REMOVAL OF SPENT FUEL FROM NUCLEAR SUBMARINES WITH SOLIDIFICATED LIQUID METAL COOLANT

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ABSTRACT

Based on the available information on storage of the unloaded nuclear fuel of nuclear submarine (NS) reactors with liquid metal coolant and that as concerned non unloaded nuclear cores (1,2.3), as well as Proceedings of 1st International Conference on Heavy Liquid Metal Coolants in Nuclear Technology (4,5,6) authors prepared a preliminary draft partnership proposal for development of the conceptual project of improvement of radiological situation at the North-West region of Russia. It is supposed that this work should be done through the removal of spent fuel from NS with solidificated lead-bismuth coolant (LBC) from the above region to the fuel reprocessing plant. A few alternatives are considered as far as concerned spent fuel treatment, including fuel transportation, dismantling and accompanying technology operations.

Taking into account a possible accident scenarios while fuel removal and transportation, both feasibility and ecology study comparison of these alternatives should be done carefully.

INTRODUCTION

During 1960 – 1990 a number of NS with liquid metal lead-bismuth coolant in the reactor primary circuit had been in operation in the former Soviet Union Navy. All of the operated reactors in question are belonged to the intermediate neutron reactor type. The reactor fuel composition included the inter- metallic compound UBe^{13} with U^{235} enriched up to ~90% and dispersed into the beryllium matrix. Metallic beryllium served as reflector in these reactors.

At present all of these NS (including so-called Alfa–class submarines) are decommissioned. Nuclear fuel has been unloaded from four nuclear submarines, while the four remained still contains nuclear fuel in their reactors with the frozen coolant.

The nuclear safety of spent nuclear fuel (SNF) is provided because of the reactor cores both inside the submarine vessel (unloaded SNF) and that in the coastal storage have been put into a deep sub-critical state, that is due to significant burn out of the fuel and full insertion of the neutron-absorbing control rods (NACR) into the cores.

However, the long-term storage of SNF has not been considered before under the mentioned conditions. It was assumed that after several years of cooling and storage the spent cores should be transported to the nuclear fuel reprocessing plant. Unfortunately, as soon as the former Soviet Union has been destroyed, the further advance of this problem has been postponed for very uncertain time with regards to SNF unload from the remaining submarine reactors.

The purpose of this work is just to attract the attention to the existent problems and, thus, to develop and realize the acceptable approach proposed for radio-ecology assessments improvement at that site, including a) unload of the SNF; b) removal SNF from the coastal technical base storage; and c) transportation SNF to the processing plant.

STATUS AND MAIN PROBLEMS

Background

The reactors of the above mentioned NS have been developed under the scientific supervision of the Institute of Physics and Power Engineering (IPPE). The first NS submarine (Project 645) had two-reactor nuclear power facility on the board. In 1968, after the accident with the core partial destruction on the left board reactor the NS was brought to the stabilized stop and then all free cavities of reactor and reactor compartment were filled with inhibitors in order to bring them into nuclear and radiation safe condition. In 1981 the submarine was dumped in the Kara Sea at ~50m depth near New Land (Novaya Zemlya) Island.

All other NS, which are known in the West as Alfa-class submarines, had one reactor on the board. One of the peculiarity features of the NS with liquid metal reactors is that their cores can be loaded and unloaded in the form of a separate removable block (SRB), using special transport technological equipment. The SRB includes the core with loaded NACR, reflector and the upper plug of biological shielding.

Having been unloaded the spent SRB are placed in the special storage at one of the coastal base on the Kola Peninsula. They were put into the steel shell, which contains a pure (non-radioactive) lead-bismuth eutectic at temperature from ~150 to ~160°C with its further cooling (melting point is 125°C) after loading of all SRB. At present the estimated residual heat release in all cores (both unloaded and loaded from the reactors) is as much as <3 kW.

There are also two spent SRB of the first run of the first NS of Project 645, which have been unloaded from the reactors in 1967 and placed into the coastal storage. Their storage conditions are the same as that for the above NS. The fuel unloading and overloading in some of the later NS was not fulfilled and, thus, their core energy output is as much as from ~10 to ~100% of the energy reserve.

