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Estimated Long-Term Health Effects

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ABSTRACT

Apart from the dramatic increase in thyroid cancer in those exposed as children (see background paper 2), there is no evidence to date of a major public health impact of the radiation exposure from the Chernobyl accident in the three most affected countries. Although some increases in the frequency of cancer in exposed populations have been reported, these results are difficult to interpret, mainly because of differences in the intensity and method of follow-up between exposed populations and the general population to which they are compared.

If the experience of atomic bomb survivors and of other exposed populations is applicable, the major radiological impact of the accident will be cancer and the total lifetime numbers of excess cancers will be greatest among the liquidators and among the residents of contaminated territories, of the order of 2 000 to 2 500. These increases would be difficult to detect epidemiologically against an expected background number of 41 500 and 433 000 respectively (size of the exposed populations: 200 000 and 3 700 000, respectively).

It is noted, however, that the exposures received by populations exposed as a result of Chernobyl are different (in type and pattern) from those of atomic bomb survivors. Predictions derived from these populations are therefore uncertain. Indeed, the extent of the increase in thyroid cancer incidence in persons exposed as children was not foreseen. In addition, only ten years have past since the accident. It is essential therefore that monitoring of the health of the population be continued in order to assess the public health impact of the accident, even if, apart from leukemia among liquidators, little detectable increase of cancers due to radiation from the Chernobyl accident is expected.

Studies of selected populations and diseases are also needed in order to study observed or predicted effects; careful studies may in particular provide important information on the effect of exposure rate and exposure type in the low to medium dose range and on factors which may modify radiation effects. As such, they may have important consequences for the radiation protection of patients and the general population in case of further accidental exposures.

The issues

Ionising radiation is one of the best studied carcinogens in the human environment. Hundreds of thousands of persons exposed to radiation around the world (atomic bomb survivors in Japan, patients irradiated for therapeutic purposes, workers exposed occupationally) have been followed-up for decades. Many large scale animal experiments have been carried out and much experimental work has been performed to understand the mechanisms of radiation damage at the cellular and molecular level and quantify its effects. The major long-term effects identified [1-5] are an increase in the frequency of cancers, cataracts and, among those exposed in utero, a higher frequency of congenital anomalies. A small increase in genetic effects has also been observed in animal experiments.

Predictions concerning the likely radiological consequences of the Chernobyl accident have been made on the basis of these data. Much of the data accumulated to date, however, comes from studies of populations having received relatively high doses in an acute or fractionated fashion, often from external radiation. Uncertainties remain concerning the exact magnitude of the health effects of the exposures received by populations as a result of the Chernobyl accident, in particular:

(a) the effects of relatively low doses[1], such as those generally resulting from environmental exposures in large areas contaminated by the Chernobyl accident;

(b) the effects of protracted exposures, such as were received by populations exposed environmentally and some of the liquidators;

(c) the effects of different radionuclides and different radiation types;

(d) the effects of factors which may modify radiation induced risks (including age at exposure, sex, possible genetic predispositions and other host and environmental factors).

Ten years have now passed since the Chernobyl accident and it is timely to summarise what long-term health effects have been observed up to now, whether they agree with predicted effects and what we might expect to see in coming years and decades. In this paper we review the organisation of the epidemiological follow-up of exposed populations in the three most affected countries of the former USSR (Belarus, the Russian Federation and Ukraine), the levels of radiation doses they received, the health consequences expected on the basis of previous epidemiological studies of populations exposed to radiation, and the main results to date. Four groups of exposed populations (see Table 1) are considered separately, where possible:

1. the "liquidators" – also referred to as "clean-up" or "emergency accident workers" – they include persons who participated in the clean up of the accident (clean-up of the reactor, construction of the sarcophagus, decontamination, building of roads, destruction and burial of contaminated buildings, forests and equipment), as well as many others, including physicians, teachers, cooks, interpreters who worked in the contaminated territories –

[1] In the range 0-300 mSv over a lifetime

2. the "evacuees" – those who were evacuated from the town of Pripyat and the 30 km zone around the Chernobyl reactor in April-May 1986 –;
3. the residents of the "strict control zones" (SCZ's): those members of the general population who have continued to live in the more heavily contaminated areas (with level of ^{137}Cs deposition greater than 555 kBq/m^2), typically within a few hundred kilometres of the Chernobyl Nuclear Power Plant. Within these areas, radiation monitoring and preventive measures have been taken to maintain doses within permissible levels;
4. the general population of the contaminated territories in the three countries.

The primary focus of this paper is the estimation of the burden of cancer – the major long-term effect expected on the basis of high dose studies – resulting from the accident. Thyroid cancer, which has been observed to increase dramatically since the accident, is discussed in more detail in background paper 2. It is too early to assess genetic effects and the absence of systematically collected data on genetic and other effects (cataracts, congenital anomalies) in most of the affected countries make any conclusions about these difficult to draw. Effects of the Chernobyl accident outside the three main countries are not discussed since, although relatively high levels of contamination were recorded in Bulgaria, Austria, Greece and Romania, followed by other countries of Central, Southeast and Northern Europe, the levels of exposure and the magnitude of the expected and observed effects to date [6-8] are very low. Acute radiation effects are discussed in background paper 1.

Background

Background scientific knowledge about radiation risks

Ionising radiation is one of the agents in our environment for which genetic and cancer risks have been best studied and characterised. This is mainly due to two facts: (1) very large numbers of exposed persons have been followed-up for decades, and (2) compared to many other environmental agents, radiation exposures are relatively easy to reconstruct, on an individual level, at least for exposures received at high exposure rates and high levels. The information available to date on radiation risks comes from several sources:

- epidemiological studies of large populations having received relatively high doses of γ- or X-radiation at a high dose rate (atomic bomb survivors, patients treated by radiotherapy for malignant or benign diseases, occupational exposures in the early years of medical exposures) or of radon in a protracted fashion over many years (hard rock, particularly uranium, miners) [1,9,10];
- more recently, large scale epidemiological studies of populations having received low doses in a protracted fashion as a result of their occupation, mainly in the nuclear industry [1,11,12];
- large scale animal experiments carried out in order to understand the effects of different radiation types, exposure levels, patterns of exposure and modifying factors [1,9,10];

- cytogenetic; molecular and genetic studies aimed at understanding the mechanisms of radiation induced carcinogenesis [2,9].

The major long-term effects identified [1-5] are an increase in the frequency of cancers, particularly leukemia, and of cataracts and, among those exposed in utero, a higher frequency of congenital anomalies. A small increase in genetic effects has also been observed in animal experiments.

The temporal patterns of radiation risks have been observed to differ markedly for leukemia and solid cancers. In the follow-up of the atomic bomb survivors, excess risk for leukemia increased sharply after the bombing, reaching a peak between 3-10 years after exposure followed by a gradual decline [13]. The temporal pattern of leukemia risk was markedly modified by age: in general, the younger the age at exposure, the higher the initial excess risk and the steeper the subsequent decline. Among those exposed as adults, the decline was less pronounced for women then men.

