Radioactive and toxic waste from decommissioning of multipurpose nuclear submarines and environmental safety assurance in the North-Western Region of Russia

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1. Introduction

Decommissioning of such large and sophisticated facilities as nuclear submarines is undoubtedly associated with additional environmental risks. Radiation hazards have long been a matter of serious concern and their assessment is more or less a traditional effort. However, submarine dismantling is also accompanied by release of numerous harmful chemical substances (HCS) and by generation of large quantities of chemical waste posing a threat to human health and environment.

Awareness of this problem lead to integrated assessment and comparison of the radiation and chemical risks arising during dismantling of nuclear submarines both under normal conditions and during some possible accidents. This effort was undertaken for the first time in 2002 on assignment of the Department for Decommissioning of Nuclear Facilities.

The experts involved came from enterprises of Minatom (NIKIET, OKBM, ICES), Rossudostroenie Agency (NIIPTB Onega, Nerpa Shipyard, A.N. Krylov Research Institute), RRC Kurchatov Institute, IBRAE (RAS), NIIPMM and REScentr.

Coordination of the activities was entrusted to the Minatom’s International Centre for Environmental Safety (ICES) which has certain experience in investigating combined environmental risks related to different electricity production methods.

The results of the effort were used in preparation of this presentation.

In assessing risks, it is necessary to take into account the climatic and topographic factors, the proximity of towns and settlements to the work site and the size of their population.

The assessments were made for the conditions of Snezhnogorsk, with a population of 15,300 people, and Nerpa Shipyard found 2.7 km away from the town. The main conclusions will also hold true for other enterprises, but the risk parameters have to be specified of each of them, as they depend on the working environment, technologies in use, location of recipients, etc.

Exposure of personnel, population and environment to factors of various nature calls for multifactor risk assessment. For risks from different factors to be compared, one common indicator should be chosen.

Following the recent practice, damage to human health was adopted as such a universal indicator. It is a dimensionless quantity expressed as the part of a year of life lost, **R**, due to man’s exposure to a risk source for one year. The indicator is calculated as follows:

$$\mathbf{R_i = r \cdot g_i},$$

where: $\mathbf{r}$ – exposure to a detrimental impact during a year,
$\mathbf{g_i}$ – lost part of a year of life due to unit impact.

This indicator is easy to interpret. Thus, R=0.1, found by calculation, means that exposure to the harmful factor in question for a period of 10 years will cost 1 year of life to the person affected (i.e. a 10 % cut).

The estimations involved the risk coefficient values from Ref. [1-3]; as regards radiation impacts, for example, $\mathbf{g_r}$ = 1 man·year/man·Sv.

In assessing the damage caused to human health, it is necessary to know the composition of the wastes resulting from submarine dismantling, their quantities, the degree of danger and the pathways of their harmful action both under normal working conditions and during possible accidents.

The first and foremost among radioactive materials is spent nuclear fuel (SNF) which contains up to 95 % of the total submarine radioactivity (~ 1 MCi). All the processes of handling it present nuclear and radiation hazards.

Next to SNF in danger are liquid radioactive wastes (LRW), mainly the primary reactor coolant. Their total quantity may be as large as 100 m^3.

Solid radioactive waste (SRW) includes reactor internals, instruments and the waste generated in cutting of hulls.

The chemical wastes posing the greatest threat to human health are the harmful chemical substances released in quantities of up to 2 t during submarine cutting in the form of gases and aerosols, including highly toxic materials placed by the State Standards (GOST) in Hazard Classes 1 and 2.

Class 2 is also represented by a considerable portion of liquid toxic wastes (LTW), such as combustible and lubricating materials and electrolyte of storage batteries (60-80 t).

The bulk of chemical waste (~ 600 t) is solid toxic waste (STW) which is dangerous in the absence of appropriate handling technologies.

It was assumed in the risk calculations that all the activities would strictly adhere to the “Concept for integrated decommissioning of nuclear submarines and surface ships with nuclear power installations”.

The most hazardous accidents caused by violations of technological procedures or by external factors were examined for radiation risks.

Similar assessment of chemical risks calls for further investigations.

2. Radiation risks

After nuclear submarine decommissioning, the greatest radioactivity is concentrated in the spent nuclear fuel of its reactors. Depending on their power, length of lifetime and operating conditions, 1 MCi is accumulated in the core, making as much as 95% of the total submarine radioactivity.

