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IAEA-CN-51/76

THE CHERNOBYL EXPERIENCE IN THE CONTEXT OF CURRENT RADIATION PROTECTION PROBLEMS

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Abstract

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Recommendations for the further improvement of radiation protection in connection with large scale radiation accidents are made on the basis of the experience gained in dealing with the consequences of the accident at Unit 4 of the Chernobyl nuclear power plant, particularly in its early stages. Many large scale measures to localize and deal with the consequences of the accident were successfully planned and efficiently implemented thanks to arrangements which had earlier been developed in the USSR for radiation protection of the population in the event of an accident at an atomic reactor — including radiological criteria for the adoption of measures to protect the population and a number of regulatory documents and guides. This made it possible to take timely decisions regarding evacuation of the population from Pripyat' and the whole 30 km zone, the application of iodine prophylaxis, the introduction of stringent restrictions and radiation monitoring in the most contaminated areas, a ban on the consumption of whole milk, restrictions on grazing of dairy cattle, the introduction of regular monitoring of foodstuffs for radioactive contamination as well as quality controls on food products, their reprocessing and utilization, the removal of children and pregnant women from towns and villages close to the Chernobyl plant for summer holidays in 1986 and 1987, etc. The effective and strict system of measures to ensure the observance of norms and regulations which was implemented with the help of tens of thousands of scientists and experts from various ministries and departments in the USSR, and which involved carrying out millions of dosimetric and radiometric measurements in a short period of time, made it possible to obtain a reliable prognosis of radiation conditions in these areas and to take steps to protect the population against radiation. The problems which arose during large scale monitoring of the population and the environment are examined as well as the methods used to solve them (the use for monitoring purposes of all available radiation monitoring instruments; stringent standardization of their use, taking into account possible areas of application, and calibration allowing for the characteristics of the radiation recorded; improvement of methods for retrospective evaluation of internal and external exposure doses; use of methods based on 'dosimetry without dosimeters'; development of temporary regulations for quality inspection of food products, contaminated beyond permissible levels; radiation monitoring of roads, buildings, transport and everyday articles).

The experience gained from the major operation to deal with the consequences of the accident at Unit 4 of the Chernobyl nuclear power plant continues to be analysed carefully, and useful lessons are still being drawn from it.

Among the many aspects of this problem, further improvement of the radiation protection system to be applied in the event of major radiation accidents is of

in Radiation Protection in nuclear energy, proceedings of an International conference Sydney 18-22 april 1988 vol. 2, p 363 ~~AIEA~~ IAEA, Vienna

The objective of the paper is to discuss a number of problems in this area arising from the events at Chernobyl. This attempt is based on personal experience gained from direct involvement in the management of the accident, particularly in the early stages, and experience in providing scientific guidance on the biomedical aspects of the problem.

First, it should be stressed that the planning and implementation of many of the large scale measures to localize the accident at the Chernobyl plant and to deal with its consequences were based on a radiation protection system which had already been developed earlier in the USSR to cope with an accident at a nuclear reactor. An important part of this system was a set of radiological criteria governing the adoption of measures to protect the public in the event of an accident at a nuclear reactor, which had been developed by myself and my colleagues in the 1960s (Table I) [1].

In accordance with these criteria (A and B in the table), the whole system of emergency measures to protect the public is determined by the external gamma and thyroid dose limits foreseen for children. The levels under criterion A are 0.25 Gy and 0.25–0.30 Gy, and under criterion B, 0.75 Gy and 2.5 Gy. If the dose limits for criterion A are not reached, the protective measures are not extensive enough to disrupt the daily life of the population.