The excess solid cancer risk, however, appeared gradually, starting 5-10 years after exposure and increased roughly in proportion to the background cancer rates (these typically increase with advancing age). The excess relative risk (i.e. the proportional increase in risk relative to background risk) for solid cancers depended on age at exposure and sex. It was generally higher for those exposed at younger ages and for women. The temporal pattern of the relative risk has been remarkably constant during the follow-up [14] except for those exposed early in life for whom the relative risk has been decreasing with the passage of time. Thyroid cancer risk has followed a similar temporal pattern [15]. A recent pooled analysis of seven studies suggests that the excess relative risk of thyroid cancer among those exposed as children (below the age of 15 years) remains elevated for many years, declining only 30 years after exposure [16].

The follow-up of populations exposed as a result of Chernobyl: organisation and problems

Chernobyl Registry follow-up

The Chernobyl Registries were established initially as a single "All-Union Distributed Registry" located in Obninsk, Russia, by a 1987 directive of the Ministry of Public Health of the USSR [17]. The aim was to set up a comprehensive registration and follow-up system for the persons most affected by the Chernobyl accident. The directive identified four groups of subjects - the groups of "primary registration" - for whom registration and "active" follow-up was mandatory: participants in the "liquidation" of the consequences of the Chernobyl accident, the so-called "liquidators"; subjects evacuated from the most contaminated territories (>1480 kBq/m^2); persons living in contaminated areas (>555 kBq/m^2); and children of the above groups. Since the break-up of the USSR, the responsibility for the State Chernobyl Registries has been passed to the individual countries.

As a consequence of this directive, all persons included in the State Chernobyl Registries are "actively" followed-up, i.e. they must undergo an annual medical examination in which they are systematically examined by a general practitioner and a number of different specialists. The subject is also directed, as appropriate, for additional examinations to oncologists and other specialists.

All data on diseases diagnosed during the annual medical examination, as well as at any other time during the year is sent to the Chernobyl Registry for inclusion in the registry data base. In addition to medical data, the State Chernobyl Registries includes demographic variables, information on location and behaviour (food and milk consumption, time spent in contaminated zones) at time of accident and on work in the Chernobyl area, and, when available, dosimetric information.

General population health monitoring

Means also exist in the affected countries to carry out "passive" follow-up of exposed persons and of the general population with the use of population registries – of mortality, cancer and other diseases.

Mortality

In each country of the former USSR, population registration is carried out at the local level in the address bureaus (where the addresses of current residents are kept) and the ZAGS – buro zapicii akta grazhdanskovo sostoyania – (which compiles all information about birth, marriage, divorce and death of persons living in the administrative area). No centralised registry exists, however, and results of a recent pilot study [18] indicate that considerable time and effort may be needed for tracing subjects who have moved from one area to another. In Belarus, centralisation of population registry data is underway; this will increase the feasibility of mortality follow-up of populations. Little information is available currently, however, on the adequacy of mortality data in the affected states.

Cancer incidence

A computerised national Cancer Registry has been functioning in Belarus since the 1970's and registers all cases of malignant neoplasms. A comprehensive registry of Haematological Diseases also exists in Belarus, in the Institute of Haematology and Blood Transfusology, and a registry of childhood thyroid cancer cases in the Institute for Thyroid Pathology in Minsk, where most of these tumours are operated. These registries have proved to be valuable tools for epidemiologic follow-up in Belarus [19-23].

In Russia and the Ukraine, no centralised cancer registration system was in place at the time of the accident. Work is underway in both countries to set one up – at least in contaminated areas in Russia – [20]. At present, however, routine data on cancer morbidity in these countries is obtained from local oncological dispensaries and verification of the completeness and accuracy of the diagnosis information and checks for duplicates is not systematically performed. For persons included in the Chernobyl Registry, moreover, information on cancer diagnosis is often obtained from the records of medical visits in local medical centres; if a patient is referred to the regional or national level for confirmation and treatment and the diagnosis is changed, the information is not necessarily sent to the Chernobyl Registry. A recent study in Russia [18] confirms that the diagnostic information in the Chernobyl Registry is not always completely accurate. The lack of verification and quality control is actively being remedied, but must be kept in mind, when interpreting results of studies of cancer frequency among exposed populations in those countries.

General morbidity

Information is also available systematically on the general (i.e. not only cancer) morbidity of the population of the three countries. In the countries of the former USSR, regional outpatient clinics systematically collect information on disease diagnoses on all the residents of the region they cover (not only on those included in the Chernobyl Registry). This information is summarised locally and is sent, on special statistical reporting forms, at yearly intervals to the Ministry of Health. These forms contain information about the number of cases of acute and chronic diseases diagnosed in a given year in the population in all areas of the country. This information is not broken down by age or sex. No verification of completeness and duplicates is possible. This passive system of collection of morbidity data on the population contrasts with the active follow-up carried out, as described above, for persons included in the Chernobyl Registry. Comparisons of morbidity based on these sources must therefore be interpreted with caution.

Ad-hoc studies

A number of factors limit the power of the routine follow-up activities listed above to detect the expected effect of radiation from the Chernobyl accident, even in the three most affected countries of the former USSR. They include, in particular, the generally low level of radiation dose received by the majority of exposed populations – and hence, presumably, low level of risk expected –, the difficulties of systematic and complete follow-up, the lack of precise dosimetry (as described below) and the important movements of populations which have taken place since the accident.

Ad-hoc analytical epidemiologic studies, focusing on specific diseases and populations, may be a more useful approach to investigate the effects of radiation among the exposed populations [24,25]. Cohort studies of well defined populations – i.e. studies of groups of individuals who are followed over time, for example the cohort of all children whose thyroid dose was measured in the days following the accident – are important tools for studying radiation effects if precise individual dose estimates can be obtained and if a systematic and complete follow-up can be achieved. When this is not feasible, for logistic and/or financial reasons, case-control studies – i.e. studies of cases of a disease of interest occurring in a given population (for example cases of leukemia occurring among liquidators) and of appropriate controls – are a cost-efficient and powerful alternative. This type of study allows the collection of relatively detailed individual information on the exposure of interest and on other risk factors (from questionnaire as well as from searches of existing records) at much less cost since the number of study subjects is much reduced.

Both cohort and case-control studies are generally much more powerful than descriptive studies for investigating dose-relationships. Indeed, the single most informative study on radiation risks today, that of the survivors of the atomic bombings in Hiroshima and Nagasaki [14], would have provided much less information concerning the relation between radiation exposure and cancer risk if the follow-up had been restricted to an examination of trends of diseases over time and comparisons with non-exposed or the general population.

Radiation doses to different groups: dose levels and available estimates

Table I presents a summary of the number of persons exposed and the levels of doses received in the four groups described above. Much effort has been directed to reconstructing doses on an individual or group level for populations exposed environmentally, mainly for those who were living in the most contaminated territories at the moment of the accident [26-33]. Less attention has been focused on reconstructing dose levels for the general population living in contaminated territories outside the strict control and evacuation zones, since, given the level of exposure they received, it is unlikely (if our current estimates of risk are correct) that any radiological effect on health could be detected in this population, even though it may well have the largest total collective dose.

Radiation dose estimates for these populations have been derived in a variety of ways: from direct whole body or thyroid counting – to determine, respectively, the individual body and thyroid burden from various radionuclides – and physical measures of dose from external radiation using individual dosimeters, to dose reconstruction using environmental models and questionnaires, and to estimation of dose using biological or biophysical markers of exposure. The accuracy of the dose estimates varies according to the estimation method and the level of dose, since, in general, more precise and numerous measurements were made in the most contaminated regions.