Therefore, the main radiation hazard is associated with the defuelling operation. Drop of a spent fuel assembly (SFA) during unloading and its ensuing damage were analysed as a possible accident. As seen from Table 1, it is this event that is the greatest contributor to the damage caused to personnel and population (including exposure during the accident mitigation activities).

In defuelling, the gravest consequences are associated with the self-sustained chain reaction (SCR) which may be initiated by erroneous actions of personnel and violations of the operating procedure. After the accident in Chazhma Bay [4], measures were taken to rule out the very possibility of such an accident, including the requirement to drain off the coolant prior to breaking loose of the reactor.

A case covered in analysis as a beyond-design-basis event was the situation created by an aircraft crash with the resulting fire in the reactor compartment.

Submarine defuelling and dismantling give rise to 100 m^3 of LRW with a total activity of 1 to 10 Ci (depending on the degree of damage to fuel claddings) and to ~10 m^3 of SRW with the activity of ~0.3-0.5 Ci.

Table 1

Main indicators of radiation risk to personnel and population during dismantling of nuclear submarines

No.	Possible accidents (initiating events)	Frequency, 1/year	Individual risk of death, r_{dth}, 1/year		Individual annual damage, **R** (lost part of a year of life/ year of exposure to risk source)	
			Personnel	Population	Personnel	Population
Normal dismantling conditions			2.8E-13	3.7E-15	5.0E-12	5.0E-14
Accidents						
1	SFA damage during unloading	6.0E-3	3.4E-5	4.4E-6	6.0E-4	6.0E-5
2	Fire in submarine	1.4E-2	3.1E-11	4.1E-12	5.6E-10	5.6E-11
3	Failure of ventilation in process compartments	3.2E-2	9.0E-12	1.2E-12	1.6E-10	1.6E-11
4	LRW spill	4.8E-3	2.7E-12	1.1E-12	4.8E-11	1.4E-11
5	Sinking of RC unit in storage	8.4E-3	1.4E-15	1.8E-16	2.5E-14	2.5E-15
6	Sinking of RC unit in shipment	5.1E-3	8.6E-16	1.1E-16	1.5E-14	1.5E-15
7	Aircraft crash with the ensuing fire in RC	5.0E-8	5.6E-11	8.0E-12	1.0E-9	1.0E-10
	Total:		**3.4E-5**	**4.4E-6**	**6.1E-4**	**6.0E-5**

In assessing the risks from radioactive wastes, it was assumed that the generated LRW was collected and treated at the existing facilities, while the SRW was placed inside the reactor compartment of the decommissioned submarine for long-term storage.

According to the calculations, the radiation risk is negligibly small for personnel, let alone population, given strict adherence to the technological requirements and operating procedure during submarine dismantling.

Assessment of damage from possible accidents involved examination of 32 initiating events. Apart from the above-mentioned defuelling-related accidents, the greatest contributors discovered were accidents caused by:

- LRW spill as a results of human faults or hose damage;
- failure of ventilation in process compartments of the controlled area with the filters inoperative;
- fire in submarine (maximum design-basis accident);
- sinking of a three-compartment unit during transportation or in interim storage site.

The greatest contribution to the total frequency of occurrence of all accidents is made by human errors (41 %) and dependent equipment failures (32 %).

The main results of assessing the radiation risks to Nerpa shipyard personnel and Snezhnogorsk population are presented in Table 1. These are conservative estimates.

The listed data show the accident with fuel assembly drop in unloading to be by far the greatest contributor. The probability of this accident may be reduced by:

- testing the hoisting gear involved in the SNF unloading;
- keeping watch over unloading;
- re-training the personnel, checking their knowledge, and performing drills before actual defuelling operations.

3. Chemical risks in dismantling of nuclear submarines

Chemical pollutants arise both at the preparatory stage and during the actual dismantling operations.

Figures 1, 2 and 3 show the pattern of toxic waste generation during dismantling, its composition and break-down in Hazard Classes according to GOST.

