# THE PACIFIC FLEET NUCLEAR POWERED SUBMARINES DEFUELING AND DISMANTLEMENT OF THEIR REACTOR COMPARTMENTS

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## ABSTRACT

In the next thousand years mankind will meet different new challenges; some of them are unknown or hidden so far. Our responsibility is to solve the problems we have already faced with, and we must settle it properly, as quickly as possible and with the minimal losses. What shall we do with retired Russian nuclear powered submarines (NPS), that bring the actual nuclear and radiation threat to Russia, the countries of the Northern Region and the Pacific Basin? The main resolutions of the basic issues caused by the necessity of spent nuclear fuel (SNF) from nuclear power plant (NPP) of NPS removal, SNF disposal, and NPS reactor compartments (RC) management are presented in the paper. Many of submarines with unloaded SNF are mooring around the naval bases and ship repair plants (SRP) at the Far East of Russia. For the last few years the Russian Pacific Fleet has only accumulated the floating NPS with SNF. All SNF ponds are now packed; the shipment of SNF from the Far East to the reprocessing plant in Siberia is practically discontinued. The fresh alternative for the integrated SNF defueling of the retired Russian NPS and its storage is developed by the Russian experts. Instead of the routine approach, the removal of an intact drained reactor pressure vessel (RPV) with its core and internals is considered to be preferred. The removed RPV is to be transferred into a two-purpose cask, and the casks with the intact RPV should be transported to the available coastal drifts which are to be used as a long term storages. A closed RPV with core and internals removes from a ship's NPP more than 99 % of high level activity waste (for non-accident NPP). It principally changes the approach to the reactor compartment management.

## 1. INTRODUCTION

Several concepts of decommissioning of NPS and other ships and vessels with nuclear propulsion has been developed in the United States and Russia (Final Environmental Impact Statement, 1984, Analytical Report, 1995, Mazokin et al., 1996, Gavrilov et al., 1996, Dovgusha et al., 1996, Gladkov et al., 1996). They are based on the principally different projects ranging: from the long-term protective storage of the written off NPS or their three-compartment vessels "in a coastal water area" and the RC holding at a special site or near-surface storages to the complete dismantlement of these ships and vessels.

In every case, the preference must be given to the nuclear, radiation and ecological safety of the defueling of the retired ships and vessels, storage of SNF and their dismantlement, first of NPS.

A long-term floating storage of these NPS with unloaded reactor cores before defueling and decommissioning poses actual everyday nuclear and radiation risks. However, the multiplicity of the writing off NPS in Russia (the number of the retired Russian NPS to be decommissioned is about 150 and almost each of them has two NPP) without necessary material and financial resources for SNF disposal and dismantlement forces to store high-enriched SNF directly in the NPP reactors as it was emphasized in the Analytical Report of 1995 (AR).

The analysis of the SNF management, including Russian fleets infrastructure, rate of core removal and shipment SNF to the reprocessing plant has proven that the storage SNF in the retired submarines NPP will take more than 20 years. It causes a nuclear and radiation threat not only for the mooring areas but for the considerably outlying regions. In addition, the defueling and decommissioning of the useless reactors and floating ships and vessels as a whole needs the proper maintenance by companies. Several billion rubles, 1997, (about one million dollars) must be spent to each of these NPS maintenance; and Russian Navy has to divert both manpower and monetary resource from the acute problems of the operating Russian Fleet.

*Therefore, now these issues are the most pressing for the majority of Russian Navy leaders and the most if not all the experts in the field* (Khlopkin, 1996, Smirnov, 1996, Mitenkov, 1997, M).

Now several Russian ship-building yards and SRP have to dismantle NPS in accordance with the principle: we take containing valuables that can be taken easily, everything else – including the environmental problems – to the successive generations. It is interesting that the reactor compartments from the plants and yards come back to the Fleets “for the holding”.

The available scheme for Russian reactor compartments management is not only bulky, capital extensive and requires immense funding, material and labour inputs for their construction and operation, while they does not resolve the final stage of the RC life cycle (AR, Gladkov et al., 1996).