Two runs of the reactor core have been worked out at the IPPE nuclear test facility – prototype of NS with liquid metal cooled reactors. The SNF of the first run was unloaded in 1961, while that of the second run in 1976. Both have been dismantled into separate cassettes and fuel element groups using the special remote control equipment at the dismantling section allocated at the test facility.

Current Status

At present four cores of the NS in question are not unloaded.
First core: The first one has worked out about 10% of the run. Due to failure of the primary circuit auxiliary pipelines and the impossibility to repair them, this NS has been decommissioned. The reactor compartment has been cut out and free volume of primary circuit has been filled by inhibitor (furfural). Besides, the bitumen layer of ~1000mm thickness was put on the reactor compartment upper deck surface including the reactor lid. Under existing condition the reactor compartment is allocated at stabilized stop point for the long-term storage without nuclear fuel unloading.

Second core: As concerned the second NS, at the start of its decommissioning the sharp deterioration of radiation situation has been occurred at the reactor lid due to destruction of the NACR, that had europium in the absorbing composition. Some amount of dust-like fraction containing Eu^{152} and Eu^{154} nuclides penetrated into the upper space of the NACR cases (reactor lid area), which resulted in the deterioration of radiation situation in the reactor compartment. That was one of the reasons, which made a complicated nuclear fuel unloading from reactor. At present the coolant in the reactor is frozen. The submarine is in the sediment stop at its registration site. As soon as the design and engineering procedures on normalization of radiation situation at the reactor lid area would be carried out, the reactor fuel could be unloaded from the reactor and placed into the coastal technical base storage in accordance with the type of already unloaded fuel from the other submarines of this class.

Third core: In 1982 as the result of the inter-circuit leakage and partial radioactive coolant spilling in the reactor compartment the operation of the third NS reactor was stopped. The coolant was frozen in the reactor. In the following the NS reactor compartment was cut out and, after welding the additional sections to its stern and nose ends for buoyancy support, was shipped afloat to the sediment stop. Probably, in the future the fuel can be unloaded from the removed reactor.

First core: Being cut the reactor block with the 3rd nuclear core was replaced by a new one with fresh core number four, and, thus, this NS was in operation up to 1993, while nuclear core workout proved to be as much as ~14% of the energy reserve. After decommissioning start the coolant was frozen in the reactor and NS was shipped afloat to the sediment stop. Under the certain conditions the fuel from the forth NS could be also unloaded and shipped to the coastal storage.

Radioactivity and Nuclear Safety

As it was mentioned, the nuclear safety of SNF is provided because of the reactor cores have been put into a deep sub-critical state. In this case the NACR drivers at the unloaded cores have been dismantled and the sealed steel caps have been installed and welded to the cases of the absorbing rods.

Both unloaded and non-unloaded SNF are placed into the "frozen" lead-bismuth alloy. Unauthorized input of the positive reactivity during the SNF storage is excluded as the LBC in the safety system cases is "frozen" and the NACR are immobilized (in the removable blocks the safety rods are also immobilized). The safety rod drivers of the NS with unloaded SNF are de-energized and the primary circuit pressurization is provided by the standard means. The possibility of appearance of open cavities in the frozen eutectic in the NS reactors is excluded by the "freezing" technology of the primary circuit coolant. Thus, the penetration of the condensed or other moister into the core in case of depressurization of the primary circuit (and introduction of the additional positive reactivity) is excluded.

In the coastal storage the covers of the steel montejus, in which the SNF is stored, were tightened after the removable blocks loading and the layer of bitumen was put additionally to the joint area in order to exclude the penetration of the condensed moisture, rain and ground water. However, the quality of storage pressurization has not been checked in a proper manner.

After unloading of the SRB the main residual reactivity of the reactor compartment is concentrated in the reactor vessel structures (more than ~99%), as well as in the equipment and the primary circuit pipelines. The later is due to induced radioactivity of the reactor steel structure, radioactive depositions on the inner surfaces of the primary circuit, radioactive coolant residues. In the following it is supposed, that after dismantling and removal of the non-radioactive equipment and its possible utilization, the NS reactor compartments with the unloaded nuclear fuel will be placed at the permanent long-term storage.