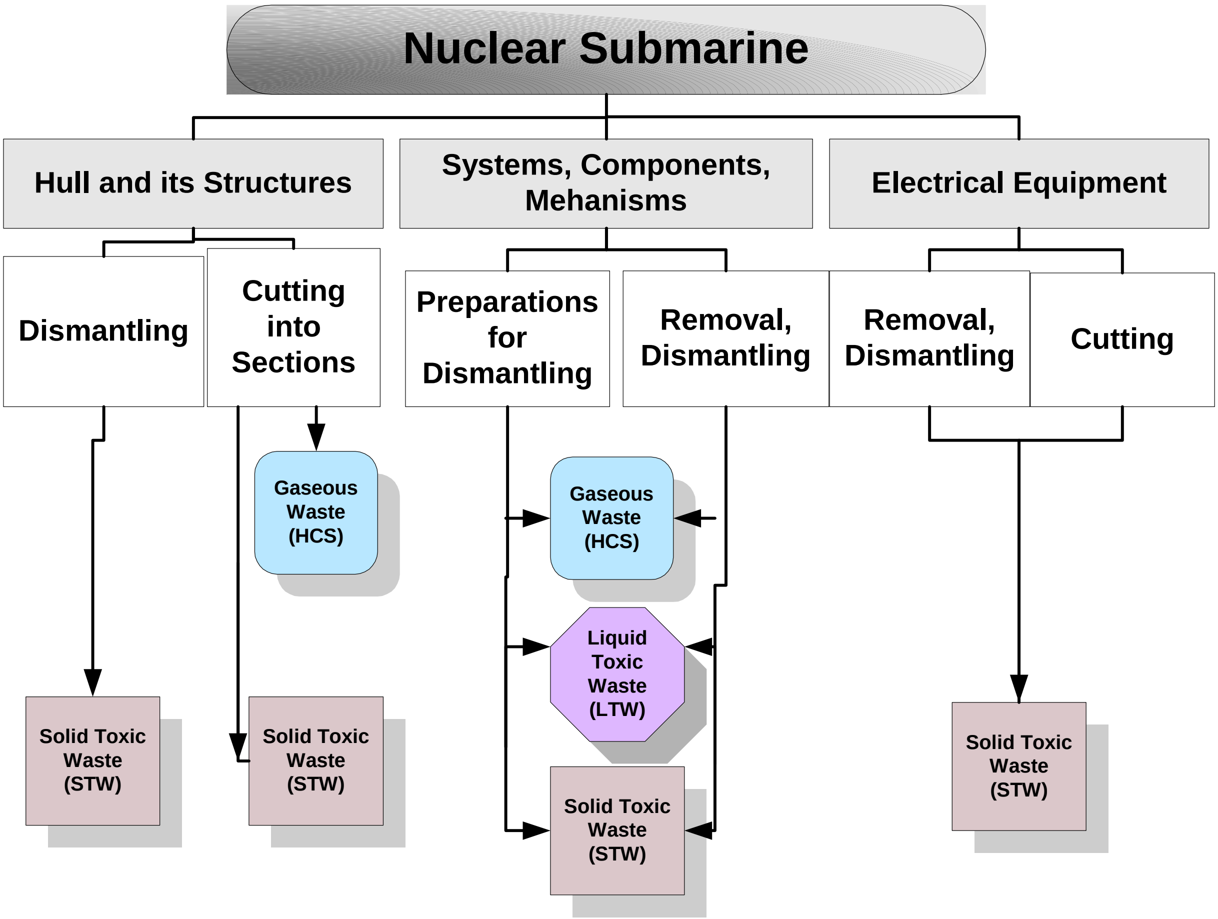


Fig. 1. Toxic waste generation in dismantling of nuclear submarines

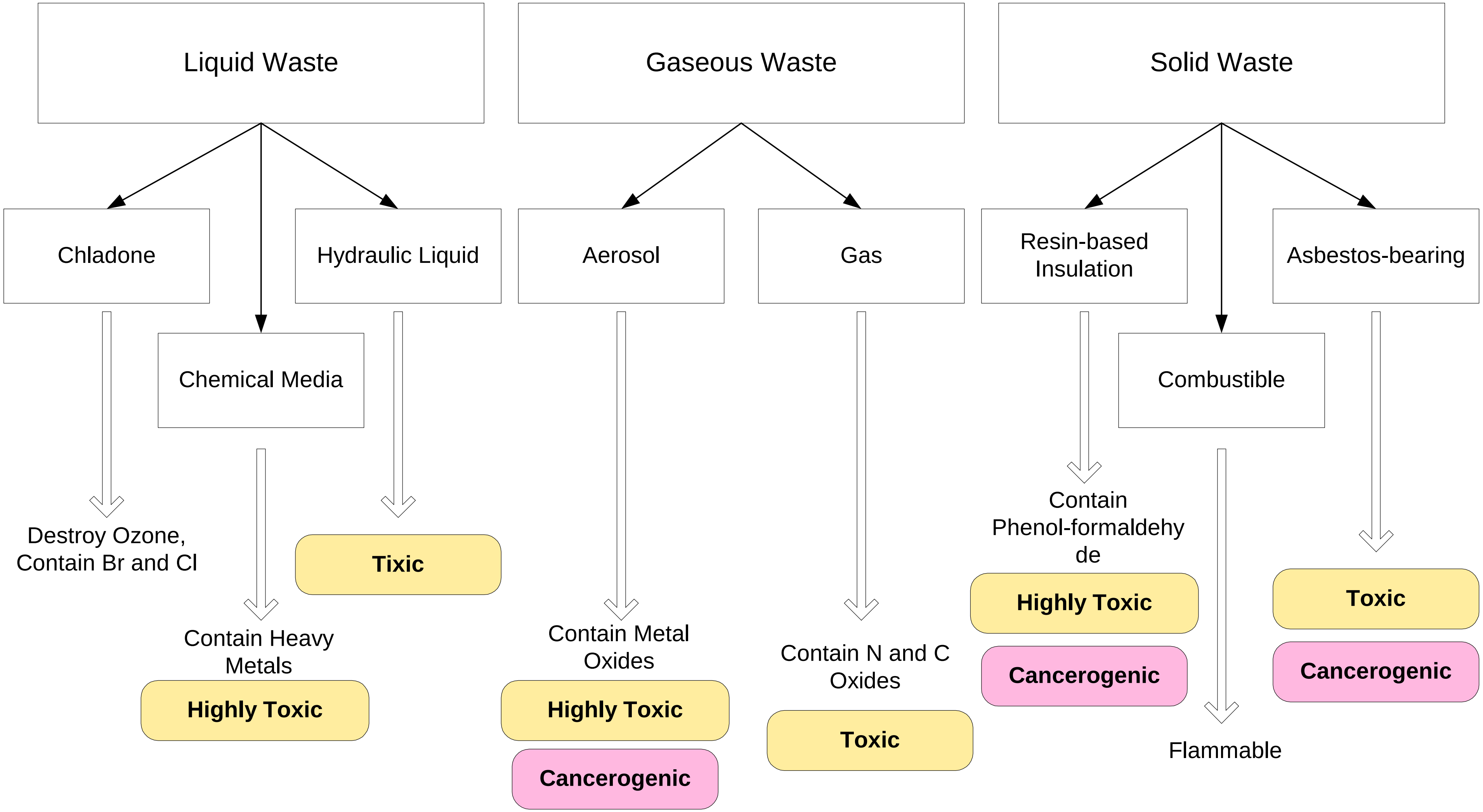
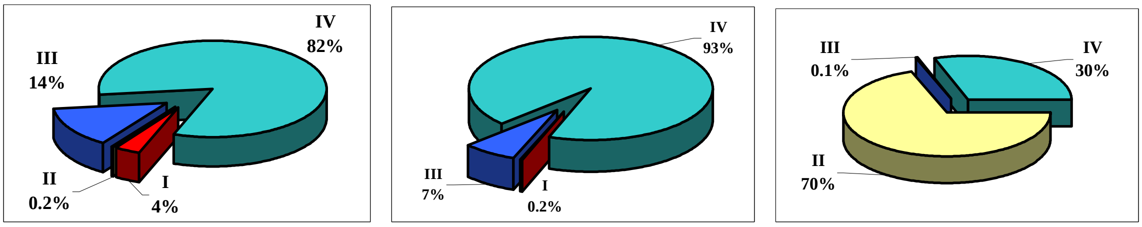


Fig. 2. Composition of toxic waste generated during submarine dismantling

In the process of submarine dismantling, over 2 t of harmful chemical substances are released to the atmosphere as aerosols and gaseous compounds. These include highly toxic materials of Hazard Classes 1 and 2 according to GOST, such as chromium, manganese and nickel oxides in amounts varying from several kilograms to several tens of kilograms, and materials of sharp directional effect, viz. – nitrogen oxide (~ 300 kg) and carbon oxide (~ 400 kg). In consequence, the air-borne loads in the working area are found in excess of the maximum permissible concentrations (MPC) by as much as ~ 15 for nickel and lead and ~ 30 for chromium. It is important to note the extremely high presence (8-17 times the MPC) of air-borne solid particles of industrial dust, which is one of the major contributors to unhealthy working conditions associated with submarine dismantling.