Liquidators

Approximately 600 to 800 000 persons took part in the clean-up activities to "liquidate" the consequences of the Chernobyl accident. This include persons who participated in the clean up of the accident (clean-up of the reactor, construction of the sarcophagus, decontamination, building of roads, destruction and burial of contaminated buildings, forests and equipment), as well as many others, including physicians, teachers, cooks, interpreters who worked in the contaminated territories and received on average much lower doses. Approximately 200 000 liquidators (see Table I) worked in the region of Chernobyl during the period 1986-87, when the exposures were more significant.

The dosimetric information available for liquidators is subject to controversy as the personal dosimeters in use in the early days after the accident were too few and generally too sensitive. A reasonable estimate of the average dose received by this group of 200 000 people is 100 mSv [28]. Thus, the collective effective dose would be approximately 20 000 Sv. It is noted that some workers received their dose in a matter of minutes - for example working on the roof of the reactor - while others received it over months or even years, and the predominant radiation type and route of exposure varied according to time and activity of liquidators.

Dose estimates have generally been derived in one of three ways:

- individual dosimetry – the liquidator was given a personal dosimeter –;
- group dosimetry – an individual dosimeter was assigned to one member of a group of liquidators;
- from itineraries – measurements of γ–ray levels were made at various points where liquidators worked, and an individual's dose was estimated as a function of the points where he or she worked and the time spent in these places.

It is thought that the level of dosimetric control and the adequacy of dose estimates may vary between civilian liquidators (construction workers, logistic support), military liquidators (soldiers and officers who worked in decontamination, dosimetric control, evacuation) and radiation specialists.

The distribution of liquidators included in the State Chernobyl Registries of Belarus, Russia and Ukraine and of their doses is shown in Table II. It is noted that doses are missing in these registries for a substantial proportion of them. Liquidators who worked in the first year generally had higher recorded doses than those who worked in subsequent years. Throughout this paper, efforts are made, where possible, to restrict the presentation to those liquidators who have worked in the 30 km zone in 1986-87 as these are most likely to be those who have actually participated in the clean-up activities.

Evacuees

The evacuees are the former residents of the 30-km zone. There were approximately 135 000 persons evacuated, including the 49 000 residents of the city of Pripyat. The evacuation of Pripyat and other locations close to the damaged reactor was completed within approximatly 40 hours of the accident. Approximately 40 000 additional residents of the 30 km zone were evacuated on 3-5 May 1986 and the evacuation of the 30 km zone was completed during the period 5-14 May [32].

Most of the dose was received in a short time period and resulted from external exposure from the passing cloud and from radionuclides deposited on the ground or other surfaces. Initial reports by Soviet scientists [30] were that this population had received a collective effective dose from external exposure of 16,000 person Sv. More recently the doses from external exposures have been re-evaluated by Likhtarev et al. [32]. This re-evaluation was based upon dose-rate data from many locations within the zone, and the results of a survey of 42 416 evacuated residents. Individual doses were reconstructed for 13 383 inhabitants of Pripyat and 17 203 residents of other settlements. The average dose to the residents of Pripyat was 11.5 mSv and that of residents of the other evacuated locations was 18.2 mSv. The calculated individual doses vary widely; the maximum value was stated to be 383 mSv. The collective effective dose from external exposure for the entire evacuated population is estimated to be 1,300 person-Sv. The collective effective dose from other exposure pathways is not believed to add substantially to the indicated total.

Human exposure in contaminated areas

Currently, there are approximately 4 million people who reside permanently in areas with ^{137}Cs deposition density of more than 37 kBq/m^2 in areas of Belarus, Ukraine and Russia. The total area covered is about 131 000 km^2 [29]. Dose to these persons resulted both from external exposures from the passing cloud and from radionuclides deposited on the ground or other surfaces and from internal exposures: inhalation of material from the passing cloud in the first days and ingestion of various radionuclides that contaminate foods.

Residents of strict control zones

About 270 000 people lived in the 10 300 km^2 of the SCZ's (with ^{137}Cs deposition density of more than 600 kBq/m^2) in 1986 (

Table III). The collective doses to these populations have not recently been estimated explicitly. However, the dynamics of dose formation have been considered and reported in detail by Balonov and collaborators [29]. From this work, it can be estimated that the average external and internal dose during the period 1986 to 1995 for the population in these areas is approximately 50 µSv per kBq/m^2 of ^{137}Cs deposition density. For the SCZ's, a reasonable estimate of the average deposition density is 25 Ci/km^2 ***(convert to kBq)*** – areas with deposition density greater than 40 kBq/m^2 were generally evacuated –. Thus, an approximate value of the average effective dose is 50–60 mSv and the collective effective dose for the 270,000 residents is 10,000–20,000 person-Sv.

Residents of other contaminated territories

An estimate of the collective dose for the remaining 3.7 million persons living in contaminated areas can be made in a similar fashion. The average deposition density is assumed to be 3 Ci/km^2 *(kBq)*. The average external and internal dose during the period 1986 to 1995 for the population in these areas is approximately 50–150 μSv per kBq m^{-2} of ^{137}Cs-deposition density (higher than in the SCZ's, as there was less control on internal dose). The average effective dose is therefore calculated to be in the range 6–20 mSv. The estimate of collective effective dose is 20 000-60 000 Sv. This estimate is compatible with the more rigorously evaluated value of 22 000 Sv by Kenigsberg et al. [31] for the entire population of Belarus. Their estimate for the average dose to the residents of the Gomel and Mogilev Oblasts is 5.9 mSv. A comparable estimate of collective dose for the entire population of Ukraine is given by Likhtarev and Kovgan [33] as 47 500 Sv, with about 15 000 Sv calculated to be delivered to inhabitants of areas with a ^{137}Cs-deposition density of less than 1 Ci km^{-2}.

It should be noted that, given the large number of persons residing in these areas, small errors in dose estimates may lead to large errors in the collective dose. Thus, the predicted health effects discussed below for this population are very uncertain and should be treated with caution.

Thyroid dose to populations in contaminated regions

An early exposure situation of special interest is the thyroid dose to the general population living in the heavily contaminated regions of the countries of Russia, Belarus, and Ukraine. This is of particularly interest due to current reports of a major increase in the incidence of childhood-thyroid cancer in all three countries [34-38]. As discussed in more detail in background paper 2 – Thyroid effects – there is now very strong circumstantial evidence that this increase is related to dose from iodine isotopes. Major efforts have been carried out and continue to reconstruct thyroid doses to the populations at risk. A summary of the results that have been reported is provided in background paper 2

Discussion

Expected health consequences

This section presents predicted health effects, particularly cancer and genetic disorders, derived from models of radiation induced risk developed from epidemiological studies of other populations exposed to radiation, mainly the Japanese atomic bomb survivors (Life Span Study, LSS). Although there are a number of epidemiological studies from which radiation risk data can be obtained, the atomic bomb studies continue to be the main source of data for risk estimation [9][26][39][40]. The atomic bomb survivors were exposed primarily externally and at high dose rates, however, and models must be used to extrapolate the effects of such exposures to the generally lower dose, and lower dose-rate exposures of concern for the majority of populations exposed as a result of the Chernobyl accident. These models are, inevitably, subject to uncertainties. Major questions relate to the choice of models for transfer of data between populations with different background cancer rates, for projection of risk over time and for extrapolation of risks following primarily external high dose and high dose-rate exposure to low dose and low dose-rate exposures involving a mixture of external and internal radiation.