Radiation and ecological safety of the SNF store is based on depth-echelon protection principles used on the ways of a possible release of the radioactivity into the environment. Actually, it represents a consequence of physical barrier chains of the safety supporting. There are fuel element matrix and shell, as well as "frozen" coolant (possessing good immobilizing properties), the sealed primary circuit (or steel montejus in the coastal storage), and strong reactor vessel, that serve as the natural barriers on the way of fission product release. In accordance to the radiation and technological control data all reactor cores both in storage and in the NS reactors practically do not have any damages of the fuel element shell. The coolant matrix, reactor vessel walls and strong vessel of submarine serve as the barriers for the radioactive products that are accumulated in the coolant and the inner vessel structures.

Possible Problems

It should be noted that the available coastal storage infrastructure does not assume the long-term storage of SNF under the above mentioned conditions. That is why during a long-term storage the unlikely but quite possible ways of the SNF system sub-criticality change cannot be excluded completely. The physical and chemical processes (galvanic and chemical corrosion, phase conversion), as well as possible diversion and terrorist acts, earthquakes, fires, can directly influence on the SNF system criticality. That is why that SNF must be undoubtedly unloaded from the reactors and coastal temporary repositories and then should be transported for reprocessing. Only in this case one of the possible sources of potential radio-ecological danger at the Russian North-West region could be eliminated and the social tension of human community of the neighboring countries would be decreased.

The study of a possible ways of the solution of this problem is the main goal of the project in question.

SCOPE OF WORK AND RELATED ISSUES

ISTC Partnership Capabilities

The preliminarily consideration based on the analysis of the background, cost effective estimations and people to be involved showed that this project could be carried our within the Partnership Project of International Science and Technology Center (ISTC).

In accordance with (7) the ISTC is an intergovernmental organization dedicated to the nonproliferation of weapons and technologies of mass destruction. The ISTC achieves its objective by funding peaceful scientific and technical research by former weapons scientists in Russia and Commonwealth of Independent States (CIS) countries.

In 1992, the ISTC was founded by international Agreement by the states of the European Communities, Japan, Russian Federation, and the United States of America. Since 1992, other countries have joined the ISTC and committed to the principles of nonproliferation, including Norway, Armenia, Georgia, Belarus, Kazakhstan, the Kyrgyz Republic, and the Republic of Korea. Sweden and Finland were independent members of the ISTC before joining the European Union. As defined in the international Agreement establishing the ISTC its objectives are as following:

- To give CIS weapons scientists, particularly those with knowledge and skills related to weapons of mass destruction and their delivery systems, opportunities to redirect their talents to peaceful activities;
- To contribute to solving national and international technical problems;
- To support the transition to market-based economies;
- To support basic and applied research;
- To encourage the integration of CIS weapons scientists into the international scientific community.

The principle activity of the ISTC is the funding of peaceful scientific research. Each month, the Center receives from 30-40 project proposals from scientific teams throughout the CIS. Each proposal is evaluated for its technical merit and adherence to the ISTC objectives. Private and public companies and institutions work with the ISTC by funding scientific research, which benefits their businesses and technology base.

Partners recognize the important benefits, which the ISTC offers to do business in Russia and CIS countries, and they assist the ISTC in meeting its nonproliferation objectives. For any project to be funded by ISTC it is important to establish international collaboration between ISTC applicants and scientists from Financing Parties working in relevant areas of R&D. The authors of a project proposal to the ISTC are recommended to seek potential collaboration at the early stages of proposal preparation.

A prerequisite for submission of a Partner project proposal is that the sponsoring organization has been introduced and accepted as an ISTC Partner. ISTC Partner project proposals are normally developed jointly between a Partner and one or more CIS institutes.