HCS (~ 2 t) STW (~ 600 t) LTW (~ 80 t)

Fig. 3. Types of toxic waste and their distribution in Hazard Classes

Harmful chemical substances originate primarily from the dismantling operations, including cutting, welding, grinding, scraping. Gas, plasma-arc and mechanical cutting methods are in use.

As shown by calculations and studies, the main source of harmful releases to the atmosphere and, hence, the main source of danger to human health is the gas cutting (Fig. 4). This method is employed at all stages of submarine dismantling where cutting is required, in distinction to the plasma-arc procedure which is only used for cutting components made of nonferrous metals and special alloys.

Fig. 4. Gas cutting during submarine dismantling

Figure 5 provides comparison of the extent of damage caused to personnel by their exposure to chemicals during the use of different cutting methods, while Figure 6 compares the risks from various chemical substances released during dismantling of nuclear submarines.

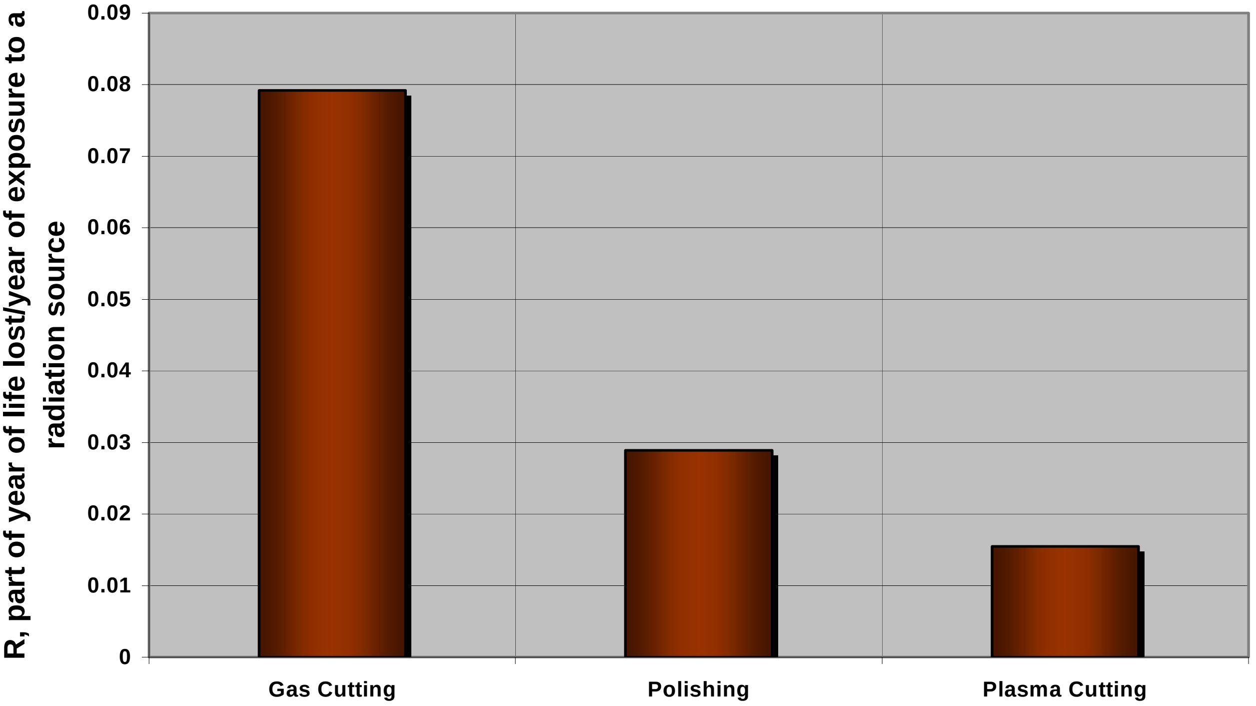


Fig. 5. Comparative assessment of risks for the main submarine dismantling operations

