Doses of Emergency Exposure to the USSR Navy Personnel

Yuriy Skaletskiy

Head of Radiation Safety Section of the Institute of National Security Problems of Ukraine
Kyiv, Ukraine

Introduction

The operation of nuclear propulsion plants on the USSR Navy submarines led to a number of incidents and accidents accompanied by overexposure of personnel including cases of lethal doses. The curtain of secrecy around Navy radiation accidents started lifting with 1990's publications in "Morskoy Sbornik" (the official journal of the Russian Navy), newspaper "Pravda" and other periodical editions. There were also books published based on recollections of the parties involved in these tragic events. One of the most comprehensive publications on radiological and radioecological consequences of Navy accidents appeared in 1999 [1].

During more than 30 years of use of nuclear reactors on the USSR Navy submarines hundreds of breakdowns and accidents of radiological significance took place. The main reasons for these situations were technical imperfections of the nuclear propulsion plants' equipment and also errors of the personnel. Not every case of deterioration of radiation conditions on nuclear-powered submarines was accompanied by personnel overexposure. In most of cases, the timely taken measures to normalize the radiation situation and radiological protection measures allowed prevention of the crew overexposure. For example, seal failures of the primary coolant circuit happened on dozens of submarines in different periods, but only one case in 1979 due to a variety of causes resulted in radiation injuries to personnel.

The structure of Navy radiation accidents accompanied by personnel overexposure is shown in Table 1. By 1991, there happened seven major accidents at submarine nuclear propulsion plants: five at sea (1960, 1961, 1968, 1979, and 1989), and two at ship repair yards during reactor refueling (1965 and 1985). Besides, there were six radiation accidents registered in the Navy related to the handling of spent nuclear fuel and of other sources of ionizing radiation.

The most severe radiation accidents took place on first-generation nuclear submarines in 1961 and 1968. According to the actual classification, six accidents by their character and scale belong to site incidents, i.e. those having only on-site (or within the vessel or shipyard) impact, and one to accidents which have off-site (outside the vessel or shipyard) impact with the risk of population overexposure [1].

In 1985 there was a particularly significant release of radioactive material following a spontaneous chain reaction and a thermal explosion of reactor on a Pacific Fleet submarine. It happened during reactor refueling on a ship repair yard in Chazhma Bay. The emission amounted to (1.9-2.6)$\times 10^{17}$ Bq. The reactor explosion led to scattering of reactor and fuel composition fragments within a radius of several dozens of meters and to massive radioactive contamination of watercraft, moorings, constructions, territory and water area in the accident zone. The radioactive plume spread downwind 30 km, and the radioactive trace area made up 45 sq. km. This accident resulted in overexposure and death

Table 1. Structure of Navy radiation accidents resulting in military personnel overexposure

Object of accident	Total	Place of accident		Type of accident	
		At sea	Ship repair yards and other places	without significant off-site risk	with off-site risk
Submarine nuclear propulsion plant	7	5	2	6	1
Spent nuclear fuel and other sources of ionizing radiation	6	-	5	5	-
Total number	13	5	7	11	1

Table 2. Structure of radiologic effects of the Navy radiation accidents by 1991

Object of accident	Overexposed, total number of persons	Radiation injured, number of persons		Deaths caused by radiation accidents, number of persons	
		Official	According to the exposure doses	Overexposure	Other causes
Submarine nuclear propulsion plant	>1000	193	85	12	10
Spent nuclear fuel and other sources of ionizing radiation	>50	37	33	-	-
Total number	~1100	230	118	12	10
Chornobyl NPP		237 (initially)	135	29	2

of people. The Chazhma accident which happened 8 months before the Chornobyl catastrophe was its sinister forerunner, analogue, though with significantly lower-scale consequences. Unfortunately, for reasons of secrecy the data on the character and the consequences of the Chazhma accident did not help to start a campaign on fundamental improvement of situation in the field of nuclear power safety in the USSR.

During the radiation accidents on nuclear-powered submarines at sea, the personnel were exposed to the combined effect of the next radiation factors:

- External uniform γ and β radiation from the cloud of radioactive noble gases and radioactive aerosols;
- External non-uniform γ and β radiation from contaminated surfaces and from conduits and reservoirs filled with highly radioactive liquids and gases;
- Inhalation of radioactive gases and aerosols, mainly radioactive isotopes of iodine;
- Deposition of radioactive aerosols on skin, mucosa, and clothes.