The process layout of NPS reactor compartments without SNF disposal into the near-surface storage (trenches) at Hanford is already realized in the United States (U.S. Naval Nuclear Powering Submarine..,1993). The same solutions have been put forward by several Russian organizations (see e.g. Mazokin et al., 1996, Borisov, 1996) but they only have not considered the pre-decommissioning to the “fuel problem”. It also hasn’t proper infrastructure. This approach is *deadlocked* (Dovgusha et al., 1996), and the absence of any advance in the trend is not occasional.

The well-known financial crisis in Russia following the economy of the transition period does not allow Russia to design and construct new ship-disassembly radiation and technological complexes (SDRTC) for the retired NPS and other ships and vessels with NPP that permits, in particular, dismantling the radioactive equipment and structures of the reactor compartments and other contaminated equipment in stationary conditions of industrially organized production, as it was suggested, for instance, in the investigations summarized by Gavrilov et al in the 1995 Workshop on *Nuclear Submarine Decommissioning and Related Problems* (G, 1996).

Both the “fuel problem” and the necessity to invest in every such SDRTC many billion rubles (several hundreds million dollars) with long-term recoupment “blocks” in the foreseeable future now this unfeasible “all-embracing” approach to Russian dismantling of NPS and ships and vessels with NPP. The Pacific Fleet’s number of retired NPS is less than at the Nothern Fleet, and it makes the settlement of the dismantlement by the common techniques even more difficult.

It should be mentioned that the most serious accident has been during reloading of nuclear fuel of NPS near the Far-eastern coast of Russia (Sivintsev, 1993), and its consequences haven’t been corrected in full so far, including dismantling of the accident NPS. It is conceivable that the consequence of this catastrophe will demand the joint efforts of a few countries, especially the nearest ones.

## 2. SNF DISPOSAL: A NEW APPROACH

### *2.1 SNF Removal: A Fresh Approach*

SNF disposal, as it is emphasized in AR based on the results of recent Research Workshop, is now the basic challenge and retardation for the NPS pre-decommissioning and the following dismantlement activities because the present shipment of SNF from Russian North and Pacific Fleets are much less than the necessary rate of its accumulation from retired and operating NPS. The limits of available interim storage capacities have already really been reached.

In default of the usual practice, the original unconventional decisions must be found, and the new concept of SNF removal (Gavrilov et al., 1997) is one of such decisions. Instead of the routine spent nuclear fuel assemblies removing from a ship reactor – also a dangerous nuclear process, as Mitenkov et al. (M, 1997) stressed – it is proposed that *the drained integral core is unloaded in the covered RPV with all rods of the systems for automatic control. scrams and shims inserted.*

The proposed approach eliminates the nuclear risk and minimizes the radiation threat during nuclear fuel removal for the population and the environment and, simultaneously, reduces the workers' exposure impact for the process. It also cuts the time for defueling with already now reasonable expenditures.

### *2.2 SNF Disposal: A Fresh Approach*

SNF may be removed from ship or submarine NPP by common practice as it is presently accepted in Russia and the USA (U.S. Naval Nuclear Powering Submarine,1993, Dual-Purpose Canister Preferred by Navy for Spent Nuclear Fuel, 1996). The available system of SNF handling in three types of canisters for dry storage of high-level radioactive waste should be used there, including canisters for damaged fuel assemblies. The canisters of every type are tailored to shipment and storage in NUHOMS-MP187 casks.

Removed Russian NPS SNF may be stored both in cooling ponds or, as it was recently supposed by OKB Mechanical Engineering (M), in complexes of small-sized reinforced concrete casks for transport and storage. They suggest placing the complexes at sites only with sheds near Russian Navy bases and SRP, and to use dry mode for SNF storage.

Nevertheless, for SNF removed from NPS using by the mentioned alternative, its shipment and storage, including long-term storage, is much more advanced, especially when simplified dual-purpose casks design are used (Gavrilov et al, 1998).

The covered RPV is the main construction - the barrier for nuclear fuel because the NPP was designed for counteraction to a possible collision impact, and absorbing elements in the core and internals are intended for neutron flux, gamma-, beta- and X-radiation from SNF, fission fragments and artificial radionuclides.

The RPV with the core is incorporated into a cask with neutron and gamma shield. The bioshield is computed with regard to selfabsorbing of the flux and radiation by SNF and its absorption by internals and RPV with lead in the “dried” mode.

