

IONIZING RADIATION: LEVELS AND EFFECTS

*A report of the United Nations Scientific Committee
on the Effects of Atomic Radiation
to the General Assembly,
with annexes*

VOLUME I: LEVELS



UNITED NATIONS

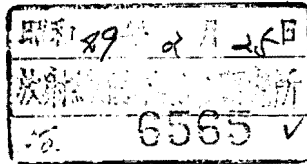
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New York, 1972

NOTE

The report of the Committee without its appendices and annexes appears as *Official Records of the General Assembly, Twenty-seventh Session, Supplement No. 25 (A/8725)*.

In the text of each annex, Arabic numbers in parenthesis refer to sources listed at the end.

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UNITED NATIONS PUBLICATION
Sales No.: E.72.IX.17

Price: \$7.00
(or equivalent in other currencies)

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ABBREVIATIONS

ILO	International Labour Organisation
FAO	Food and Agriculture Organization
WHO	World Health Organization
WMO	World Meteorological Organization
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiological Units and Measurements

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* *

ABCC	Atomic Bomb Casualty Commission
AEC	Atomic Energy Commission
JNIH	Japanese Institute of Health

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* *

AGR	Advanced gas-cooled graphite-moderated reactor
ATB	At the time of bombing
BWR	Boiling light-water cooled and moderated reactor
CMD	<i>Per caput</i> mean marrow dose
DNA	Deoxyribonucleic acid
ECBI	Extracorporeal blood irradiation
FBR	Fast breeder reactor
GCR	Gas-cooled reactor
GSD	Genetically-significant dose
HVT	Half-value thickness
ICD	International classification of diseases
LET	Linear energy transfer
LWR	Light-water reactor
NIC	Not in city at the time of bombing
OMR	Organic moderated and cooled reactor
PHWR	Pressurized heavy-water moderated and cooled reactor
PWR	Pressurized light-water moderated and cooled reactor
RBE	Relative biological effectiveness
RNA	Ribonucleic acid
SST	Supersonic transport
WL	Working level
WLM	Working level month

INTRODUCTION

1. This is the sixth substantive report of the United Nations Scientific Committee on the Effects of Atomic Radiation¹ to the General Assembly. It reviews the levels of radiation received from all sources to which man is exposed and, among the effects of ionizing radiation, it considers the genetic effects, the effects on the immune response and the induction of malignancies in animals and man. These are not the only effects of ionizing radiation. The acute consequences of massive amounts of radiation that may be received accidentally or during nuclear warfare are not reviewed here (the short discussion of this subject in the 1962 report is still largely valid, at least as an introduction), nor are the effects on the nervous system and the induction of chromosome anomalies in somatic cells, which were both considered by the Committee in its 1969 report.

2. Unlike previous reports of the Committee, the present report is submitted to the General Assembly without the technical annexes in which the evidence considered by the Committee is discussed in detail and in which the bases for the Committee's conclusions, which are stated in the report, are fully documented. However, the annexes are being made available at the same time as the report in a separate publication, issued in two volumes² and the Committee wishes to draw the attention of the General Assembly to the fact that the separation of the report from the annexes is for convenience only and that major importance attaches to the scientific evidence given in the annexes.

3. The preparation of the report took place at the twentieth, twenty-first and twenty-second sessions of the Committee.³ Most of the work was done in meetings of groups of specialists which considered working papers prepared by the Secretariat and modified as the drafting proceeded, on the basis of the Committee's requests. The report itself was drafted at the twenty-second session. Professor B. Lindell (Sweden), Dr. V. Zeleny (Czechoslovakia) and Professor L. R. Caldas (Brazil) served as Chairman, Vice-Chairman

and Rapporteur, respectively, at the twentieth session. Professor B. Lindell (Sweden), Professor F. H. Sobels (Belgium) and Professor L. R. Caldas (Brazil) served as Chairman, Vice-Chairman and Rapporteur, respectively, at the twenty-first session; and Professor L. R. Caldas (Brazil), Professor F. H. Sobels (Belgium) and Dr. A. Nelson (Sweden) served in the same capacity, respectively, at the twenty-second session. The names of those experts who attended the twentieth, twenty-first or twenty-second sessions of the Committee as members of national delegations are listed in appendix I.