In the predictions presented below, the atomic bomb survivor estimates were applied directly to the populations exposed as a result of the Chernobyl accident assuming that, for a given dose of radiation, the resulting cancer risk is the same regardless of the pattern and type of exposure. It is noted that, in extrapolating the risk estimates based on high dose and high-dose-rate exposure to low dose and low dose-rate exposures, the International Commission for Radiological Protection (ICRP) has used a reduction factor (the Dose and Dose-Rate Effectiveness Factor or DDREF) of two [40].

Solid cancers and leukemia

Lifetime risk estimates (through age 95 years) were computed for solid cancers and leukemia (excluding CLL) for the liquidators and the populations living in contaminated areas of Belarus, Russia and Ukraine. The methods used follow those of the UNSCEAR 1994 Report [1], allowing for the modifying effects of age at exposure and sex (for leukemia). Table IV presents the predictions of lifetime risk (numbers of deaths) from solid cancers and leukemia. The number of deaths predicted in the first 10 years after the accident are also presented for leukemia but not for solid cancers as the model assumes a 10 year latency period between an exposure and the resulting increase in cancer.

For both solid cancers and leukemia, the predicted proportions of excess deaths among all deaths from these diseases (i.e. the "attributable fractions") are small. For solid cancers, they range from less than 1% among the populations evacuated from the 30 km zone and the residents of contaminated areas outside the SCZ's to about 5% for the liquidators who worked in 1986 and 1987. The lifetime attributable fraction for leukemia is greater than that for solid cancers in each population, ranging from 2 to 20%. It should be noted that the fraction of excess leukemia cases is much higher for the first 10 years.

Thyroid cancer in children

The projections of numbers of thyroid cancer cases were made for populations exposed as children, i.e. between the ages of 0 and 14, in the various Oblasts of Belarus and in Bryansk Oblast in Russia, for which both dose and population data were available (Table V). Two sets of published thyroid cancer incidence data were used to estimate the background (naturally occurring) thyroid cancer incidence: the 1983-87 Belarus incidence data and the 1983-1987 US White (SEER) cancer incidence data [41]. The US incidence data were used because it was considered likely that the Belarus thyroid rates underestimate the true incidence, especially before the accident when the registry may not have been as active as afterward. The risk projections were made both for lifetime and for the first 10 years after the accident; in both cases a 5-year latent period is assumed.

The predicted lifetime excess number of cases ranges from 0.01% in Vitebsk Oblast to about 1% in Gomel Oblast using the US incidence rates, while the attributable fraction ranges from 5 to 77%. The total number of cases expected in the Oblasts of Belarus for the first 10 years after the accident varies between 39 and 128, depending on the baseline rates used.

Birth defects and genetic effects

The basic assumption made in estimating genetic effects was that, in the first generation offspring of a population of 1,000,000 persons including all ages and both sexes, 30 cases with genetic disorders will be observed per 480,000 births per 10 mSv to each parent [42]. The genetic disorders considered here include autosomal dominant, X-linked, recessive, chromosomal, and congenital abnormalities. The background (naturally occurring) genetic disorders were estimated using the 1993 UNSCEAR Report. The projection model used here follows those of the US Nuclear Regulatory Commission Report [42] and provides the *upper limit* of the risk.

Results presented in Table VI show very low predicted occurrence of radiation induced genetic effects, ranging from 0 to 0.03% of all live births and from <0.1% to 0.4% of all genetic disorders among the live births to the exposed population.

Summary of available results

Cancer

Table VII presents the number of observed and expected cases of cancer in 1993-94 among liquidators having worked in 30 km zone around Chernobyl reactor in the period 1986-87 and among the populations living in oblasts with territories with ^{137}Cs contamination levels above 185 kBq/m^2 in the three countries. The observed numbers of cancer cases were obtained from the National Cancer Registry in Belarus and from the State Chernobyl Registries in Russia and Ukraine. No information could be obtained systematically for evacuees and residents of the SCZ's. The expected numbers are based on the general national population; in Belarus, they were also obtained from the Cancer Registry while in Russia and Ukraine they are based on data from regional oncological dispensaries summarised annually at the national level. These results are adjusted for age and sex; for liquidators, they are restricted to men since the majority of exposed liquidators were men.

Liquidators

There was no increase in the incidence of cancers as a whole among liquidators compared to the general population in Belarus. In Russia, a small but marginally statistically significant increase was noted, of the order of 11%. There was no consistent difference in the incidence of specific types of cancer, in Belarus or Russia, compared to the general population.

In Ukraine, a 20% increase in the incidence of all cancers was observed, as well as increases in the incidence of several specific cancer types. As discussed above (section 0), these results must be treated with caution, since the cases have not yet been verified and the increase may reflect the effect of increased surveillance of the liquidators and underregistration of cases in the population in a country where no systematic centralised cancer registry existed at the time of the accident [43].

A total of 46 leukemia cases were reported among the liquidators in the three countries during the two-year period. A non-significant two-fold increase (based on 9 observed cases) was observed in Belarus. In Russia, there was no significant difference in leukemia incidence among liquidators compared to the general population. In Ukraine, a significant increase was reported, which, as indicated in the paragraph above, must be treated with caution.

An increase in the incidence of thyroid cancer was noted in all three countries, based on relatively small numbers of cases (28 cases in 1993-4). Significant radiation doses to the thyroid may have been received from short-lived iodine isotopes by the liquidators who worked in the 30 km zone in the first days after the accident; these data, however, have not yet been analysed according to the time of work in the zone; information about the histology of the tumours and their mode of confirmation is also not yet available. This result must, therefore, be interpreted with caution, especially since, as indicated above, the follow-up of liquidators is much more active than that of the general population in the three states: for thyroid cancer in adults, the depth of screening may greatly influence the observed incidence [44,45].

Residents of contaminated areas

No increase was observed in the incidence of all cancers in Ukraine. In Russia and Belarus, a marginally statistically significant 3% increase in all cancer mortality was noted, while no increase was observed for leukemia in any of the three countries. For thyroid cancer, a 1.5 to 2- fold increase was seen in the three countries. Again, because of increased awareness of the consequences of the accident, and because of the more intensive medical follow-up of populations living in contaminated regions, these findings must be interpreted with caution and further analyses are needed before confirming or refuting this finding.

A number of authors have recently reported increasing trends in cancer morbidity in the populations living in contaminated territories over time [43,46]. Care must be taken in interpreting these findings, particularly in countries where no centralised cancer registration exists and for cancer types for which increased ascertainment may result in an apparent increase in incidence. Prisyazhniuk and collaborators [43] have analysed trends in cancer morbidity in the contaminated territories of Belarus, Russia and Ukraine. Although they observed increases in the incidence of all total cancers and of leukemia, they noted that this increase was consistent with pre-existing increasing trends in the incidence of these diseases. The increases were, moreover, not related to the levels of exposure in the regions. The predominant difference with pre-accident rates was noted for cancers in the oldest age group considered (65 years and over) and started as early as one year after the accident, thus most likely reflecting increased ascertainment of diseases in this population. For leukemia, the increase primarily concerned chronic lymphocytic leukemia – a subtype not seen to be associated with radiation exposure in other studies –.