Radiation protection of a cask may be manufactured from polymers incorporated boron or polyethylene with lead and boron in the area of core to reduce flux and radiation; led and reinforced concrete or the same composite and concrete are to be used for cutting both neutron flux and rate of gamma-, beta- and X-radiation from the surface of the cask. There considerable amount of such material is in NPS that must be decommissioned, and an average activity of the materials is several magnitudes less than recommended by IAEA for unrestricted release.

Small residual heat rate from fission-product decay at the ship core, especially because at submarines' high-enriched fuel is usually used and NPS before an inactivation are near shores for many years, permits maintaining heat withdrawal by the system SNF - assemblies - internals - RPV - walls of cask to the heat dissipation in the environment. If necessary, a convection heat transfer may be forced by in-vessel volume circulation of air or gas.

For this purpose two unions are to be welded into in-nozzle plugs. The unions should be applied for removal of coolant, drying in-vessel volume and filling the volume by noble gas. A control of the in-vessel volume could be performed by special instruments.

Casks with RPV are to be placed in the coastal underground drifts at the Far East of Russia and the Kola peninsula available near the Nothern and Pacific Fleets bases. The drifts are already investigated for such use, first for storage of unloaded RC of NPS (Mazokin et al., 1996) till placing in them civil NPP designed at the base of suitable NPP-building technologies (Kotenko, 1993). The existing adits at the Novaya Zemlya archipelago might be also used.

Special ships for transport of SNF, including a shipment for a long distance, e.g. from Europe to Japan, are both in Russia and abroad (Miller, 1995), though for optimal shipment of the suggested casks new ships might be required.

Moist air in the drifts and even water leakage from their roofs demand hydraulic insulation of the casks. The insulation may be also fabricated with polymers with boron from NPS to be decommissioned.

The coastal drifts allow anti-attack, anti-terrorist etc external protection. It is very important for high-enriched fuel (Petrov and Sergeyev, 1993). These drifts were created near the submarine bases of Russian Navy especially in the "anti-attack" option, and it allows to cut expenditures for an erection of long-term storages and to facilitate SNF shipment and its placement.

## 3. REACTOR COMPARTMENT DISMANTLING: A NEW APPROACH

Several concepts for domestic NPS reactor compartments management, from long-term storage to dismantling are suggested by Russian experts but each of them has principal shortcomings that obstructs their embody in the execution (AR).

The withdrawal of core in RPV permits not only to "uncover path" to NPS and other ships and vessels with NPP decommissioning. This operation removes the main, usually 99 or more per cent of total radioactivity, including all the fissile material and the largest part of high activity structures and equipment (Final Environmental Impact Statement.., 1984, Dovgusha et al., 1996, Yezovit et al., 1996)[1].

The following operation of disposal radioactive waste is the removal of the I contour equipment: steam generators, pumps, pressurizer etc placed in the caisson (steel - water shielding tank) pits.

The other radioactivity caused, first, by induced radionuclides in the walls of a caisson, mainly the first and, partly, the second ones, and in the hull directly under the reactor. As it has been proven by the survey of the radioactivity of retired Russian NPS (Tsypin et al, 1993), the activity in constructions, including radiation protection materials, external to the caisson is "almost non-radioactive". The same could be argued by data on the activation of the USA Navy NPS hull spot under RPV (Final Environmental Impact Statement.., 1984) and considerably less because the better radiation protection to bottom of RPV activation of Russian NPS hulls (Kotlov, 1996).

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[1] In the paper we consider only NPS and other ships and vessels with NPP written off by schedule. The NPS with damaged cores and long-term wrecked or sunken NPS or their RC as well as NPS with liquid metal coolant isn't viewed.

Because of a rather long, usually 5-10 years, “mooring with cooling” of Russian NPS all nuclides with short and partly of intermediate half times transmute into the stable isotopes, and the total activity in their constructions is many factors smaller than the initial one. Nevertheless, for facilitation RC dismantlement after RPV with core and main equipment of NPP removal it might be desirable.

Thus, in the RC equipment and structures should be only small (by activity, not mass) amount of low-level activity solid waste, both induced and contaminated, mainly in the field of removed RPV. Liquid radioactive waste (LRW) from RC must be transported to the facility for its treatment or conditioning.