4. The Committee wishes to recall that in 1971 it submitted to the Secretariat of the United Nations Conference on the Human Environment a basic paper on the assessment and control of environmental contamination based on the Committee's experience with artificial radio-activity. The Committee recognizes that, under its present terms of reference as laid down in General Assembly resolution 913 (X), the Committee and its resources can become an element of value in the environmental strategy of the United Nations which may evolve as a result of the Conference on the Human Environment, and it is prepared to play such a role. The Committee further recognizes that, in the present state of affairs, it can continue to discharge its current responsibilities while reporting to the General Assembly less frequently than heretofore. The Committee therefore requests to be relieved from the obligation to report to the General Assembly before the twenty-ninth session and, subject to the acceptance of that request by the Assembly, is not planning to meet before the end of 1973, unless it is asked to undertake new tasks in the context of the environmental strategy of the United Nations or to respond to any other special demand.

5. The Committee was assisted in the preparation of the present report by a small scientific staff and by consultants appointed by the Secretary-General. The scientific staff and consultants were responsible for preliminary review and evaluation of the technical information received by the Committee or published in the scientific literature. Although the Committee itself assumes full responsibility for the report, it wishes to acknowledge the help and advice given by those scientists whose names are listed in appendix II. The Committee owes much to their co-operation and scientific expertise.

6. Representatives of the International Labour Organisation (ILO), the Food and Agriculture Organization of the United Nations (FAO), the World Health Organization (WHO), and of the International Atomic Energy Agency (IAEA), as well as of the International Commission on Radiological Protection (ICRP) and the International Commission on Radiation Units and Measurements (ICRU), attended sessions of the Committee held during the period under review. The Committee wishes to acknowledge with appreciation their contribution to the discussion.

¹ The Scientific Committee was established by the General Assembly at its tenth session in 1955. Its terms of reference are set out in resolution 913 (X). It is composed of the following Member States: Argentina, Australia, Belgium, Brazil, Canada, Czechoslovakia, Egypt, France, India, Japan, Mexico, Sweden, Union of Soviet Socialist Republics, United Kingdom of Great Britain and Northern Ireland and United States of America. For the previous substantive reports of the Committee, see *Official Records of the General Assembly, Thirteenth Session, Supplement No. 17 (A/3838)*; *ibid.*, *Seventeenth Session, Supplement No. 16 (A/5216)*; *ibid.*, *Nineteenth Session, Supplement No. 14 (A/5814)*; *ibid.*, *Twenty-first Session, Supplement No. 14 (A/6314)*; and *ibid.*, *Twenty-fourth Session, Supplement No. 13 (A/7613)*. They will be referred to as the 1958, 1962, 1964, 1966 and 1969 reports, respectively.

² *Ionizing Radiation: Levels and Effects* (United Nations publications, Sales Nos.: E.72.IX.17 [This is a reference to the present publication] and E.72.IX.18).

³ The twentieth session was held at the United Nations Office at Geneva from 21 to 25 September 1970, the twenty-first and twenty-second sessions at Headquarters from 14 to 25 June 1971 and 13 to 24 March 1972, respectively.

7. The reports received by the Committee from States Members of the United Nations, and members of the specialized agencies and the International Atomic Energy Agency, as well as from these agencies themselves, between 17 May 1969 and 24 March 1972, are listed in appendix III of this report. Reports re-

ceived before 17 May 1969 were listed in earlier reports of the Committee to the General Assembly. The information received officially by the Committee was supplemented by, and interpreted in the light of, information available in the current scientific literature or obtained from unpublished communications of individual scientists.

Chapter I

SOURCES AND DOSES OF RADIATION

A. ENVIRONMENTAL RADIATION⁴

1. *Natural radiation*

8. Man has been continuously exposed to natural radiation since his appearance on earth and, until less than a century ago, was exposed to natural radiation only. Even now, despite the widening use of radiation-producing devices, the widespread radio-active contamination from nuclear weapon tests and the increasing applications of nuclear energy and radio-isotopes, natural sources are the main contributors to the radiation exposure of most of the human population and are likely to remain so in the foreseeable future.

9. Natural radiation is of two origins, extraterrestrial and terrestrial. Extraterrestrial radiation originates in outer space as primary cosmic rays and reaches the atmosphere, with which the incoming energy and particles interact, giving rise to secondary cosmic rays—those to which living beings on the earth's surface are exposed. The rate at which doses from cosmic rays are delivered is fairly constant at any one point on the earth's surface but varies with latitude and, to a greater extent, with altitude. Typical values at sea level in temperate latitudes are of the order of 30 millirads per year. As the altitude increases, dose rates approximately double every 1,500 metres up to a few kilometres above earth.