If the radiation exposure level exceeds criterion A but does not reach B, protective measures, including evacuation of the population, are taken on an ad hoc basis, in the light of the actual situation. If it is predicted that criterion B will be reached, it is essential to adopt emergency measures and, first and foremost, to evacuate the population from the exposure zone. The main task in the early stages of the accident was to avoid exposure of the population within the A–B range and in any case to prevent whole body gamma exposure of the population outside the evacuation zone from exceeding 100 mSv during the first year after the accident. The decision to evacuate the town of Pripyat' was taken not when the exposure level of the population had reached or exceeded level A, but when predictions of the radiation situation showed it was possible that level A might be exceeded [2]. In practice, it turned out that as a result of the evacuation of the population of 45 000 from Pripyat' and the population from the zone of 30 km radius around the plant, individual total exposure doses for the town's inhabitants were generally about 15–50 mGy, whereas for some of the inhabitants (doctors, militiamen, municipal workers — those who spent long periods of time outdoors) the average individual gamma dose was 130 ± 30 mGy. In evacuating the population from the 30 km zone, there were only a few towns and villages (Tolstyj Les, Kopachi and a few others) where, owing to continuous variations in the radiation conditions, it was not possible to prevent all the inhabitants from receiving doses above level A However, the radiation burden for these people did not reach level B. Thanks to timely iodine prophylaxis, the thyroid dose commitment for 97% of the children from Pripyat' was less than 0.3 Gy; for 2% it was 0.3–1 Gy; and for less than 1% of children it was 1.1–1.3 Gy. As part of the accident management operation, an emergency standard of 0.25 Sv for whole body exposure was immediately introduced in the 30 km zone. Wide scale medical examinations involv-

TABLE I. CRITERIA FOR TAKING DECISIONS ON MEASURES TO PROTECT THE POPULATION IN THE EVENT OF A REACTOR ACCIDENT (APPROVED 4 AUGUST 1983) [1]

(Two radiation intervention levels — A and B — have been established as the criteria for decisions on measures to protect the population)

Nature of exposure	Level of exposure A	Level of exposure B
External gamma radiation (rad)[a]	25	75
Thyroid exposure due to intake of radioactive iodine (rad)	25–30	250
Integrated concentration of ^{131}I in air [(μCi·d)/L][b]		
Children	40	400
Adults	70	700
Total intake of ^{131}I with food (μCi)	1.5	15
Maximum contamination by ^{131}I of fresh milk (μCi/L), or of daily food intake (μCi/d)	0.1	1
Initial ^{131}I fallout density on pasture ($\mu Ci/m^2$)	0.7	7

[a] 1 rad = 1.00×10^{-2} Gy.
[b] 1 Ci = 3.70×10^{10} Bq.

If exposure or contamination does not exceed level A, there is no need to take emergency measures that involve the temporary disruption of the normal living routine of the public.

If exposure or contamination exceeds level A but does not reach level B, it is recommended that decisions be taken on the basis of the actual situation and local conditions.

If exposure or contamination reaches or exceeds level B, it is recommended that emergency measures be taken to ensure the radiation protection of the public: the public should immediately seek shelter indoors; time spent outdoors should be restricted; on the basis of the actual situation, rapid evacuation should be organized; prophylactic iodine should be distributed; the use of contaminated products in food should be banned or limited; dairy cattle should be switched to uncontaminated pasture or fodder.

ing about one million people revealed no cases of acute radiation sickness among the population examined. With the exception of those affected at the site of the Chernobyl plant itself at the time of the accident (237 persons with a diagnosis of acute radiation sickness), no case of radiation sickness was found in those involved in the accident management operation.

Thus, the experience of providing radiation protection for the public and those involved in dealing with consequences of the accident within the 30 km zone in the early stages after the accident, and even more so at subsequent stages, demonstrated the vital role of pre-established exposure regulations to provide guidance for those responsible for taking decisions under such complicated and difficult circumstances.

In addition, an effective system for rapid monitoring of the observance of these regulations is just as important. It was only by ensuring such observance that cases of human overexposure could be virtually excluded.

The Chernobyl accident posed a number of very difficult problems, so that decisions about radiation protection measures required not only a high level of organizational efficiency but also the ability to make on the spot recommendations. The main reason for this lay in the special nature of the accident at Unit 4, characterized, as we know, by two main events: the explosive rupture of the core containment and the graphite cladding fire which released gaseous aerosols containing large amounts of radioactive material into the environment over a period of ten days [3].

All these factors, together with highly changeable weather conditions in the accident area, led to serious radioactive contamination of a number of regions.