Background paper 2 describes the distribution of number of cases and incidence of childhood thyroid cancer in the contaminated regions of the three countries since the accident. As indicated in that paper, a dramatic increase has been observed in contaminated territories of Belarus, Ukraine and, more recently, and to a more limited extent in Russia. The circumstantial evidence for this increase to be related to iodine isotopes released by the stricken reactor is very strong. A number of questions remain to be answered, however. In particular, the observation of such a large increase in incidence of a very rare cancer in children raises the possibility that host and environmental factors may be playing a role in the risk of radiation induced cancer

General morbidity

A number of authors have considered the general morbidity of liquidators in the affected states and compared it to that of the general population in these countries (see for example [23,46,47]). Apparent increases in the morbidity from a number of broad disease classes (diseases of the endocrine system, of the blood and blood-forming organs, mental disorders, diseases of the circulatory and digestive systems) have been reported. It is difficult to interpret these results. These observations may at least be partly explained by a bias introduced by the active follow-up of liquidators and by the impossibility of taking into account the effects of age and sex in the analyses (see sections 0 and 0, above). On the other hand, they may reflect a real increase in morbidity following the Chernobyl accident. If so, based on existing epidemiological studies of radiation exposed populations, it is unlikely that they are related to the radiation exposure, although they could be related to stress and economic difficulties following the accident (see background paper no. 4).

General mortality

Recent reports indicate an increase in mortality rates (accompanied by a decrease in the average life-span) in states of the former USSR (*refs.?*). These increases, which do not appear to be related to radiation exposure – since the pattern does not differ between regions with different levels of contamination –, may again be related to social and economic difficulties (see background paper no. 4). They must, however, be taken into account when interpreting time trends in exposed populations.

Comparisons to expected effects

Leukemia

On the basis of the data from other populations exposed to radiation, the major radiological impact expected to date (i.e. within the first 10 years after the Chernobyl accident), if the experience of the atomic bomb survivors is applicable, is leukemia.

As indicated in Table IV, the increase is mainly expected among liquidators – indeed, out of 190 cases of leukemia expected in the first 10 years among 200 000 liquidators, 150 (79%) would be expected to have been induced by radiation. Such an increase can be detected epidemiologically. No consistent increase has been reported to date. The results reported above, in section 0, only concern a two year period, however, and the power to detect such an increase is thus much reduced.

The expected increase in leukemia incidence in the first 10 years after the accident in the SCZ's and in the contaminated areas is much lower than among liquidators, of the order of 1.5 and 1.05 fold, respectively. This is consistent with the fact that no increase in leukemia incidence was observed among residents of contaminated regions in the three countries. Indeed, such increases would be very difficult to detect epidemiologically.

All cancers

If risk models from other studies of populations exposed to ionising radiation are applicable, no increase in all cancer incidence should be detectable to date. The findings of a 10-20% increase among liquidators in Russia and Ukraine and a 3% increase in the populations residing in contaminated regions in Belarus and Russia, particularly in the absence of a consistent increase in leukemia incidence in these populations, are therefore not consistent with predicted effects.

The increases observed may be real. They may also, however, be an artefact of the above mentioned differences in follow-up disease between exposed populations and the general population of the affected countries (section 0).

Thyroid cancer

The number of thyroid cancer cases expected for the first 10 years after the accident among persons exposed to iodine isotopes during childhood is presented in Table V. The discrepancies between the projected numbers based on the Belarus background data and observed numbers (see background paper 2) are outstanding. When the US white background rates are used, however, the discrepancies are less pronounced. The notable exception is the Gomel population, which shows a remarkably higher number of cases observed than expected.

It should be noted that our predictions include cases which are adolescents and even young adults at the time of diagnosis. The predicted number of cases diagnosed among children is considerably less. Since the numbers presented in background paper 2 only refer to cases who were children, not only at the time of the accident but also at the moment of diagnosis, the discrepancy is even larger than it appears.

future prospects

If the experience of atomic bomb survivors and of other exposed populations is applicable, the total lifetime numbers of excess cancers will be greatest among the liquidators and among the residents of contaminated territories, of the order of 2 000 to 2 500, respectively. These increases, however, would be difficult to detect epidemiologically against an expected background number of 41 500 and 433 000 respectively.

Predictions based on other exposed populations, and preliminary results to date, indicate that the significant health effects most likely to be detected at this time and in the future, besides thyroid cancer, is leukemia risk among liquidators. Indeed, if careful large-scale studies of liquidators are carried-out, they will not only have the power to detect an increased risk, but may provide important information concerning the effects of exposure protraction and perhaps of radiation type in the relatively low dose (0-500 mSv) range.

The extent of the increase in thyroid cancer is very difficult to predict, as the observed incidence in those exposed as children is, particularly in the Gomel area of Belarus, considerably greater than what would have been expected based on past studies. Background paper 2 discusses the predictions in more detail. Uncertainties mainly concern the temporal behaviour of the increase; if the relative increase stays constant over time, a very large increase in the incidence of thyroid carcinoma may be observed in the next century in adults who were exposed as children.

An increase in the incidence of thyroid cancer in adults (liquidators and populations residing in contaminated territories) has also been noted in recent years. At present, however, this increase needs verification and it is unclear whether it is related to exposure from the Chernobyl accident or to changes in the ascertainment of this disease due to more active follow-up of exposed populations. Predictions of thyroid cancer risk in those exposed as adults are therefore very uncertain.

Because of the absence of established population based registries in the affected countries (and in most countries around the world), it is difficult to monitor trends in genetic effects. Given the levels predicted, however, it is unlikely that, if data from other studies are applicable, any increase could be detected in the offspring of the exposed populations.

As indicated in section 0, a number of factors limit the power of the routine follow-up activities listed above to detect the expected effect of radiation from the Chernobyl accident, even in the three most affected countries of the former USSR. They include, in particular, the generally low level of radiation dose received by the majority of exposed populations – and hence, presumably, low level of risk expected –, the difficulties of systematic and complete active follow-up, the lack of precise dosimetry and the important movements of populations which have taken place since the accident.

Ad-hoc analytical epidemiologic studies, focusing on specific diseases and populations, may be a more useful approach to investigate the effects of radiation among the exposed populations. Both cohort and case-control studies are generally much more powerful than descriptive studies for investigating dose-relationships. To be informative, however, studies of the consequences of the Chernobyl accident must fulfil several important criteria: they must cover very large numbers of exposed subjects; the follow-up must be complete and non-selective and precise and accurate individual dose estimates (or markers of exposure) must be available. In particular, the feasibility and the quality of epidemiological studies largely depend on the existence and the quality of basic population-based registers, and on the feasibility of linking information on a single individual from different data sources.

Studies of leukemia and thyroid cancer risk among liquidators are now underway or planned in all three countries. They are designed as cohort studies, and in some cases as case-control studies (since pilot studies have shown that cohort studies of these populations would require substantial financial and human resources). Given the distribution of known doses among the liquidators, the power of such studies in individual countries is relatively low, however, and it is essential that studies carried out in different affected countries be similar so that the results can ultimately be compared and combined. Dosimetry still poses an important problem as dose estimates are missing and of uncertain quality for a substantial proportion of the liquidators in the three countries. Efforts are being made to estimate radiation levels from detailed questionnaires of activities in the Chernobyl area. If these conditions are met, studies of liquidators will provide important information concerning the effects of exposure protraction and perhaps of radiation type in the relatively low dose (0-500 mSv) range.