10. Special problems arise with aircraft flying at high altitudes. In that case, not only is the cosmic-ray dose rate consistently higher than at lower altitudes, but it may also, on rare occasions, suddenly rise as a consequence of the emission of high-energy particles from solar flares. The dose rates may, on occasion, be sufficiently high to require the aircraft to descend into the lower protective layers of the atmosphere in order to prevent unacceptable exposures of crew and passengers. The crews of supersonic transports airborne for more than 500 hours per year at high altitudes and latitudes will probably receive exposures somewhat higher than those received by the crews of current subsonic jets. Passenger doses per kilometre flown are likely to be about the same in supersonic transport as in conventional jet aircraft owing to the shorter flight time of the supersonic transports.

11. Terrestrial radiation is emitted from radio-active nuclides present in varying amounts in all soils and rocks, the atmosphere and the hydrosphere, and from those radio-nuclides that, transferred to man through food chains or by inhalation, are deposited in his tissues. Terrestrial radio-activity, therefore, leads to both external and internal exposure. External dose rates vary depending on the nature of the ground and of building materials, whereas internal dose rates are relatively constant. The largest part of the world population receives dose rates of the order of 50 and 20

millirads per year from external and internal terrestrial radiation, respectively. Dose rates higher by an order of magnitude are received by populations (a few hundred thousand people) living in areas where soils have a high content of uranium and thorium.

2. *Man-made environmental radiation*

(a) *Atmospheric and surface nuclear weapon tests*

12. Tests of nuclear weapons have been carried out in the last few years at a much lower rate than during earlier periods. Those carried out before 1963 still represent by far the largest series of events leading to global radio-active contamination. However, the debris that these tests had injected into the stratosphere has been almost entirely deposited on the earth's surface so that most of the residual, undecayed, radio-activity from earlier tests is now present in soil, crops and animal tissues, from which it is steadily removed by a number of physical and biological mechanisms. As in the past, the Committee has reviewed the contribution made by the radio-nuclides produced by nuclear tests to the total average doses that will accrue to certain tissues by the year 2000.

13. The intake of strontium-90, a nuclide that is deposited in bone, is now lower than in the past because comparatively small amounts of it are absorbed from the soil by plants used as food-stuffs or animal feed, whereas direct deposition on vegetation, which was the main mechanism of contamination when fall-out rates were high, now contributes very little to the intake. As a result, levels of strontium-90 have considerably decreased both in children and in adults. The fact that rates of deposition of strontium-90 are now so much lower than a few years ago has made it possible to evaluate more realistically the rates at which this nuclide is taken up from soils and is eliminated from the human body. These values differ from those that the Committee, in the absence of direct estimates, had so far assumed, and lead to estimates of dose commitments smaller than those accepted by the Committee in its last report. Conversely, the estimates of external doses to all tissues from fall-out deposited on the ground have now been revised upwards. As a result, although the total inventory of long-lived nuclides produced by nuclear tests has changed only slightly, the relative importance of strontium-90 as a contributor to the total dose to be received by the year 2000 is less than in the past, the main contribution being now from those nuclides, in particular caesium-137, that give rise to external irradiation. The total *per caput* dose to be received between 1955 and 2000 by the whole world population from tests carried out between 1955 and the end of 1970 is equivalent to about two years of exposure to natural sources. However, since nuclear weapons tests have not ceased in 1971, it cannot be excluded that a further dose commitment must be added.

⁴ For details, see annex A.

14. Iodine-131 is a radio-nuclide that poses special problems because it is concentrated in the thyroid and irradiates that gland more than any other tissue, the doses per unit intake (mostly through milk) being highest in infants. The presence of iodine-131 in milk has been reported in a number of countries of the southern hemisphere after each of the 1970 and 1971 series of tests in the southern hemisphere. The annual average doses to the thyroids of infants were of the order of several tens of millirads and the highest annual doses remained markedly lower than those reported in the northern hemisphere before 1963.

(b) *Power production from nuclear fission*

15. Large-scale production of electric power by nuclear fission presupposes a cycle of complex operations, most of which involve some discharges of radio-active material to the environment and a corresponding radiation exposure of the population at large. The exposures that have resulted so far and may result in the future from operational discharges throughout the world have been considered by the Committee on the basis of published information or of information directly submitted to the Committee. While such information was available from only a few of the countries in which power reactors are in operation, there is no reason to believe that the population exposure associated with the power-production cycle differs markedly in other countries. The Committee has not reviewed the contamination that may result from future accidental releases of radio-activity.

16. In the full production cycle—from mining and milling of ore to fuel fabrication and enrichment, to power production in reactors and finally to reprocessing of spent fuel—the last two operations are at present the main contributors to the total population dose resulting from nuclear power production, largely because of occupational exposure of workers in these two parts of the cycle.