Given these circumstances, the most important factor for obtaining an overall assessment of the radiological conditions, and for organizing and implementing, wherever necessary, measures to protect the population and the environment against radiation, was a health and environmental radiation monitoring programme carried out on an unprecedented scale. Thousands of scientists and specialists from various civil departments and representatives of the Ministry of Defence, as well as local subsections of the State Committee on Hydrometeorology, radiological teams from medical and epidemiological stations attached to the Ministries of Health in the Union Republics, the radiological services of the veterinary and agricultural supervisory authorities, etc., were promptly involved in these activities. In a short time, millions of dosimetric and radiometric measurements were carried out and then analysed; conclusions were drawn locally, at regional centres and by the scientific methodology section of the State Commission.

Although this vast programme of work was, on the whole, effectively carried out, many problems and questions arose. Below we consider some of the problems which should be noted in the interest of further improvements to the radiation monitoring system.

First, all available dosimetric equipment and radiometric facilities were used.

Experience has shown that this equipment should be further standardized, more strictly regulated with regard to possible applications, and that sensitivity thresholds and limits in relation to accident conditions should be determined more accurately. It is important that instrument readings should be appropriate to the characteristics of the radiation recorded, and that the instruments themselves should be compact and simple to use. One essential step is to standardize the measuring scales of these instruments in accordance with the system of units adopted.

It is also particularly important to develop better methods for retrospective determination of absorbed doses in the human body following external and internal exposure. We saw once again that the methods known as 'dosimetry without dosimeters' are very promising for the reconstruction of absorbed doses from external exposure (e.g. by electron spin resonance or radiolyoluminescence signals in different materials, including samples of hair, nails, tooth enamel and clothes). The doses to three persons who died from radiation sickness were determined at our Institute by measuring the ESR signal from tooth enamel and gave a close correlation with the severity of the damage suffered. The Chernobyl accident demonstrated the importance of assessing the dose to exposed areas of human skin. For instance, the results obtained with multilayer thermoluminescence dosimeters developed at our Institute [4] for measuring doses of beta and low energy gamma radiation absorbed in the skin suggest that such dosimeters should be included in the emergency individual dose monitoring system.

Second, the amount and frequency of the monitoring that has to be done can vary a great deal, depending on the particular radiation situation that develops. For example, ^{131}I is known to have been the dominant reference radionuclide in the environment and in foodstuffs during the first few days or weeks after the accident. In a very short time, methods of measuring ^{131}I in environmental samples were established for those cases where it was not possible to perform gamma spectrometry measurements (because of the enormous number of samples and the shortage of gamma spectrometers at sites such as farms and other places where it was necessary to draw tentative conclusions about, say, the radioactivity in milk samples). The methodological problems of making mass measurements of the intensity of gamma radiation from the thyroid (exposure dose rate) were solved for cases where portable gamma radiometers were used. Models were developed for calculating individual thyroid doses from inhalation of radioiodine, allowing for different living conditions in the contaminated area and different patterns of consumption of dairy products, and including the necessary tabular data with numerical values for the parameters used in the calculation formulas.

Thus, the Chernobyl accident required a large number of different measurements of radioactivity in environmental objects and samples of environmental objects, and also measurements on the human body. In particular, lifetime ^{131}I, ^{134}Cs and ^{137}Cs concentrations in the body were measured in more than 600 000 persons. This vast mass of data, given the calculational methods of evaluation available, made it possible to classify population groups according to exposure levels and, on this basis, to take the necessary sanitary, medical and organizational measures to normalize the situation and to mitigate the radiological impact.

The main conclusion drawn from this experience is that the whole system of dosimetric and radiometric monitoring, and also the volume of control performed in the wake of a major accident, must be further improved.

Before the Chernobyl accident, both in the USSR and in other countries, regulations governed only the annual limits on the intake of radionuclides in food products. There were also regulations governing the maximum permissible concentrations (MPCs) of nuclides in drinking water (Standards of Radiation Protection SRP-76). On the other hand, there were no regulations governing radionuclide concentrations in individual foodstuffs. A standard for ^{131}I was specified in the event of an accident (the thyroid dose for children should not exceed 300 mSv). This requirement was met with a limit on the permissible concentration in milk of 3700 Bq/L.