The set of radiation factors and the character of personnel exposure in the accidents on submarines staying at the ship repair yards were not different from those characteristic of the Chornobyl NPP accident in 1986 [2, 3]. Several persons were affected by the external γ-n radiation with a minor neutron component. The personnel overexposed as a result of safety violations in the work with spent nuclear fuel and other sources of ionizing radiation were mainly affected by external γ radiation.

In the Navy accidents, more than 1000 persons were affected by overexposure (Table 2). 230 of them (according to the official medical documents) suffered acute radiation injuries of different severity degrees. In 12 cases radiation injuries were fatal. Another 10 persons died in 1985 from blast injuries. The doses of γ radiation the most of the deceased had received would have given hope for their recovery from radiation injury.

The main cause of death of the submariners was not the external γ radiation but β radiation exposure of skin and upper respiratory tract, that is, a radiation factor the effect of which is rather easy to prevent. Regretfully, the same reason caused death of 2/3 of the deceased Chornobyl catastrophe witnesses and emergency workers in 1986, that is, 25 years after one of the biggest radiation accidents occurred on the nuclear-powered submarine K-19 [2, 3] in 1961. In the accident of 1961, the exposure doses to thyroid gland which the K-19 personnel received due to intake of iodine radionuclides reached several dozens of Grays [4]. In 1986 several persons from the Chornobyl NPP personnel and emergency workers received the same doses to thyroid [2].

Thus, the prompt radiological effects of the Navy accidents are similar to the effects of the Chornobyl NPP accident in 1986. Considering the wide range of doses to the exposed personnel and the term of approximately 50 years after the exposure the results of clinical-epidemiological examination of this cohort along with other similar groups (Hiroshima and Nagasaki atomic bomb survivors, population affected by the nuclear test explosion on the Marshall Islands and others) are of particular scientific interest. However, one of the issues of concern about the organization of such examination of the overexposed Navy personnel is the uncertainty in their radiation exposure doses.

Radiation dose to Navy personnel

In the Navy accidents there were practically no cases of dose registration with individual dosimeters. For this reason, the personnel exposure doses were assessed involving calculation, and exposure doses which resulted in manifestation forms of radiation injuries were improved according to the clinical-laboratory indices.

Doses of internal exposure (in this case, doses to thyroid from iodine radioisotopes) were assessed on basis of the results of thyroid radiometry held in the first days after an accident. However, considering that the first Navy radiation accidents happened in the 1970s when methodological approaches to the reconstruction and the verification of exposure doses were imperfect, it is reasonable to apply modern methods of retrospective radiation dose assessment in order to correct the doses of emergency overexposure to the submarines personnel.

As far as we know, there were two attempts of trueness verification of the officially registered doses to this cohort and also of the diagnosed severity degrees of radiation injuries. The first attempt was made in 1991 and later continued in 2001. In 1991 experts from the Central Medical Laboratory of the Navy together with the Institute of Medical Radiology of the USSR Academy of Medical Sciences (nowadays Medical Radiological Research Center of the Russian Academy of Medical Sciences, MRRC) recovered the addresses of the majority of persons making up this cohort, recollected materials about the doses, the character of exposure, clinical-laboratory indices in the acuity, and examined in the MRRC hospital 15 persons who had suffered from acute radiation syndrome of different degrees of severity [4]. In 2001, in the 32nd Central Navy Clinical Hospital (CNCH, situated in the town of Kupavna, Moscow region, Russian Federation) another 24 persons from the same cohort were examined with the participation of the personnel of the MRRC and the French Institute for Radioprotection and Nuclear Safety [5].

The second attempt was made in 1995 by the experts from the Ukrainian Military Medical Academy who examined 12 crewmen, residents of Ukraine, from the submarines which had suffered accidents. The examination was held in the Principal Military Clinical Hospital (PMCH) of the Ministry of Defence of Ukraine with the participation of its medical personnel [6-10]. In total, there are about 50 persons overexposed in the Navy accidents that now reside in Ukraine, so there is a possibility to increase the number of the people being examined.