17. The exposure of the population is both local, to limited populations living in the proximity of nuclear installations, and global. Most of the population exposure is external, from gaseous discharges through the stacks, whereas a lesser contribution is made by discharges through liquid effluents. Global doses to be received annually by the general public as a result of the continued operation of the energy production cycle at the 1970 production rate are estimated to be one hundred thousandth of the average dose received annually by the world population from natural sources. Local doses can be several times higher than global ones.

18. According to estimates provided by the International Atomic Energy Agency, the world generating capacity will increase more than two hundredfold by the year 2000. With current technology and operational practice, if the nuclear power production were to stabilize at the estimated level reached by the year 2000, annual global radiation doses from the power-production cycle might be as high as two thousandths of those received annually from natural sources. The magnitude of the average increase in the local doses is more difficult to predict for these depend on the population density as well as on the output of the installations, but doses to be received annually as a result of continued power production at the level estimated for the year 2000 are unlikely to exceed greatly the annual global

doses received from these sources. Technological advances may make it possible to reduce these expected doses considerably.

(c) *Peaceful nuclear explosions*

19. Nuclear explosives have a virtually unused potential for peaceful applications. Those that have some prospects of being developed in the near future are the recovery of underground natural resources (particularly natural gas and oil) or the provision of underground storage cavities by contained explosions, and the construction of reservoirs, harbours, canals, etc. by exploiting the earth-moving effect of subsurface cratering explosions. Both types of explosions potentially involve population exposure, associated mostly with the radio-activity of the resources recovered in one case, and with the release of radio-active material to the environment in the other. Their practical applications will probably require international agreements to ensure the protection of the public.

20. A detailed evaluation of artificial radio-activity in the natural gas recovered from the first experimental contained explosion has indicated that, if the gas had been introduced into the distribution network that supplies gas to the 7 million inhabitants of the Los Angeles, California (USA) area, they would have received a dose of the order of a few ten thousandths of that received annually from natural sources. The explosive used in this experiment had not been designed for gas stimulation, however, and it is to be expected that the new explosives that are now being developed will make it possible to keep gas contamination to such low levels that distribution of gas for industrial and even domestic consumption may become justifiable.

21. Cratering explosions, by their very nature, always involve at least some venting of radio-activity into the atmosphere. Few have been carried out experimentally so far, but one has been used in the Soviet Union for the creation of a water reservoir. Current technology may make it permissible to use cratering explosions for small projects in isolated areas. For bigger ones, the safety of the populations living near the site of the project, as well as long-range contamination, are powerful limiting factors, and will restrict the use of these projects unless they are overcome by major technological advances.

B. MEDICAL EXPOSURE⁵

22. Radiation is used in medicine for diagnostic purposes and for the treatment of diseases, particularly cancer. The local doses received by individual patients in the course of diagnostic investigations may vary from being about equal to the average doses received annually from natural sources (~ 0.1 rad) to 50 times as high. Radiation treatments, on the other hand, may involve individual doses thousands of times higher than those received for diagnostic purposes and are usually delivered over several weeks to part of the body only. Both for diagnosis and for therapy, irradiation is mostly external, but an increasing number of radiological procedures now involves the administration of radio-active materials which result in internal irradiation.

23. The mean doses received by the population are determined by a combination of the doses deliv-

⁵ For details, see annex B.

ered by the individual procedures and the number of cases in which these procedures are applied. In the 10 years since the Committee last reported on this topic the frequency of diagnostic radiological examinations has increased by a few per cent per year in a number of technologically advanced countries, as more facilities for medical care became available and new developments in techniques and instrumentation have been introduced. The aim of medical radiology is to provide maximum benefit to the population served, and therefore an increase in frequency of examinations is likely to be fully justified, particularly in the developing countries. Since it is probable that a large proportion of the world population does not have easy access to modern x-ray facilities, the number of such facilities must increase greatly if local health standards are to improve substantially.

24. Most surveys of medical exposure have been concerned with doses to the reproductive cells. Because such doses, when received after completion of a person's reproductive life, will make no contribution to genetic effects in subsequent generations, individual dose estimates are weighted by the child expectancy of the patient so as to obtain an estimate of the "genetically-significant dose". The estimates so obtained vary for different countries by a factor of almost 10 and range from less than one tenth to more than one half of the annual dose from natural sources. Therapeutic irradiation being most frequently carried out on patients unlikely to have any more children, most of the genetically-significant dose is due to diagnostic irradiation, and different types of examination contribute to different extents to the mean dose. It is very important to note that some of the lowest doses have been reported from countries with the highest health standards, indicating that, with the use of modern radiological techniques and equipment (in particular strict control of field size), the best medical care need not at present involve genetically-significant doses higher than one fifth of the annual dose from natural sources.