After the Chernobyl accident, we needed a quick and efficient solution to problems associated with the assessment of radioactivity in foodstuffs, in the form of tests and, when required, prohibitions on the consumption of certain food products. Accordingly, standards (MPCs) were calculated and immediately introduced for the ^{131}I content of medical raw materials and 24 food products, including dairy products (curds, sour cream, cheese, butter), leafy green vegetables, meat, poultry, eggs and berries, taking into account their actual contribution to the diet. Subsequently, late in May 1986, MPCs for ^{134}Cs and ^{137}Cs were introduced as well owing to the increased relative contribution of these nuclides to the contamination of meat, milk and a number of other food products. These standards were calculated on the basis of a permissible dose of 50 mSv to the whole body and internal organs over the first year following the accident. Temporary permissible levels for surface contamination (in buildings, transport, equipment, clothes, shoes, individual protection devices and skin) were calculated and approved to prevent additional internal and external exposure of people and to prevent the anthropogenic escape of radioactive materials from the 30 km zone. Moreover, corrected permissible levels of contamination were adopted for the ground surface and external and internal surfaces of buildings after decontamination work had been carried out. To improve the system of controlling radionuclide concentrations in agricultural products, 28 regulatory documents were prepared governing procedures for the treatment, processing and final preparation of various livestock, poultry, fodder, fur products, etc.

The most difficult regulatory problems were encountered in making arrangements for radiation monitoring of roads, buildings, transport, everyday articles, and so on. For such large scale operations as these, we needed standards which were safe and at the same time realistic in the light of the situation. As radiation conditions returned to normal, the standards set at the beginning of May 1986 were repeatedly reviewed with a view to greater stringency, the aim being to bring them closer to the SRP-76 values. In particular, after the main decontamination work on Units 1 and 2 and the construction of the 'tomb' for Unit 4, we returned to the SRP-76 standards for beta particles for contamination of unit premises, and the SRP-76 standards for exposure of workers' skin were set as permissible levels for the contamination of clothes at the edge of the 30 km zone. On the whole, the experience of setting standards and organizing radiation monitoring showed that, even in the event of such a major accident, the measures taken — scientifically founded as they were — made it possible to prevent the spread of radioactive material beyond the boundaries of the 30 km zone, to reduce very substantially the danger of contamination of people, their belongings and houses: all this was achieved through a massive and extremely laborious decontamination operation which, together with other public health measures and practical actions, greatly mitigated the adverse effects of the accident. One of the most important things was the establishment of a temporary dose limit for exposure of the public in areas with high radiation levels.

This limit for exposure of the public in the event of a full design basis accident was taken as an individual dose limit of 100 mSv, introduced as a temporary limit for the first year after the accident. Later, the State Committee on Radiation Protection introduced a stricter standard, namely 30 mSv, for the second year after the accident. These regulations formed the basis for protection during the vast amount of work performed under the accident management programme.

From analysis of the actual data, with allowance for all the protective and preventive measures taken, it is possible to draw the following conclusions. Average individual doses for the critical population groups living in the regions under strict control did not exceed the basic temporary dose limits set for the first and second years after the accident (100 and 30 mSv, respectively). Also, external gamma doses to the population living permanently in the contaminated areas did not exceed 50 and 15 mSv, respectively, for 97% of the inhabitants. Internal doses from incorporated radioactive caesium did not exceed 50 mSv for the first year and 20 mSv for the second year after the accident for 99% of the population, and in approximately 90% of the inhabitants of the regions under control they did not exceed 10 mSv, either for the first or second year after the accident.

In other words, the doses received by the majority of the population in the regions under control proved to be less than half the temporary dose limits in the first and second years after the accident (for about 95% of the population in the first year and 90% in the second year). Concentrations of caesium in the bodies of those living in the controlled regions were 2–5 times lower in the summer of 1987 than in the summer of 1986, and in some cases the difference was measured by factors of 7 to 10.

Finally, in 1987, the contribution of internal exposure to the total dose showed a more marked tendency to decrease, as it did not exceed 20–30%.