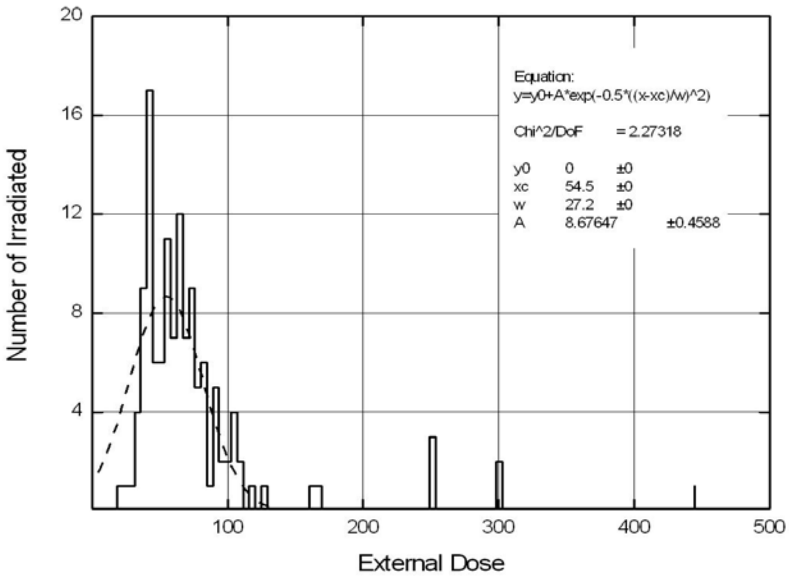

Fig. 1. Diagram of external exposure dose distribution (cGy) to the K-19 crewmen who were overexposed in 1961 (n=119). The dotted line is the fitted probability density function for the normal distribution.

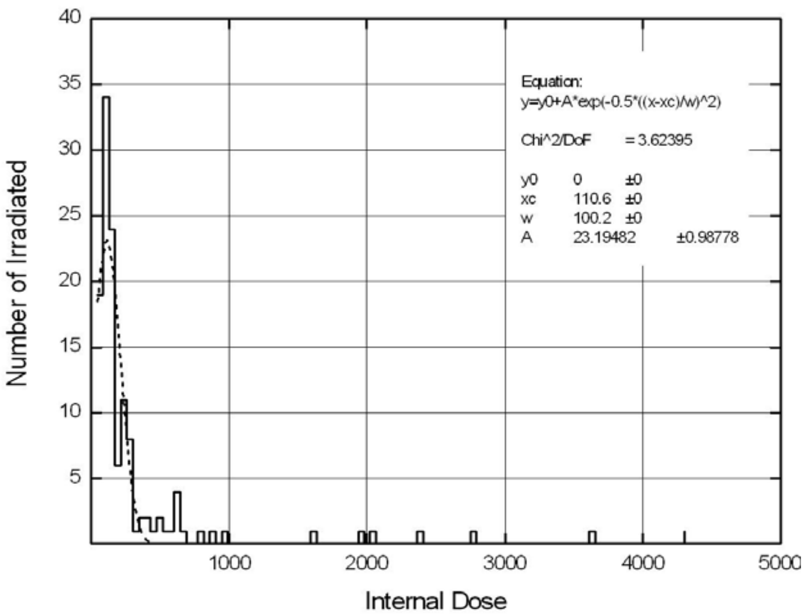

Fig. 2. Diagram of internal exposure dose distribution (cGy to thyroid) of the K-19 crewmen who were overexposed in 1961 (n=119). The dotted line is the fitted probability density function for the normal distribution.

Crew members from the submarines which suffered accidents were examined at the MRRC (1991), CNCH (2001), and PMCH (1995). The examination included, apart from the conventional methods, the so called biological dosimetry: electron paramagnetic resonance (EPR) spectroscopy of tooth enamel as well as almost all existing cytogenetic methods. It was made by means of the routine method of analysis of stable and unstable chromosome aberrations using a common light microscope, and also methods of analysis of stable chromosome breakages by fluorescence *in situ* hybridization (FISH) and by complete karyotyping of differentially G-stained chromosomes (G-banding).