However, a proposal submitted to the Center through the regular channel may become a Partner proposal, provided Partner expresses in writing its readiness to provide full funding for the project. Among the main benefits for the foreign Collaborator as a Partner of the Project in question there are as following:

- Contact with high-level and highly-skilled CIS scientists and engineers
- Participation in experiments at unique installations and facilities
- Early access to results arising from ISTC Projects
- Improved focus and efficiency of R&D activity through information exchange and consultation
- Potential partnership in commercialization of results

In accordance with Article VIII of the ISTC Agreement, Project recipients will give to the Center and to each Party, which wholly or partly finances a project the right of access to carry out on-site monitoring and audit of all activities of the project. Project agreements will specify the portions of facilities, equipment, documentation, information, data systems, materials, supplies, personnel, and services which will concern the project and therefore will be made accessible for monitoring and audit. Project recipients shall have the right to protect those portions of facilities that are not related to the project.

Thus, while at WM'01 Conference authors of this work would like to attract attention and understand the interest of the potential Partners and preliminarily discuss a detailed work plan and budget in order to build the ISTC Partnership Collaboration.

Participating Organizations and Personal

The current Project works will be carried out mostly by the Institute of Physics and Power Engineering (IPPE) and Research and Development Bureau "Gidropress" (GIDROPRESS), including participants, which have the necessary experience in development and decommission of heavy liquid metal cooled reactors for NS.

Table I. Scope of Work. A brief description of the main tasks of the work that could be fulfilled in the framework of the above collaboration.

Task Description	Duration, months	Estimated Efforts, man-months
Task 1. Inventory of radioactivity accumulated in loaded and unloaded spent removable blocks (SRB) of NS reactors, structure materials, coolant, gas system of the first circuit, in reactor volume in the whole, as well as radioactivity time change.	3	10
Task 2. Development of possible transportation – technology scheme of removal of SRB from the storage area to dismantling site.	6	30
Task 3. Development of conceptual proposals on creation of the simplified points for dismantling of SRB to separate cassettes or fuel element assembly directly at storage site or fuel reprocessing plant.	6	30
Task 4. Revision of available infrastructure of transportation – technology complex existing at the coastal technical base. Formation of the list of missing equipment, as well as that requiring repair or change, modernization of building structures, and organization-technical measures in order removal of the remaining unloaded removable blocks.	3	30
Task 5. Revision of technical system condition, radiation situation at NS with spent nuclear fuel. Study of possibility of removal of SRB from the NS reactors.	3	30
Task 6. Analyses of requirements for accepting of SNF at fuel reprocessing plant and formation of list of necessary technological equipment and fitting out.	3	20
Task 7. Formation of list of emergency situation while treatment with SRB during different phases of realization of transportation - technology scheme: unloading from reactor, on-cite dismantling ore removal, possible accidents while transportation.	6	45
Task 8 Development of possible scenarios and models of release of radionuclides into the environment in case of accidents.	6	30
Task 9. Estimation and analysis of risks and radioecological consequences in case of accidents.	6	50
Task 10. Feasibility study and ecology-economics comparison of different approaches of treatment of spent fuel from reactors with liquid metal coolant.	6	60
Task 11. Development of technical recommendations on NS reactor vessels with unloaded and loaded removable blocks.	6	45
Task 12. Preparation of quarterly, annual and final reports.	6	30

Project Cost, Total Efforts and Deliverables

The total estimated cost is as much as 150000$, while total task efforts is ~410 man-months and work duration is 18 months. During that period 3 meetings are planned to be held in order to correct the project work plan (in Russia), to discuss how works are fulfilling in general (in Partner's Country), and to discuss the final report and results (in Russia).

Within working period the following deliverables should be made:

Reporting Period	Deliverables
Every Quarter	Short Quarterly Reports
After 12 months	Full Annual Report
After 18 months.	Final Report

CONCLUSION

In order to start the joint collaboration authors are going to present as early as in February 2001 detailed work plan of this study while at the WM'01 Conference. The subject of study could be validation of optimal way of nuclear fuel unloading and core dismantling and its after-utilization. The main technical issues of work plan to be discussed are as follows:

- Creation of database on radioactivity composition and its time distributions.
- Determination of radiation heat depositions in the cores.
- Analysis of possible accidents in the course of work fulfillment.
- Prediction of accident radiation consequences, including personnel and population dose stresses and radiation risk level.
- Ecology and economics analysis of variants of transportation and technology scheme of the core delivery at dismantling area.
- Elaboration of the expert recommendations.

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