of submarines, as nuclear submarines finally dismantled.

It will apparently take several dozen years in order to accomplish a feasible submarine disposal program. Thus, the priorities must be given to the following tasks.

1. Keeping decommissioned submarines afloat.
2. Defueling the reactors of decommissioned submarines.
3. Managing the spent nuclear fuel of submarine reactors, accumulated at fleets.

At least, accomplishing these tasks will allow solving other problems in a controlled situation and avoiding taking urgent "fire" measures - which, unfortunately, has become a traditional policy in our country. Decommissioning of nuclear submarines will cause costs to grow continuously and will cause environmental problems for the years to come. The magnitude of the problem is not really known to the broader public.

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