The rest of the reactor compartment structures, after decontamination if necessary, may be dismantled for special production, e.g. manufacturing canisters for spent nuclear fuel or radioactive waste from restricted material, or for unrestricted release. In the average, one RC promises up to one thousand tons of metal, including mild and stainless steel, non-ferrous and noble metals, polymers with boron, etc.

The requirements to a dismantlement of the beforehand “cleaned” from high- and immediate-level waste reactor compartment are much less than the ones to SDRTC (G). In particular, a remote equipment and robotics as well as hot chambers shouldn’t be practically used.

Instead of a huge ship-disassembly radiation and technological complexes - a new enormous multi-stage plant with a line of huge works equipped by the unique equipment, facilities and remote cells, it is sufficient to erect (or re-equipped at the available) works at the Northern and Far-eastern SRP which are already reutilize NPS. And the level of necessary investment for the utilization is to be admissible now.

Moreover, the re-using of valuable materials must cut the period of investment repayment in this production. Considerable cutting of erection or renovation work, raising output (dismantling of NPS per year) and labour-saving because dose exposure personnel reduction serves to the same goal.

As a result, the solution to the total problem from the “conceptual approach” goes over to the feasibity stage, and its execution is determined by years instead of abstract decades.

Certainly, the dismantlement of RC is impossible if the problem of low-level liquid and solid waste has not been solved. Thus, low-level activity metals are to be additionally cleaned by re-melting and, perhaps, will be used for restricted, as, for instance, materials for casks manufacturing.

## 4. DISCUSSION AND CONCLUSIONS

Lately Russian experts have put forward two complementary approaches (Dovgusha, 1966, M, Gavrilov, 1977, Gavrilov, 1998) permitting to solve effectively SNF removal from NPS, surface ships and vessels, its disposal, and dismantling of reactor compartments.

The suggested strategy of RC dismantling logically extends the issues of ship and vessels SNF removal and disposal. It allows to reutilize the NPS to be decommissioned and the ones to be retired in the next years, NPS within a short time, in comparison with the current approach. Moreover, the decommissioning of each RC may be begun just after its inactivation, and it permits to avoid the radioecological problems caused by anywhere obliged storage of the retired ships and vessels or the reactor compartments of NPS.

SNF is removed, conveyed and storage in the RPV with head - additional barrier - in a standard core without coolant directly to reduce the criticality. All absorbing rods in the core are used for the same cause. The rods as well as internals and RPV and nuclear fuel itself absorb neutrons and other types of radiation from SNF and high-level activity constructions.

The strategy, to contract the available one, doesn’t require necessary and rather expensive shipment of high-enriched ships’ and vessels’ SNF by rail to the “Mayak” plant in Siberia through densely populated areas and cities. It can be placed into local storages in the existing drifts.

The availability of all used infrastructure for NPS standing up for tens years and thereafter their decommissioning of Russian Navy in the strategy isn't necessary.

During the preliminary stage to SNF into RPV disposal a considerable part of high- and intermediate radioactive equipment and a large volume of low-level waste are to be removed.

The overwhelming majority, more than 99.9 per cent, of the total activity of NPS (surface ship or vessel) is removed for the preparation for SNF disposal and for this process.

It is the reason for changing the existing approaches to RC management of the Russian Fleets.

It permits to secure an appropriate nuclear and radiation safety of population and environment, both in nearest and distant countries of Pacific basin already in the first decade of the next century, to reduce staff radiation exposure and manning level that especially important for the Far-eastern plants, to cut material inputs and cash expenditures with curtailing a necessary investments and its payback period for creation of ecologically safe global world.

The basic techniques and facilities for tackling the issues are being patented.

The principal "findings" of the proposal for ships and vessels permit:

1. To use RPV with the core incorporated spent nuclear fuel as a small bulk "can" for removing, shipment and storage of drained SNF. It makes possible to protect from nuclear accident and accelerate the process of SNF removal in comparison with the routine technique.

2. To use a covered RPV as an additional barrier to keep the environment clear of radioactive waste during a SNF removal, transportation and storage of SNF.

3. To use SNF in the core, screens and other internals and RPV with its cover as an absorbed radiation structure for cutting the radiation rate by a factor of 100 - 1,000 times (for non-accident reactors).