Besides, the doses and the severity degrees of radiation injuries of the examined people were revised retrospectively by comparing their neutrophil and platelet dynamics graphs in the acuity of the acute radiation syndrome (ARS) with the corresponding dose calibration curves of these blood parameters [11].

As we see on the diagrams, dose distribution of external (Fig.1) and internal (Fig.2) exposure of the K-19 crewmen (suffered accident in 1961) is near-normal, which can be indicative of their stochastic nature and of the precision of doses reconstruction. In the Figures 1 and 2 we can also see the doses distribution parameters for external and internal (to thyroid) exposure.

The dependence of the internal and the external doses of the K-19 personnel is shown on the Fig. 3. From the figure we can see that the higher the external and the internal exposure doses are, the stronger is their correlation. Within the range of external exposure doses lower than 140 cGy and internal exposure doses lower than 410 cGy there is a weak linear dependence of these values (average value of correlation factor is 0.13). At the same time we can observe a strong correlation of internal exposure and

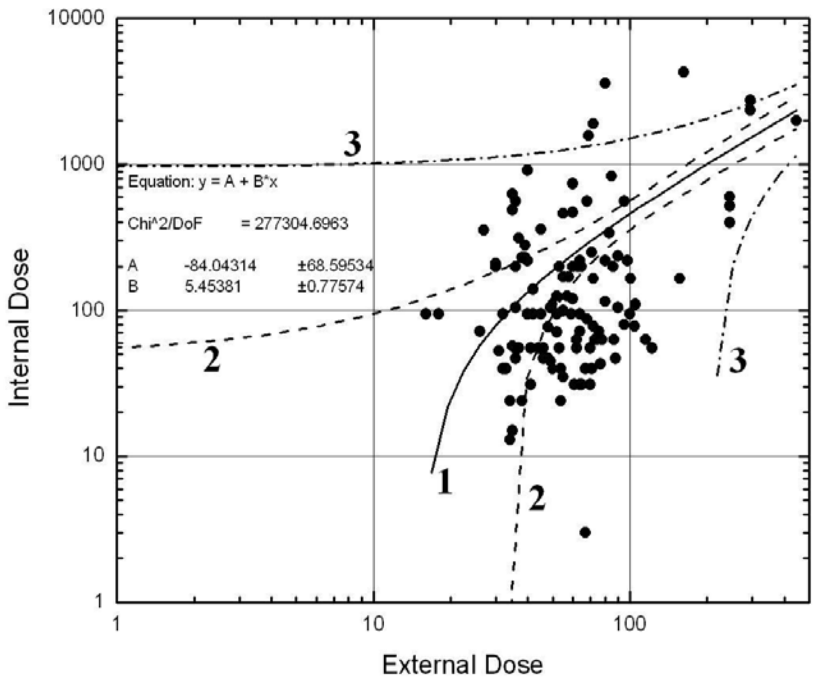

Fig. 3. Dependence between the internal and the external doses to the K-19 crewmen overexposed in 1961 (n=119): • – actual personnel exposure doses; 1 – fitted curve; 2 – fit confidence interval (confidence probability of 0.95); 3 – predicted distribution range of actual points (confidence probability of 0.95)

external exposure doses in the range higher than 140 cGy for the external exposure and higher than 410 cGy for the internal exposure. The plot points in this range of doses are closer to the fitted curve than in the range of the lower doses. This can also evidence the trustiness of doses reconstruction for submarine personnel, as the radiation conditions in the submarine compartments during the accident were determined also by the radioactive aerosols air concentration, and respiratory protective devices were not always used even while in the compartment of the damaged nuclear power plant. The individual cases of discrepancy between the internal and the external doses could be a result of violations of radiation safety requirements during food intake. Food contaminated with iodine radionuclides could have provided a substantial supplement to the doses received through the inhalation pathway.