On the whole, the measures taken brought a 5 to 20 fold decrease in the anticipated thyroid dose burden for children, a 1.3 to 2.5 fold decrease in the external gamma dose (depending on age and occupation), and a 10 fold or greater decrease in internal doses.

These special measures included essentially:

(1) Evacuation of the population from the 30 km zone, including Pripyat'
(2) Establishment of a 30 km circular zone around the Chernobyl plant site with a strict system of restrictions and radiation monitoring to prevent anthropogenic transfer of radioactivity from the 'contaminated' zone to 'clean' areas
(3) Prophylactic administration of stable iodine compounds to those dealing with the consequences of the accident, to the population of Pripyat' and the population of regions bordering upon the 30 km zone
(4) A ban on the consumption of whole milk, restrictions on the grazing of dairy cattle or transfer to uncontaminated pastures or fodder, monitoring of radioactivity in foodstuffs and quality inspection, processing and utilization of food products
(5) Decontamination of population centres and adjacent areas
(6) Evacuation of children and pregnant women from these centres for health holidays in the summer of 1986 and 1987

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(7) A complex of measures aimed at replacing, in a number of areas, local food products by products imported from elsewhere
(8) Agrotechnical and agricultural land improvement measures.

All these measures, as stated above, brought a significant decrease in the doses to the population (from both external and internal radiation).

Thus, our experience of regulating permissible reference levels of environmental contamination and permissible dose limits for exposure of those involved in the accident management operation and of the population in the region affected by the products of the accidental release showed that this aspect of radiation protection was of vital significance in determining the accident management strategy and in providing a reasonably achievable reduction in the exposure of different groups of people.

In addition, the experience of carrying out the above and other measures clearly demonstrates that, given radioactive contamination of areas covering thousands of square kilometres, it is extremely difficult to deal with a problem such as external gamma radiation, especially after the radiation conditions have become relatively stabilized. Unlike the more 'controllable' problem of internal exposure, as can be seen from the above estimates, the methods of dealing with external gamma irradiation depend primarily on the decontamination of the human environment. In contrast to the decontamination work at the plant site and immediately adjacent areas, the decontamination of population centres, forests, fields and farms must obviously rely on mechanical removal of the radionuclides without the benefit of any special decontamination solutions containing active chemical components.

The most difficult part of the complex and laborious decontamination work (it is sufficient to indicate its scale — see Refs [3–7]) was decontamination of forests.

Nevertheless, decontamination work is continuing, with due allowance for the characteristics of the objects to be treated. It should be stressed that a further decrease in gamma dose rates will depend largely on vertical migration of nuclides in the soil; this will involve deep ploughing, wherever possible, among other things.

It might be worth mentioning that the possibility of soil decontamination as a result of large scale uptake of radionuclides (including ^{137}Cs) by the aerial parts of plants during the first few years after the accident must be considered as insignificant: the gamma dose rate is not substantially reduced thereby.

The problem of assessing the possible radiological impact of the accident on the population of the USSR has already been discussed [2, 7]. An analysis of field material and the corresponding calculations, taking into account the efficiency of the measures which have been taken and which are still being carried out, suggest that the collective effective dose equivalent commitment for the entire population is about 326 000 man·Sv. If we take a non-threshold dose–effect relationship and the International Commission on Radiological Protection (ICRP) risk factors [8] for stochastic effects, excess (additional) mortality from cancer may be expected theoretically to represent a few hundredths of a per cent of the spontaneous level, and the corresponding number of genetic defects in the first two generations born of exposed