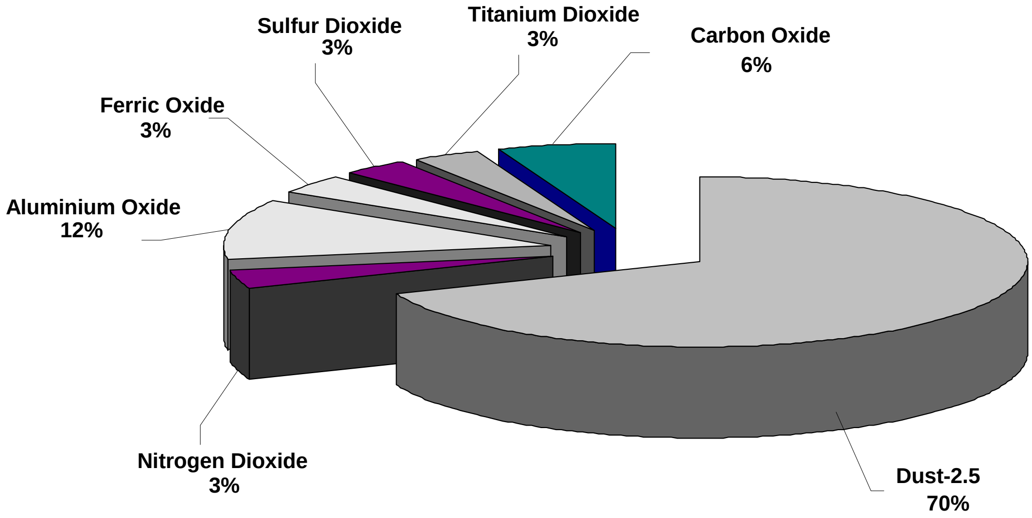


Fig. 6. Contributions to risk from materials released during submarine dismantling

The quantity of liquid toxic waste (without industrial wastewater) per submarine is assessed at ~ 60 t, including waste of Hazard Class 2, such as spent electrolyte, waste oil and diesel fuel. There are problems with the paraffin-glycerol-water liquid and chladone, making ~ 20 t in aggregate, which are building up in storage at enterprises due to the absence of efficient treatment technologies.

Solid toxic waste (~ 600 t per submarine, including ~ 400 t of rubber coatings) is the main source of environmental pollution. A major concern is resin-based waste, including insulation materials, which give off phenol-formaldehyde. The Nerpa shipyard has no facilities for treatment of such wastes and they are being stockpiled on the site.

Wastes of Hazard Class IV are allowed to be taken to industrial waste disposal grounds, although much of them (~ 10 t) are materials containing asbestos, which is known to be a carcinogen. The environment is seriously affected by the processes of asbestos and resin washout, by spread and migration of polymers destroyed by ultra-violet radiation, such as elastron, linoleum, polyethylene, etc.

A problem yet to be resolved is the dust aggregating with litter, which results in mixing of wastes belonging to different hazard classes. Besides, some materials are combustible, which is an additional hazard when wastes are placed on the enterprise territory or industrial waste disposal sites.

In handling toxic wastes from dismantling of nuclear submarines, it is possible to have accidents with release of toxic substances to the environment. Such accidents may be caused by failures of facilities and components, violations of technological procedures, as well as by external factors, such as fires and explosions, including acts of sabotage. Regardless of the accident initiator, both people and environment are threatened by gases and aerosols emitted to the atmosphere and by toxic materials dumped into water bodies in concentrations exceeding those found during normal operation.

Chemical risks from possible accidents have not been assessed on account of insufficient input data.