When analyzing exposure doses in this contingent we can see a certain discrepancy between the exposure doses to the personnel and the extent of severity of the acute radiation syndrome (ARS). ARS was diagnosed to all the 138 members of the K-19 submarine crew. It is known that ARS of 1st degree develops in a person after receiving a dose of 0.75 Gy or more, thus even considering the effect of a combined exposure the diagnosis of ARS can be made to only 32 members of the crew. It is considered that the diagnosis of radiation injury was made even to the persons who received low doses in order to provide them a higher level of social protection. The same approach to the diagnosing of ARS to the overexposed personnel was used in other cases of Navy accidents. It should be noted that the cases of ARS diagnosis for social reasons also took place in 1986 among the overexposed Chornobyl NPP personnel and clean-up workers [3].

In that way, social reasons in diagnosing radiation injury resulted in 4 times overstatement of the number of radiation illness cases for this crew, mainly on the account of the overdiagnosis of the 1st degree of ARS. This brings up the question whether the severity degrees in more serious cases of ARS correspond to the exposure doses.

Analysis of individual cases

Figure 4 represents the actual neutrophil dynamics in the acuity of ARS for three members from the submarine K-19 personnel who had the diagnosis of the 2nd degree of ARS, compared to calibration curves of neutrophil dynamics for the doses of 1 and 2 Gy. It can be seen that the actual curves of neutrophil dynamics in the first two cases (the examined persons-P. and -E.) are closer to the calibration curve for 1 Gy, and with certain conservatism it can be said that they lay between the two calibration curves and the actual received dose was close to 1.5 Gy which corresponds to the 1st degree of ARS.

According to the calculations (officially) the external doses to the examined persons were 0.36 and 0.8 Gy, and internal doses (to thyroid) 5.6 and 36.0 Gy respectively. For person-C., the actual curve of neutrophils dynamics has a good agreement with the calibration curve for 2 Gy. The actual dose to person-C. may also be higher because the concomitant radiation skin injury which is present in this case can attenuate the degree of neutropenia manifestation and the depth of the second depletion [11]. Thus in this case the diagnosis of ARS of 2nd degree is appropriate, though the officially registered external dose for person-C is 0.65 Gy and the internal dose is 2.0 Gy – that is, the external dose in this case is understated.

During hospitalization of the overexposed submarine personnel which took place 30-35 years after