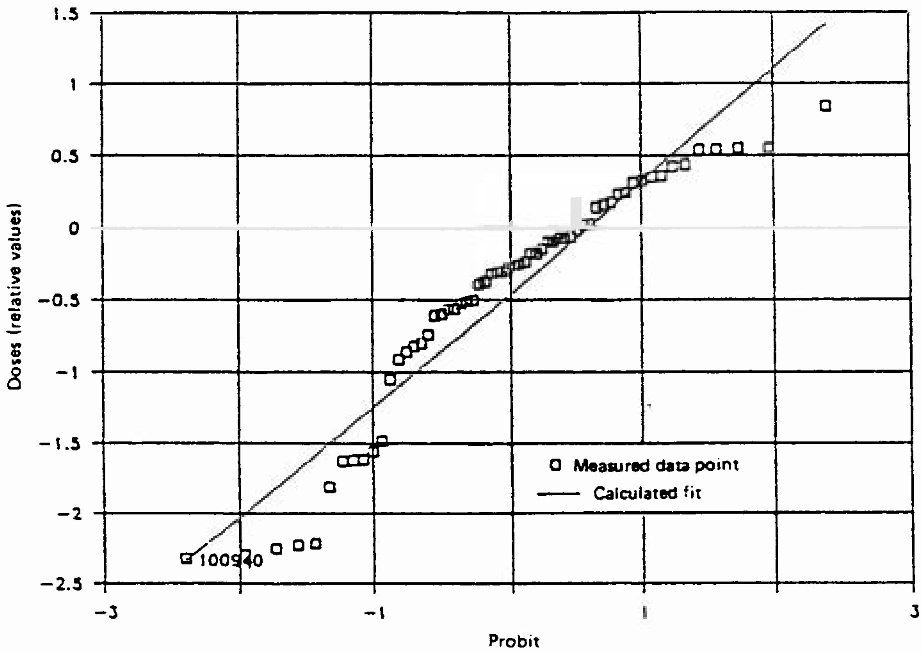

FIG. 1. Probability distribution of individual doses.

parents a few hundredths or thousandths of a per cent. Our data show a satisfactory correlation with more recent frequency estimates of expected late radiological effects of the Chernobyl accident on the population of Western Europe [9] and in the Northern Hemisphere as a whole [10].

The basic data for calculations made in the USSR are presented in a series of figures. It should be stressed, first of all, that analysis of the actual and calculated relationships has shown a log normal distribution of individual doses irrespective of region; a typical distribution is shown in Fig. 1. Figure 2 shows a distribution for the whole population of the USSR according to the individual dose equivalent commitment, including a comparison with the analogous doses from natural background radiation (but ignoring the increase in background radiation due to technological activities (see Fig. 3)). It is interesting to note that the individual dose equivalent commitment for the majority of the USSR population (about 250 million people) will be less than 1 mSv. Moreover, calculations suggest (see Fig. 4) that the 'dose pressure' contributed by this part of the population to the total collective commitment for the population of the whole country (278.8 million people) will not exceed 15%. Consequently, the example of Chernobyl shows that reducing the lower limit of the individual dose equivalent commitment to zero has virtually no effect on the collective dose equivalent commitment. It is worth considering this conclusion in the light of the discussions at the ICRP meeting held in Como, Italy, in September 1987:

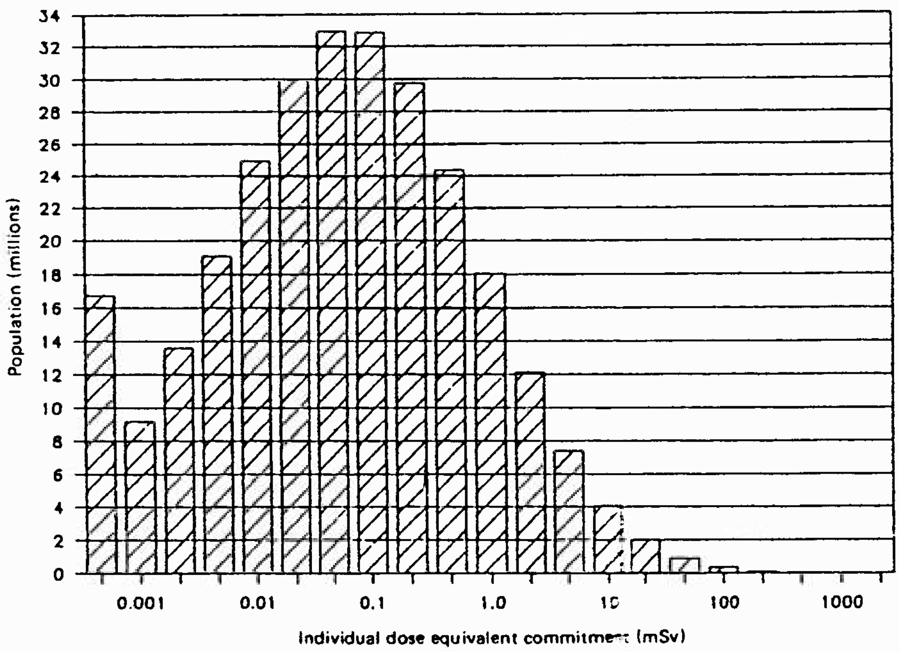

FIG. 2. Distribution of individual dose equivalent commitment for the whole population of the USSR.

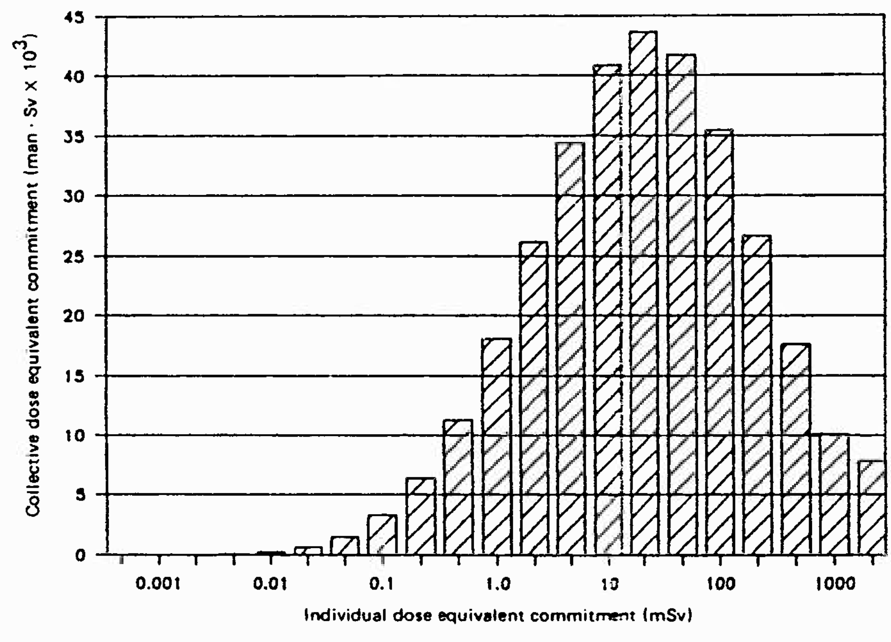

FIG. 3. Distribution of collective dose equivalent commitment according to the individual dose equivalent commitment in the USSR.

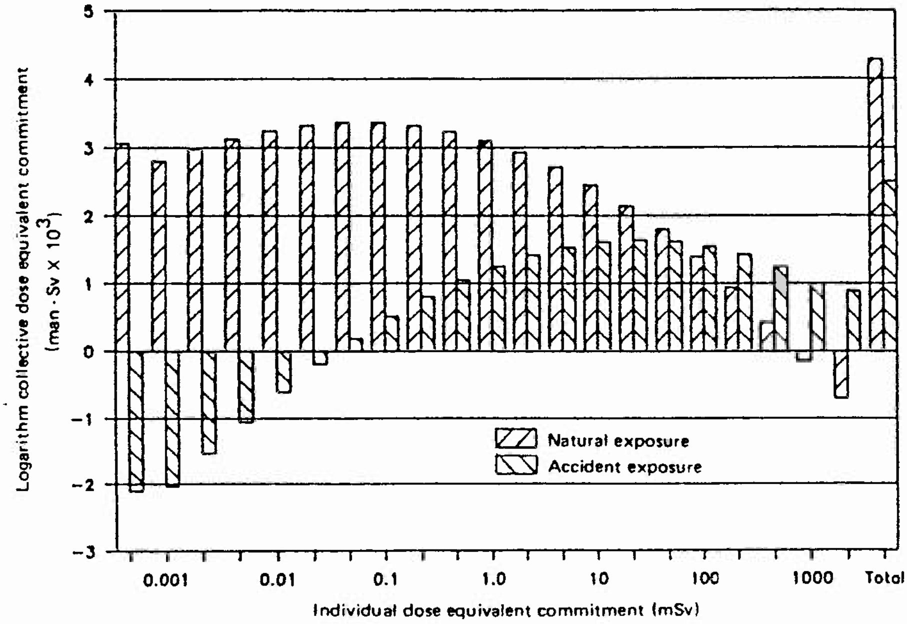

FIG. 4. Distribution of the collective dose equivalent commitment from natural and accident exposures in the USSR.