Non-specific studies of cancer risk among the general population exposed in the contaminated regions are unlikely to be informative for radiation risk estimation because of the generally lower doses received by the majority of these populations, the difficulties in estimating these doses and following these populations. An exception is the study of thyroid cancer risk in populations exposed as children, the incidence of which has been observed to increase dramatically in the first years following the accident. Careful cohort and case-control studies are underway and planned in all countries. They may provide important information on radiation induced thyroid cancer risk, as well as a unique opportunity to increase our understanding of factors which modify the risk of radiation induced cancer and thus have important consequences for the radiation protection of patients and the general population

The predictions described here were made using risk models derived from studies of atomic bomb survivors. As discussed above, models must be used to extrapolate the effects of such exposures to the generally lower dose, and lower dose-rate exposures and radiation types of concern for the majority of populations exposed as a result of the Chernobyl accident. These models are, inevitably, subject to uncertainties. Indeed, the extent of the increase in thyroid cancer incidence in persons exposed as children was not foreseen. It is essential therefore that monitoring of the health of the population be continued in order to assess the public health impact of the accident, even if, given the level of the dose received, no detectable increase of cancers due to the Chernobyl accident is expected except in liquidators.

As discussed above, although 10 years have passed since the Chernobyl accident, results published to date are difficult to interpret, mainly because of differences in the intensity and method of follow-up between exposed populations and the general population to which they are compared. In order for results of such monitoring in the future to be unambiguous, it is important that they are based on systematic and complete population based registries, in particular registries of mortality and of cancer. Russia and Ukraine currently lack national population-based cancer registries. It is therefore important for monitoring that such registries be established (at least in the contaminated regions in Russia) or improved, where appropriate. Such registries will be useful, not only for assessing the public health impact of the Chernobyl accident, but also for other research and public health planning and monitoring activities in these countries.

Conclusions

Ten years after the Chernobyl accident, apart from the dramatic increase in thyroid cancer in those exposed as children, there is no evidence of a major public health impact to date of the radiation exposure from the Chernobyl accident in the three most affected countries. No major increase in all cancer incidence or mortality has been observed which could be attributed to the accident. In particular, no major increase has been detected in rates of leukaemia – even among liquidators –, one of the major concerns after radiation exposure. This is generally consistent with predictions based on studies of other radiation exposed populations, in particular the survivors of the atomic bombings in Japan.

Increases in thyroid cancer among those exposed as children were observed, in the more heavily contaminated regions of Belarus, Ukraine and Russia, at rates much higher than predicted from previous studies. These increases, which are discussed in more detail in background paper 2, may reflect a particularly sensitive population, because of host or environmental factors, or underestimated doses to the thyroid, or the high carcinogenic potential of very short lived iodine isotopes. Increases are now also reported among liquidators and the general population. These must, however, be verified before being attributed to the Chernobyl accident.

There is a tendency to automatically attribute fluctuations and/or increases in cancer rates over time to the Chernobyl accident. It should, however, be noted that increases in the incidence of some neoplasms have been observed in some countries in the last decades, prior to the accident. A general increase in mortality has, moreover, been reported in recent years in many areas of the former USSR and does not appear to be related to radiation levels. This must be taken into account when interpreting the results of studies.

Increases in the frequency of a number of non-specific detrimental health effects other than cancer among exposed populations, particularly among liquidators, have been reported. It is difficult to interpret these findings because exposed populations undergo a much more intensive and active health follow-up than the general population. If real, these increases may be attributable to stress and anxiety resulting from the accident; they are discussed in background paper 4.

Only ten years have passed since the accident. Based on epidemiological studies of other populations, the increases in frequency of cancers other than leukemia are usually not visible until at least ten years after exposure. It is noted that the exposures received by populations exposed as a result of Chernobyl are different (in type and pattern) from those of atomic bomb survivors. Predictions derived from these populations are therefore uncertain and it is essential to continue monitoring the health of the exposed populations through population based disease registries.

Studies of selected populations are also needed in order to study observed or predicted effects; careful studies may in particular provide important information on the effect of exposure rate and exposure type in the low to medium dose range and on factors which may modify radiation effects. As such, they may have important consequences for the radiation protection of patients and the general population in case of further accidental exposures.

References

[1] UNSCEAR (UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION). Sources and Effects of Ionizing Radiation. UNSCEAR 1994 Report, United Nations, New York (1994).

[2] UNSCEAR (UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION). Sources and Effects of Ionizing Radiation. UNSCEAR 1993 Report, United Nations, New York (1993).

[3] SHIMIZU, Y., KATO, H. ET AL. Studies of the mortality of A-bomb survivors. 9. Mortality, 1950-1985: Part 2. Cancer mortality based on the recently revised doses (DS86). *Radiat. Res.*, **121**, 120-141 (1990).

[4] OTAKE, M. AND SCHULL, W.J. A Review of Forty Five Years Study of Hiroshima and Nagasaki Atomic Bomb Survivors. II. Biological Effects. K Radiation Cataract. *J. Radiat. Res.* **32**, 283-293 (1991).

[5] OTAKE, M., SCHULL, W.J. ET AL. A Review of Forty Five Years Study of Hiroshima and Nagasaki Atomic Bomb Survivors. II. Biological Effects. I. Microcephalus, mental retardation and intelligence. *J. Radiat. Res.*, **32**, 249-264 (1991).

[6] SALI, D., CARDIS, E. ET AL. Cancer consequeces of the Chernobyl accident in Europe outside the former USSR: a review , *submitted.*

[7] PARKIN, D.M., CLAYTON, D. ET AL.Childhood leukaemia in Europe after Chernobyl: five year follow-up. Brit J Cancer (in press)

[8] LITTLE, J. The Chernobyl accident, congenital anomalies and other reproductive outcomes. *Paediatric and Perinatal Epidemiology*, 7, 121-151 (1993).

[9] US NAS (NATIONAL ACADEMY OF SCIENCES COMMITTEE ON THE BIOLOGICAL EFFECTS OF IONIZING RADIATION). Health Effects on Populations of Exposure to Low Levels of Ionizing Radiation. BEIR V Reports, US National Academy of Sciences, Washington DC (1990).

[10] US NAS (NATIONAL ACADEMY OF SCIENCES COMMITTEE ON THE BIOLOGICAL EFFECTS OF IONIZING RADIATION). Health Effects of Radon and Other Internally Deposited Alpha-Emitters. BEIR IV Report, US National Academy of Sciences, Washington DC (1988).

[11] IARC STUDY GROUP ON CANCER RISK AMONG NUCLEAR INDUSTRY WORKERS. Direct estimates of cancer mortality due to low doses of ionizing radiation: an international study. *Lancet*, **344**, 1039-1043 (1994).

[12] CARDIS, E., GILBERT, E.S. ET AL. Effects of low doses and low dose-rates of external ionizing radiation: Cancer mortality among nuclear industry workers in three countries.. *Radiat. Res.*, **142**, 117-132 (1995).