4. To minimize replacing of high-enriched SNF by a unit sea shipment to a coastal shift.

5. To guarantee a high-reliability storage of high-enriched SNF with, if necessary, its removal.

6. To diminish, in comparison with the routine manner, a number of casks to be used for shipment and storage of naval SNF, with a plausible lowering of requirements to their design.

7. During inactivation and pre-decontamination to remove from RC all high- and intermediate and considerable part of low-level waste.

8. To dismantle reactor compartments with previously removed largest part of radioactive waste in conditions of industrially organized pose production at the plants of the Nothern and Far-eastern regions of Russia.

9. To use a dismantling of reactor compartments the most up-to-date technologies and facilities for decontamination and treatment of radioactive liquid and solid waste and, if necessary, to use the same techniques and plants for operation radioactive waste of Russian Navy management.

In several countries of the Pacific Basin before our eyes are formed a new type *information societies,* based on the free access to scientific knowledge, high level of education of all population and capability to accelerate the introduction of the advanced technologies. And all the accumulated scientific knowledge and current technology must be used to minimize the present technological, social and ecological threat (Rakitov, 1997), including the danger to the Mankind from retired nuclear powered submarines with spent nuclear fuel or without it, in the next century.

## 5. REFERENCES

The Analytical Report Based on the Proceedings of the Advanced Research Workshop, *Nuclear Submarine Decommissioning and Related Problems,* Moscow, Russia, June 19-22, 1995.

Borisov, V.V., V.A. Mazokin, M.Ye. Netesha, Yu.V. Orlov, G.A. Stanislavsky and V.K. Ulasevich, "Basics of the Concept of Reactor Compartment Handling (Including Off-Normal) when Recycling Nuclear Submarines. Top-Priority R&D"; *Nuclear Submarine Decommissioning and Related Problems,* Advanced Research Workshop, Moscow, June 19-22, 1995. Proc. NATO ASI Series, Kluwer Academic Publ., p. 41, 1996.

Dovgusha, V.V., V.I. Kvasha and Yu.P. Shulepko, "Radioecological Problems Related to Disassembly and Recycling of Decommissioning Nuclear Submarines", *Ibid.,* p. 77.

"Dual-Purpose Canister Preferred by Navy for Spent Nuclear Fuel", *Weapons Complex Monitor,* Vol. **7**, *Issue* 59, p. 7, 1996.

Final Environmental Impact Statement on the Disposal of Decommissioned, Defueled Naval Submarine Reactor Plants, Department of the Navy and Department of Energy, v. 1, May 1984.

Gavrilov, S.D., V.A. Kremnev, V.A. Maksakov and B.M. Nevzorov, "Decommissioning and Recycling of Nuclear Submarines and Other Nuclear Powered Ships and Vessels"; *Nuclear Submarine Decommissioning and Related Problems,* Advanced Research Workshop, Moscow, June 19-22, 1995. Proc. NATO ASI Series, Kluwer Academic Publ., p. 67, 1966.

Gavrilov, S.D., P.L. Smirnov, M.K. Barskov, V.S. Topilin and N.I. Shumkov, "Spent Nuclear Fuel from Nuclear Powered Submarines", Proc. ANS Meeting *Decommissioning, Decontamination and Reutilization of Governmental and Commercial Facilities*, Knoxville, Tennessee, September 7-12, 1997, American Nuclear Society, La Grand Park, Illinois, p. 397, 1997.

Gavrilov, S.D., P.L. Smirnov, M.K. Barskov, V.P. Shcherbak and N.N. Yurasov, "Shipment and Storage of Spent Nuclear Fuel from Nuclear Powered Submarines and Other Ships and Vessels with Nuclear Power Plant", *1998 ASME/JSME/SFEN ICONE-6,* Sun Diego, California, May 10-15, 1998 ASME International, New York, NY (to be published).

Gladkov, G.A., V.N. Lystsov, B.G. Pologikh, Yu.V. Sivintsev and A.P. Zotov, "Principles of Handling Decommissioning Ship Reactors"; *Nuclear Submarine Decommissioning and Related Problems,* Advanced Research Workshop, Moscow, June 19-22, 1995. Proc. NATO ASI Series, Kluwer Academic Publ., p. 115, 1996.