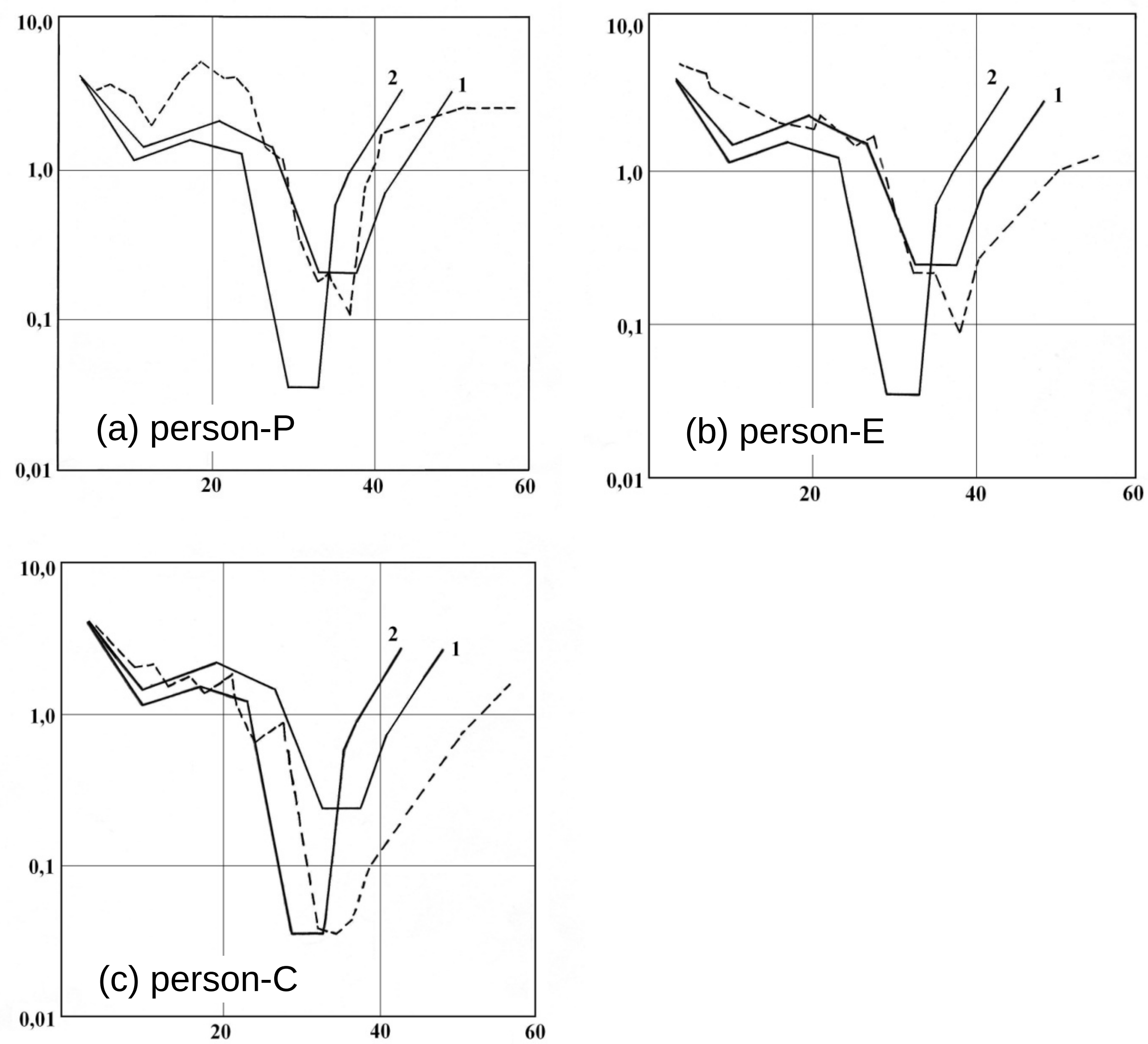

Fig. 4. Dynamics of neutrophil counts for the submarine personnel members -P (a), -E (b) and -C (c), diagnosed ARS of 2nd degree. Solid lines are the calibration curves of neutrophils dynamics (figures near the curves are doses in Gy); dotted lines are actual dynamics of neutrophil counts for the examined persons in the acuity of ARS.

The axis of ordinates shows the neutrophil counts $\times10^9$ l^{-1} on a logarithmic scale.

The axis of abscissas shows the number of days after the overexposure.

the accident, their complaints and levels of hematological, biochemical, and immunologic indices corresponded to the diseases diagnosed during the examination and had a bad correlation with the estimated exposure doses [6-9].

We would like to mention a high social adaptation of the great majority of military personnel affected by the nuclear submarine accidents. The majority of them have lived a productive life succeeding in professional activity and making a good career without having particular social benefits and privileges.

General frequency of chromosome aberrations in routine stained preparations in a long term after the overexposure (30-35 years) made up in the examined persons 5.10±0.46 per 100 metaphases and significantly exceeded the background level, but had no correlation with the dose [8, 10].

The differentially G-stained metaphase chromosomes analysis [10] showed the level of chromosome aberrations per 100 metaphases of 26.28±1.93, which statistically exceeds the indices of respective control and 5 times exceeds the results of routine examination. Chromosome-type aberrations were the prevailing type of chromosome damage with the frequency of 25.68±1.91%. Stable markers of radiation action were represented by translocations, inversions, and insertions registered with an average frequency of 10.07±1.32%, being their relation to the frequency of unstable markers of radiation action as 34 to 1. This may give a possibility of use of chromosome damage analysis in differentially stained preparations for retrospective exposure doses assessment but presently strong relationship between these effects and exposure doses is unknown. In the above mentioned work [5], method of fluorescence *in situ* hybridization (FISH method) was used to detect stable chromosome breakages. The results also confirmed to some extent the trueness of officially registered exposure doses to the submarines personnel who suffered accidents.

Dose assessment using electron paramagnetic resonance (EPR) spectroscopy of tooth enamel, though having its disadvantages, is considered to be a better method for retrospective evaluation of low exposure doses. Dose assessment using EPR spectroscopy in the examined persons 30-35 years after the accidents showed a high grade of correlation with the officially registered doses, which can evidence a rather exact calculation of exposure doses which did not induce manifest forms of ARS (Table 3) [4].