[13] PRESTON, D.L., KUSUMI, S. ET AL. Cancer incidence in atomic bomb survivors. Part III. Leukemia, lymphoma and multiple myeloma, 1950-1987. *Radiat. Res.*, **137**, S68-97 (1994).

[14] PIERCE, D.A., SHIMIZU, Y. ET AL. Studies of the mortality of A-bomb survivors. Report 12, Part 1. Cancer: 1950-1990. Radiat Res (in press);

[15] THOMPSON, D.E., MABUCHI, K. ET AL. Cancer incidence in atomic bomb survivors. Part II: Solid tumors, 1958-87. *J. Radiat. Res.*, **137**, 517-567 (1994).

[16] RON, E., LUBIN, J. ET AL. Thyroid cancer after exposure to external radiation: a pooled analysis of seven studies. *Radiat. Res.*, **141**, 259-277 (1995).

[17] TSYB, A.F. AND ET AL. Registry material. *Radiat. Risk*, **1**, 67-131 (1992).

[18] OKEANOV, A.E., IVANOV, V.C. ET AL. Study of cancer risk among liquidators, Report of EU Experimental collaboration project 7: Epidemiologic Investigations including Dose Assessment and Dose Reconstruction. IARC Internal Report. 95/002, International Agency for Research on Cancer, Lyon (1995).

[19] OKEANOV, A.E., POLYAKOV, S.M. ET AL. Development of cancer registration system in Belarus. *First International Conference of the European Commission, Belarus, the Russian Federation and the Ukraine on the radiological consequences of the Chernobyl accident (Minsk, Belarus, 18-22 March 1996)*, IOS Press, Amsterdam (in press).

[20] STORM, H.H., PRISYAZHNIUK, A.E. ET AL. Development of infrastructure for epidemiological studies in the three CIS republics. *First International Conference of the European Commission, Belarus, the Russian Federation and the Ukraine on the radiological consequences of the Chernobyl accident (Minsk, Belarus, 18-22 March 1996).*, IOS Press, Amsterdam (in press).

[21] IVANOV, E.P. Haematological diseases in the Belarus Republic after the Chernobyl accident. *Proceedings of the WHO International Conference on the Health Consequences of the Chernobyl and other radiological accidents, Geneva, 20-23 November 1995,* Geneva (in press).

[22] IVANOV, E.P., TOLOCHKO, G. ET AL. Child leukaemia after Chernobyl [letter]. *Nature*, **365**, 702 (1995).

[23] OKEANOV, A.E., CARDIS, E. ET AL. Health Status and Follow-up of Liquidators in Belarus. *First International Conference of the European Commission, Belarus, the Russian Federation and the Ukraine on the radiological consequences of the Chernobyl accident (Minsk, Belarus, 18-22 March 1996)*, IOS Press, Amsterdam (1996).

[24] GOLDBERG, M. AND CARDIS, E. Epidemiologie et rayonnements ionisants: quelques aspects methodologiques. *Radioprotection*, **29**, 11-43 (1994).

[25] CARDIS, E. AND ESTEVE, J. Epidemiological designs in radioepidemiological research. *Soz. Praventivmed.* **36**, 279-285 (1991).

[26] UNSCEAR (UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION). Sources and Effects of Ionizing Radiation. UNSCEAR 1988 Report, United Nations, New York (1988).

[27] ILYIN, L.A., BALONOV, M.I. ET AL. Radiocontamination patterns and possible health consequences of the accident at the Chernobyl nuclear power station. *J. Radiol. Prot.*, **10**, 3-29 (1990).

[28] IVANOV, V.K. AND TSYB, A.F. National Chernobyl Registry: Radiation risk analysis [abstract]. *Proceedings of the EC/WHO/IAEA International Conference: One Decade after Chernobyl, Vienna, April 1996,* (submitted).

[29] BALONOV, M., JACOB, P. ET AL. Pathways, levels and trends of population exposure after the Chernobyl accident. *First International Conference of the European Commission, Belarus, the Russian Federation and the Ukraine on the radiological consequences of the Chernobyl accident (Minsk, Belarus, 18-22 March 1996),* IOS Press, Amsterdam (in press).

[30] IAEA (INTERNATIONAL ATOMIC ENERGY AGENCY). Summary report on the post-accident review meeting on the Chernobyl Accident. Safety Series Report. 75-INSAG-1, IAEA, Vienna (1986).

[31] KENIGSBERG, Y.I., MINENKO, V.F. ET AL. Collective exposures doses of population of Belarus after the Chernobyl accideln and prognosis of stochastic effects. *Nine years after Chernobyl: Medical Consequences.* 61-69, Ministry of Health. Minsk (1995).

[32] LIKHTAREV, I.A., CHUMAK, V.V. ET AL. Retrospective reconstruction of individual and collective external gamma doses of population evacuated after the Chernobyl accident. *Health Phys.*, **66**, 643-652 (1994).

[33] LIKHTAREV, I.A. AND KOGAN, I.N. Personal communication.(1996)

[34] TSYB, A.F., PARSHKOV, E.M. ET AL. Disease indices of thyroid and their dose dependence in children and adolescents affected as a result of the Chernobyl accident. 9-19, Elsevier Science, B.V.. Amsterdam (1994).

[35] TRONKO, N.D., EPSTEIN, Y. ET AL. Thyroid gland in children after the Chernobyl accident (yesterday and today). 31-46, Elsevier Science, B.V.. Amsterdam (1994).

[36] DEMIDCHIK, E.P., KAZAKOV, V.S. ET AL. Thyroid cancer in children after the Chernobyl accident: clinical and epidemiological evaluation of 251 cases in the Republic of Belarus. 21-30, Elsevier Science, B.V.. Amsterdam (1994).

[37] KAZAKOV, V.S., DEMIDCHIK, E.P. ET AL. Thyroid cancer after Chernobyl. *Nature*, **359**, 21 (1992).

[38] STSJAZHKO, V.A., TSYB, A.F. ET AL. Letter to the editor. *Br. Med. J.*, **310**, 801 (1995).

[39] NIH (NATIONAL INSTITUTES OF HEALTH). Report of the National Institutes of Health Ad Hoc Working Group to Develop Radioepidemiological Tables. NIH Publications. 95-2748, US Department of Health and Human Services, Washington DC (1985).

[40] ICRP (INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION). Recommendations of the International Commission on Radiological Protection. ICRP Report 60, Pergamon Press, Oxford (1990).

[41] IARC (INTERNATIONAL AGENCY FOR RESEARCH ON CANCER). Cancer Incidence in Five Continents. Volume VI. IARC Scientific Publication. 120, IARC, Lyon (1992).

[42] US NUREG (US NUCLEAR REGULATORY COMMISSION). Health effect models for nuclear power plant accident consequence analysis. Modification of models resulting from recent reports on health effects of ionizing radiation. Low-LET radiation. Part II: Scientific bases for health effect models. NUREG/CR. 4214, Washington, DC, Nuclear Regulatory Commission (1991).

[43] PRISYAZHNIUK, A.E., FEDORENKO, Z. ET AL. Epidemiology of cancer in population living in contaminated territories of Ukraine, Belarus and Russia after the Chernobyl accident. *First International Conference of the European Commission, Belarus, the Russian Federation and the Ukraine on the radiological consequences of the Chernobyl accident (Minsk, Belarus, 18-22 March 1996)*, IOS Press, Amsterdam (in press).