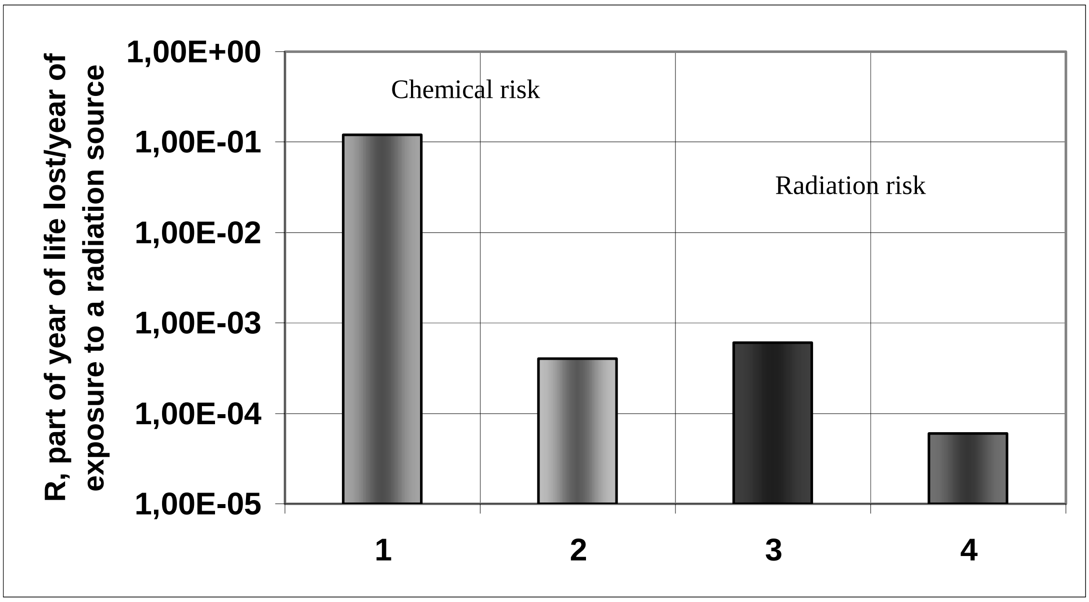
4. Results of comparative risk assessments

Review of submarine dismantling risk assessments shows that both personnel and local people are exposed to negligible radiation risks during dismantling of nuclear submarines. The associated chemical risks are by far higher, especially for personnel (Fig. 7), counting emissions alone and leaving out of account possible accidents, whose consequences may present a serious hazard to people and environment.

The following measures may be helpful in reducing the chemical risks:

- use of more efficient equipment for forced ventilation and air filtering in closed compartments of the working area;
- thorough cleaning of surfaces from varnish, paint and other coatings, removal of remaining outer protective layers before cutting;
- wider employment of plasma-arc cutting;
- use of the “rotation” approach in arrangement of cutting operations.

It is obvious that the absence of chemical risk assessments for cases of possible accidental toxic releases detracts from the capabilities of chemical risk management during dismantling of nuclear submarines. It is essential to analyse the possible accidents and their consequences and to identify the recommended procedures for chemical waste management, which will be both economically efficient and environmentally friendly. Such studies have been started for the Zvezdochka site and should be carried out for all enterprises.



where 1 – personnel, chemical risk, 1.2E-1;
2 – population, chemical risk, 4.0E-4;
3 – personnel, radiation risk, 6.1E-4;
4 – population, radiation risk, 6.0E-5.

Fig. 7. Comparison of estimated radiation and chemical risks in submarine dismantling

5. Conclusions and proposals

Analysis and comparison of environmental risks arising in decommissioning and dismantling of nuclear submarines show that personnel are exposed to negligibly small risk, while the main hazard lies in release of harmful chemical substances during cutting operations. Concentrations of some of them in the working area are tens of times higher than the MPC. Use of better equipment for filtering of air and cutting will reduce this risk, making it more tolerable for the personnel.

The radiation and chemical substances pose no hazards to the population of the nearest town.

However, such is not the case with liquid and solid toxic chemical wastes which arise in large quantities and are kept on the enterprise sites or taken to the nearest disposal grounds. They are a potential threat to people and environment, which should be tackled in the same energetic and coordinated way as it is done in handling radwaste during dismantling of nuclear submarines.

It is generally known that there used to be serious problems in managing spent nuclear fuel, liquid and solid radwaste. With the help of our foreign colleagues, appropriate technologies were developed and facilities built for LRW treatment, SRW compacting and storage, SNF unloading, shipment and interim storage. As a result, the safety of handling spent fuel and radwaste was significantly enhanced.

The same effort should be taken to deal with toxic chemical wastes with special regard for their threat to the areas where submarines are dismantled. Continued storage of these materials in the same conditions could have serious repercussions for people and environment, especially for the major fishing areas in the North-West of Russia.

In our opinion, it is necessary to work out a concept for management of such wastes and to select technologies best suited for their treatment. In other countries, there exist facilities designed for treating household and industrial wastes in an environmentally safe and economically sound way. Such are, for instance, facilities with high-temperature chemical reactors for waste gasification with simultaneous power and heat generation, this capability having a special appeal for enterprises in the North-West Russia.