Khlopkin, N.S., "Defueling of Spent Nuclear Fuel from Nuclear Submarines to Be Decommissioned Is the Most Important Top-Priority Issue", *Radioactive Waste, Storage, Transportation, Recycling, Environment and Human Impact.*, St.Petersburg, October 14-18, 1996, D-1, *Abstr., TsNIIKM "Prometheus" Publ.*, St.Petersburg, 1996 (In Russian).

Kotenko, Ye.A., V.F. Dorodnov, E.L. Petrov, Yu.V. Litinski, V.I. Titkov, V.Kh. Tohtarov, A.N.Titkov, M.N. Kofanov, Yu.V. Kritinin and I.V. Gorkavetz, "Feasibility Studies of Tunnel-Boated Underground Power Plants in the Primorski Region on the Basis of Vessel Reactors of Conversion Navy"; *Nuclear Energy and Human Safety*, Abstr. 4th Meeting of Nuclear Society (Moscow), NS Publ. M., Vol. 3 p. 841, 1993.

Kotlov, V., "Minatom of Russia and the nuclear powered submarine fleet", *NIMB*, Publ. Central Board of Russian Nuclear Society, Issue **3**, p. 21, 1996 (In Russian).

Mazokin, V.A., V.V. Borisov, M.E. Netesha, Yu.V. Orlov, G.A. Stanislavsky and V.K. Ulasevich, "Basic Aspects of the Concept of Reactor Compartment (Including Damaged Compartments) Management During

Utilization of Nuclear Powered Submarines. High Priority R&D", *Global Advances in Nuclear Engineering, ICONE-4,* New Orleans, March 10-14, 1996, ASME International, New York, NY, Vol. 3 p. 1, 1996.

Miller, M.L., "The Sea Transport of Irradiated Nuclear Fuel"; Proc. 5th Conf. on Radioactive Waste Management and Environment Remediation *ICEM'95,* Berlin, September 3-7, 1995, ASME International, New York, NY, Vol. 1 p. 310, 1995.

Mitenkov, F.M., Ye.I. Aksenov, V.N. Vavilkin and N.G. Sandler, "Priority Problems of Nuclear Submarines Decommissioning and Utilization", *Russian Atomic Energy,* Vol. **82,** p. 146, 1997 (In Russian).

Petrov., E.P., I.V. Sergeyev, "Underground Space for Commercial NPP. Radiation Safety", TsNII after A.N. Krylov, 1993 (In Russian).

Rakitov., A., "Science in the Epoch of Global Transformations", *Free View*, 1997, *Issue* 7 p. 56 (In Russian).

Sivintsev, Yu.V., V.L. Vysotsky and V.A. Danilyan, "Radiological Consequences of the Radiation Accident in the Nuclear Powered Submarine at the Czazhma Bay", *Nuclear Energy and Human Safety*, Abstr. 4th Meeting of Nuclear Society (Moscow), NS Publ. M., Vol. 1 p. 183, 1993 (In Russian).

Smirnov, P.L., "Spent Nuclear Fuel of the Pacific Fleet: Issues and Visible Methods of SNF Management", *Radioactive Waste, Storage, Transportation, Recycling, Environment and Human Impact.,* St.Petersburg, October 14-18, 1996, F-25, *Abstr., TsNIIKM "Prometheus" Publ.,* SPb (1996, In Russian).

Tsypin, S.G., V.V. Lysenko, Yu.V. Orlov and O.Yu. Koryakin, "Radiation Surveying of Decommissioning Nuclear Powered Submarine", *Russian Atomic Energy,* Vol. **75,** p. 230, 1993 (In Russian).

U.S. Naval Nuclear Powering Submarine: Inactivation, Disposal and Recycling, *U.S. Department Navy,* September 1993.

Yesovit, Eh.S., V.A. Mazokin, M.E. Netesha and Yu.V. Orlov, "Radiation Factors Specifying Safety in Reactor Compartments in the Process of Decommissioning Nuclear-Powered Submarines"; *Global Advances in Nuclear Engineering, ICONE-4,* New Orleans, March 10-14, 1996, ASME Publ., New York, Vol. 3 p. 21, 1996.

## KEY WORDS

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