Method of biological dosimetry by estimating the frequency of chromosome aberrations in

Table 3. Exposure doses to the submarines personnel who suffered accidents assessed by EPR spectroscopy of tooth enamel compared to the officially registered data (based on calculations) [4]

No.	Examined persons' initials	Officially registered (calculated) doses, Gy	Doses based on the results of EPR spectroscopy, Gy
1.	V.N.A.	0.12	0.062
2.	P.Yu.V.	0.15	0.075
3.	R.Ye.N.	0.05	0.08
4.	S.V.S.	0.08	0.12
5.	K.L.L.	0.11	0.21
6.	P.V.P.	0.2	0.29
7.	B.V.M.	0.49	0.57
8.	R.A.S.	4.0	3.6
M±м		0.73±0.48	0.63±0.43

Table 4. Military personnel exposure doses resulting from the safety violations during preparation of a submarine nuclear power plant to refueling

No.	Exposed persons	Dose, Gy			
		According to the calculations	According to the cytogenetic indices	According to the hematologic indices dynamics	According to the final diagnosis of ARS
1.	A.	2.60±0.20	3.08*; 3.20**; 3.70***	<4.0	4.0-6.0
2.	Z.	2.25±0.15	1.50	>1.0	2.0-4.0
3.	K.	2.40±0.15	1.00	1.0	2.0-4.0
4.	Ch.	1.90±0.15	<0.25	<0.5	1.0-2.0

* according to the part of aberrant cells

** according to the general frequency of chromosome aberrations

*** according to the frequency of dicentrics and rings peripheral blood lymphocytes immediately after exposure was for the first time used in the Navy in 1984 for the evaluation of the doses to 4 seamen who were overexposed during the preparation of a submarine nuclear power plant for refueling. The integrated data on exposure doses for these overexposed persons received by different methods of retrospective dosimetry including the cytogenetic are shown in Table 4.

From this table we can see that the dose calculation by spatial-temporal characteristics of exposure and source radiological parameters even in the nearest time after the exposure not always shows results close to the true ones. The dose values determined on the basis of cytogenetic indices and dynamics of hematological indices are nearly equal, but they were not adequately taken into account when making a final diagnosis. For this reason the degree of severity of ARS is overstated. The official diagnosis to person-A is 2-3rd degree of ARS, with 2nd degree to person-Z and person-K and 1st degree to person-Ch. Objectively, according to the data in the table the severity of ARS is one degree lower than other examined persons, while in the case of person-Ch we can speak only of overexposure.

For illustration purposes, Figure 5 presents calibration curves (D=1 Gy) and actual neutrophil and platelet dynamics curves for person-Z (a), and platelet dynamic curve for person-Ch (b). For person-Z the dynamics of the both indices in the second depletion phase descend more than the respective calibration curves for 1 Gy dose in the second depletion phase. For person-Ch, the platelet counts correspond to the physiological standards. Therefore, the dose values assessed on the basis of cytogenetic indices and those assessed on the basis of hematologic indices are almost congruent.

Summing up it should be noted that in general the officially registered doses to the overexposed submarine personnel assessed on the basis of calculation method are close to the true ones, and the correlation between the primary and the final assessment of ARS cases in the Navy and in the case of the Chornobyl catastrophe (Table 2) are similar. This gives evidence of a high professional qualification of the