Prompt and efficient solution of this problem would be difficult without international support and coordination of activities in selecting the technologies and implementing them. A first step in this direction may be made by the international project "Development of a concept for management of toxic waste arising in dismantling of nuclear submarines".

The next step would be to provide facilities for treatment of toxic wastes at the enterprises dealing with submarine dismantling and thereby to clean up the existing sites of their storage, including industrial and household waste disposal grounds. In such a case, environmental safety in the North-West Region may be assured even with accelerated dismantling of a large number of nuclear submarines.

6. List of acronyms

HCS – harmful chemical substances;
LRW – liquid radwaste;
LTW – liquid toxic waste;
SFA – spent fuel assembly;
SNF – spent nuclear fuel;
MPC – maximum permissible concentration;
RC – reactor compartment;
SCR – self-sustained chain reaction;
SRW – solid radioactive waste;
STW – solid toxic waste.

7. References

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3. Radiation Safety Rules (NRB-99), Ministry of Health, Moscow, 1999.

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Appendix 1

Development of the Concept for Management of Toxic Waste Arising from Decommissioning of Nuclear Submarines

Decommissioning of all types of nuclear submarines results in considerable quantities of non-radioactive waste which poses threats to the health of personnel and local people as well as to the environment.

The greatest hazards to personnel are the harmful chemical substances which arise as gases and aerosols (in amounts of up to 2 t per submarine) and carry tens of kilograms of highly toxic agents belonging to hazardous Classes 1 and 2 (oxides of chromium, manganese, nickel, lead, etc.) as well as hundreds of kilograms of carbon and nitrogen oxides. Human health is also badly affected by high loads of airborne industrial dust and aerosols produced by condensation during welding.

Respirators and air filters, currently in use, allow reducing the impacts of chemicals but their effectiveness leaves much to be desired. For personnel engaged in cutting of harmful chemical materials, the lost lifetime is estimated at 12 % of the work time, which means that exposure to chemicals over 100 hours of working makes the life of the worker 12 hours shorter.

Improvements in the system of individual protection and air purification system and, most important, use of more environmentally friendly cutting processes will reduce considerably the harm caused to human health.

The risk to personnel and population from other types of waste is much lower, although their quantities are significantly larger. Decommissioning of nuclear submarines leaves in its wake ~ 60-80 t of liquid toxic waste (combustible and lubricating materials, spent electrolyte, etc.) and ~ 600 t of solid waste. Some of these materials are burned, others are utilised, but the bulk of the waste is stored at factory sites or is removed to industrial dumping grounds.

Really troublesome are wastes of the third Hazardous Class, coming to several tens of tones. These are insulation materials which give off phenol-formaldehyde and other toxic compounds during storage. There is no technology for their treatment and enterprises pile up these materials on their territories.

Waste materials of the fourth Hazardous Class, making the greater part (~ 600 t) of all solid toxic wastes, are allowed to be taken to general industrial dumping grounds in the absence of a technology for their treatment, which would reduce their volume and would prevent washout of harmful substances. The result is soil and groundwater contamination. Besides, some of these materials are combustible, which is another risk factor. Fires – accidental or intentional – may cause injuries to personnel and population, contamination of groundwater, and ingress of toxic agents into rivers and seas.

This hazard will grow as more and more nuclear submarines are disposed of and the capacity for storing the most dangerous materials at factory sites is exhausted.

To prevent the possible environmental repercussions, it is imperative to take urgent action and to join forces for developing a toxic waste management technology and for setting up facilities for the waste treatment. In doing so, it is necessary not only to have financial backing from foreign partners, but also to draw on their expertise in tackling similar problems.

As a first step, an international project is proposed under the title of “Development of a concept for management of toxic waste resulting from decommissioning of nuclear submarines". The project has the following milestones:

- Review of the system for toxic waste management practiced at various Russian enterprises in decommissioning of nuclear submarines:
    - waste mix and quantities, the extent of hazards and the pathways by which these materials affect human health and environment in normal conditions and during possible accidents;
    - environmental risk assessment;
    - processes and facilities employed for waste treatment and disposal.
- Review of toxic waste management technologies used in other countries (treatment, reclamation, storage or disposal).
- Analysis of possibilities for using foreign expertise at Russian enterprises. Review and comparison of various processes and facilities from the viewpoint of their environmental efficiency and safety.
- Preparation of recommendations, technical and economic studies, and demonstration of the environmental safety of the technology adopted.