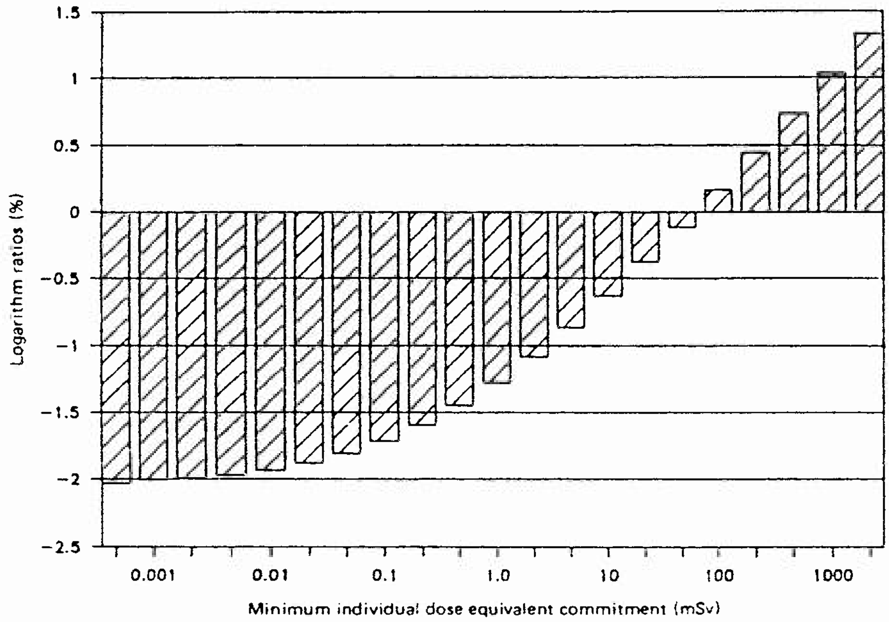

FIG. 5. Ratios of radiation induced to spontaneous cancers according to the minimum individual dose equivalent commitment in the USSR.

there, arguments were put forward in favour of setting a lower limit for individual dose equivalent commitment based on biologically significant levels of exposure. For many reasons, this approach seems to be more realistic than that currently used. One should also take into account the fact that the initial meaning of the collective dose concept made it a useful tool for solving radiation protection problems, but not for assessing the late effects of accident exposure.

If, in the context of our analysis, the lower level for individual dose equivalent commitment is taken to be 10 mSv (which constitutes only about 15% of the corresponding cumulative dose from natural background radiation), the following conclusions may be drawn: the expected excess of fatal cancers will mark a 0.23% increase over the spontaneous level (Fig. 5) (for a population of 7.5 million, the collective dose equivalent commitment will be 2.2×10^5 man·Sv), and the absolute number of predicted cases of cancer will be 30% less than the initial estimates for a population of 280 million people.

Finally, as can be seen from these calculations, existing epidemiological methods would fail to register the above malignant tumour excess.

In conclusion, it should be noted that a large number of radiation protection problems highlighted by the Chernobyl accident have not been touched upon in this report. The problem of radiation phobia is one of these, and it continues to play an important role.

There is still a great deal of work to be done in this area.

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PROCEEDINGS OF AN INTERNATIONAL CONFERENCE
ON RADIATION PROTECTION IN NUCLEAR ENERGY
ORGANIZED BY THE
INTERNATIONAL ATOMIC ENERGY AGENCY
AND HELD IN SYDNEY, 18–22 APRIL 1988

In two volumes

VOLUME 2

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 1988