[44] ASTAKHOVA, L.N., BEEBE, G.W. ET AL. Thyroid cancer in Belarus children after the Chernobyl accident. *Proceedings of the WHO International Conference on the Health Consequences of the Chernobyl and other radiological accidents, Geneva, 20-23 November 1995*, in press (1996).

[45] SCHNEIDER, A.B., RON, E. ET AL. Dose-response relationships for radiation-induced thyroid cancer and thyroid nodules: evidence for the prolonged effects of radiation on the thyroid. *J. Clin. Endocrinol. Metab.*, 77, 362-369 (1993).

[46] WHO (WORLD HEALTH ORGANISATION). Report of the International Project for the Health Effects of the Chernobyl Accident. WHO, Geneva (1995).

[47] IVANOV, V.K. AND TSYB, A.F. Morbidity, disability and mortality among persons affected by radiation as a result of the Chernobyl accodent: radiation risks and prognosis. *Proceedings of the 4th Symposium on Chernobyl-related Health Effects, Tokyo, Japan, 13-14 December, 1994* (in press).

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Table I Estimates of collective effective doses for population groups of interest.

Population	Number	Collective effective dose (Sv)
Evacuees	135,000	1,300
Liquidators (1986 1987)	200,000	20,000
Persons living in contaminated areas[a]:		
Deposition density of 137Cs >15 Ci km 2	270,000	10,000 20,000
Deposition density of 137Cs >1 to 15 Ci km–2	3 700 000	20,000–60,000

[a]These doses are for the 1986 1995 time period; over the longer term (1996 2056), the collective dose will increase by approximately 50%.

Table II Distribution of liquidators and their doses in the three most affected states of the former USSR

	Number of liquidators	Dose (mGy)				
		% known	Mean	Median	75% percentile	95% percentile
Belarus						
1986-89	63 000	13.8	43.0	23.5	67.3	119
1986-87, 30km zone	31 000	28.4	39.1	20	67	111
Ukraine						
1986-87	102 000	N.A.[2]	N.A.	N.A.	N.A.	N.A.
sample studied	*15 700*	*51.9*	*163.4*	*134.3*	*N.A.*	*N.A.*
Russia						
1986-89	148 000	63.2	106.6	92	180.3	240
1986	69 000	50.8	168.7	194	220	250
1987	53 000	70.5	91.6	92	100	208
1988	20 500	82.5	34.0	26	45	94
1989	6 000	73.0	31.6	29.5	48	52

[2] N.A.: not available

Table IV Predictions of background and excess deaths from solid cancers and leukemia in populations exposed as a result of the Chernobyl accident

Population	Population size/ average dose (mSv)	Cancer type	Period	Background number of cancer deaths		Predicted lifetime excess		
				Number	%	Number	%	AF[3]
Liquidators, 1986-7	200 000	Solid cancers	Lifetime (95 years)	41 500	21%	2 000	1 %	5 %
	100 mSv	Leukemia	Lifetime (95 years)	800	0.4 %	200	0.1 %	20 %
			First 10 years	40	0.02 %	150	0.08 %	79 %
Evacuees from 30 km zone	135 000	Solid cancers	Lifetime (95 years)	21 500	16 %	150	0.1 %	0.1 %
	10 mSv	Leukemia	Lifetime (95 years)	500	0.3 %	10	0.01 %	2 %
			First 10 years	65	0.05 %	5	0.004 %	7 %
Residents of SCZ's	270 000	Solid cancers	Lifetime (95 years)	43 500	16 %	1 500	0.5 %	3 %
	50 mSv	Leukemia	Lifetime (95 years)	1 000	0.3 %	100	0.04 %	9 %
			First 10 years	130	0.05 %	60	0.02 %	32 %
Residents of other contaminated areas	3 700 000	Solid cancers	Lifetime (95 years)	433 000	16 %	2 500	0.05 %	0.6 %
	7 mSv	Leukemia	Lifetime (95 years)	13 000	0.3 %	200	0.01 %	1.5 %
			First 10 years	1 800	0.05 %	100	0.003 %	5.5 %

[3] AF: attributable fraction = excess deaths / total deaths from the same cause

Population	Population size/ average dose (mSv)	Period	Background incidence	Background number of cancers		Predicted lifetime excess			Total expected to 1996
				Number	%	Number	%	AF[4]	
			US white	15	0.00%	1	0.00%	6%	15
Minsk Oblast	399 000	Lifetime (95 years)	Belarus	478	0.12%	104	0.03%	18%	
			US white	1400	0.35%	300	0.08%	18%	
	20 mSv	First 10 years	Belarus	6	0.00%	<1	0.00%	5%	6
			US white	20	0.01%	1	0.00%	5%	20
Mogilev Oblast	294 000	Lifetime (95 years)	Belarus	352	0.12%	350	0.12%	50%	
			US white	1 000	0.34%	1 000	0.34%	50%	
	90 mSv	First 10 years	Belarus	4	0.00%	1	0.00%	20%	5
			US white	14	0.00%	4	0.00%	22%	19
All Belarus Oblasts	2 140 000	Lifetime (95 years)	Belarus	2 558	0.12%	2 157	0.10%	46%	
			US white	7 400	0.35%	6 200	0.29%	46%	
	80 mSv	First 10 years	Belarus	31	0.00%	7	0.00%	18%	39
			US white	105	0.00%	24	0.00%	19%	128
Russian Federation									
Bryansk Oblast	92 000	Lifetime (95 years)	Belarus	110	0.12%	42	0.05%	28%	152
			US white	300	0.33%	120	0.13%	29%	420
	35 mSv	First 10 years	Belarus	1	0.00%	<1	0.00%	50%	2
			US white	5	0.01%	<1	0.00%	<20%	5

Table VI Predictions of background and excess numbers of genetic disorders in populations exposed as a result of the Chernobyl accident

Population	Population size/ average dose (mSv)	Total live births	Total background cases with genetic disorders		Total cases with radiation-related genetic disorders		
			Number	%	Number	%	AF[5]
Liquidators, 1986-7	200 000 100 mSv	250 000	19 000	7.60	80	0.03	0.42 %
Evacuees from 30 km zone	135 000 10 mSv	65 000	5 000	7.69	5	0.01	0.10 %
Residents of SCZ's	270 000 50 mSv	130 000	10 000	7.69	40	0.03	0.40 %
Residents of other contaminated areas	3 700 000 7 mSv	1 800 000	137 000	7.61	80	0.00	0.06 %

[5] AF: attributable fraction = excess deaths / total deaths from the same cause

Table VII Standardised incidence ratio for all cancers (ICD 9 codes 140-208) among male liquidators having worked in 30 km zone around the Chernobyl reactor in the period 1986-87 and among residents in oblasts with contaminated territories[6] compared to the general national population. Incidence for the period 1993-4.

All cancers	O	E	SIR	95% Ci
Male liquidators				
Belarus	102	135.6	75	61-91
Russia	449	404.7	111	101-121
Ukraine	399	329	121	109-133
Population in contaminated territories				
Belarus	9 682	9 387	103	101-105
Russia	17 260	16 800	103	101-104
Ukraine	22 063	22 245	99	98-101

[6] > 185 kBq/m^2