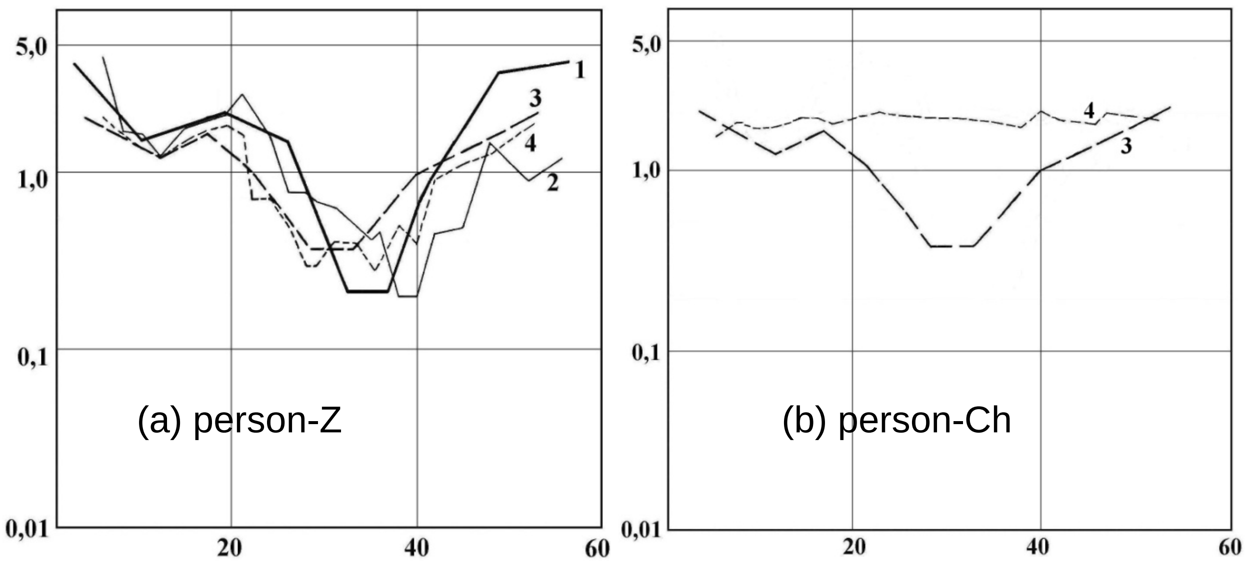

Fig. 5. Dynamics of hematological indices for person-Z (a) and person-Ch (b). 1 – neutrophil dynamics calibration curve for 1 Gy dose; 2 – actual neutrophil dynamics for the examined persons; 3 – platelet dynamics calibration curve for 1 Gy dose; 4 – actual platelet dynamics for the examined persons. The axis of ordinates shows the neutrophil counts $\times 10^9$ l^{-1} and platelet counts $\times 10^{11}$ l^{-1}. The axis of abscissas shows the number of days after exposure

Navy radiologists (specialists of clinical and preventive medicine) 25 years before the accident at the Chornobyl NPP. At the same time, organization of radiation epidemiological investigations of this category of persons needs more accurate dose estimations with the use of more informative modern methods of retrospective dosimetry. This, in its turn, will lead to a reconsideration of radiation injuries severity.

All these studies are indicating good sense with relation to scientific truth. But regarding the social aspect, the situation should not be changed or the level of social protection of these military personnel should even be improved. The authorities had been hushing up these tragedies for too long, and the military personnel overexposed in the submarine radiation accidents had been receiving no attention or care from the state.

Conclusions

1. Radiological consequences of the Soviet Navy accidents are significant and the number of ARS cases is comparable to the number of ARS cases to Chornobyl catastrophe witnesses and clean-up workers in 1986.
2. Results of a careful clinical-epidemiological examination of the personnel overexposed in the Navy accidents not only have value for radiobiology and radiation medicine specialists but can also become a basis for the evaluation of the effectiveness of social protection strategy for the Chornobyl catastrophe clean-up workers.
3. The officially registered exposure doses to persons affected by the Navy radiation accidents in some cases differ from the actual ones due to the imperfections of radiation monitoring facilities at the time of the accidents.
4. There was a tendency of clinical overstatement of the exposure doses resulting in diagnosis of 1st degree of ARS to persons who received external doses lower than 0.75. In some cases even 0.2 Gy was overstated as ARS severity for 2nd, 3rd and 4th degrees.
5. In general, exposure doses to the affected by the Navy accidents and their ARS severity degrees were evaluated with rather good accuracy.
6. The use of modern methods and approaches to the retrospective dose assessment allows more accurate evaluation of the submarine personnel exposure doses as well as verification of every ARS case, thus creating a necessary dosimetric basis for the organization of a correct radiation epidemiological investigation for persons of this contingent.
7. Regretfully, tragic experience of nuclear power plants operation at the Navy vessels was not subject to analysis of specialists in order to improve nuclear safety, radiation protection, and emergency response organization in other fields of nuclear energy use in the USSR.

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