25. Only three surveys of doses to blood-forming cells in the bone marrow have been carried out so far. Their results indicate mean annual *per caput* doses from medical procedures ranging from one third to two times the annual dose from natural sources.

26. There is sufficient agreement between the surveys carried out in the various countries to assess the magnitude of the average doses for particular examinations within an order of magnitude. However, surveys have additional value in indicating where changes in radiological practice or technical advances may achieve significant reductions of the population exposure, and can help in identifying those groups of patients that, having received high doses of radiation, may need continuing surveillance to detect possible increases in late radiation effects. But it is questionable whether emphasis should continue to be placed on the conduct of dose surveys alone or whether more attention should not be given to the other means of achieving the minimum practicable dose to the patient commensurate with the needs of diagnostic radiology.

27. Three basic approaches can contribute variously to this improvement, depending, in any particular case, on the availability of funds and trained staff—educational programmes, surveys of the frequency of examination and of the doses received, and administrative control measures. Educational programmes can be aimed at (a) the radiation staff and the conduct

of their day-to-day work, (b) the clinical staff that prescribe investigations involving radiation and (c) the general public and the development of an awareness of the need for radiation protection. The provision of educational training programmes and the establishment of some administrative control may be much more important than dose surveys, particularly where resources are limited.

C. OCCUPATIONAL EXPOSURE⁶

28. Individuals may be exposed to radiation in the course of their occupation. In industrially developed countries the number of persons liable to receive radiation exposures in the course of their work is reported to be between one and two per thousand of population. Close adherence to the recommendations of such bodies as the International Commission on Radiological Protection, the International Labour Organisation, the World Health Organization and the International Atomic Energy Agency ensures that most workers receive very low exposures, and that very few workers exceed the recommended maximum permissible doses. The maximum permissible annual dose to the whole body is about 50 times that received from natural sources.

29. The mean radiation dose received annually by workers in most types of work involving radiation exposure is reported to be less than six times that received from natural sources, although some types of workers (including industrial radiographers and medical radium workers) tend to receive doses several times higher. The yearly contribution of occupational exposure to the genetically-significant dose of the whole population has been estimated in various countries to be less than one hundredth of the annual dose received from natural sources.

30. Radiation injuries are now very rare and, when they happen, can usually be attributed to carelessness. Most of the reported injuries occur in industrial radiographers, in research workers using x-ray crystallographic machines, and in medical workers using hand-held fluoroscopes. Such injuries can be prevented by adherence to recommended practice. Underground miners, not only in uranium mines but in some other types of mines as well, are exposed to radio-active materials in the air they breathe. Considerable efforts are being made to improve conditions in mines so as to reduce this form of radiation exposure, which, at sufficiently high levels, has been shown to be associated with an increased incidence of lung cancer.

D. MISCELLANEOUS SOURCES⁷

31. The general public may be exposed to ionizing radiation from a wide variety of miscellaneous sources. The most widespread are consumer products containing radio-active materials and electronic tubes emitting x rays but not designed for that purpose. Until a few years ago, appreciable doses could be received from self-luminous wrist watches and from colour television sets. Owing to international recommendations and national regulations, the exposure from these sources has rapidly decreased. Although no recent study of the annual genetically-significant dose has been published, it is estimated to be less than 1 per cent of the annual dose from natural sources.

⁶ For details, see annex C.

⁷ For details, see annex D.

Chapter II

GENETIC EFFECTS OF RADIATION⁸

32. The genetic material consists of chromosomes—microscopically visible structures within cell nuclei—and genes—the functional units of which the chromosomes are composed and which cannot be distinguished microscopically. Although these structures are present in all body cells, only those in the reproductive cells are transmitted to the fertilized ovum (the zygote) and hence from one generation of individuals into the next. When the reproductive cells are irradiated, changes may be produced in the genes or in the chromosomes of these cells and subsequently transmitted to the descendants of the irradiated individual. These genetic changes are of different kinds: (a) gene mutations i.e., alterations in the function of individual genes; (b) chromosome aberrations resulting from breakage and reorganization of the chromosomes; and (c) changes in the number of chromosomes. Some of these changes result in offspring suffering abnormalities which may range from mildly detrimental to severely disabling or lethal disorders.

33. Since adequate human data are not available, the estimates of genetic risks ensuing from radiation exposure of the human reproductive cells are based on results obtained with other species, notably mice.

A. GENE MUTATION

34. The two reproductive cell stages most important for the assessment of genetic risks are spermatogonia in the male and oöcytes in the female. At high acute doses of radiation the rate of induction in spermatogonial cells is estimated to range between 100-5,000 recessive mutations per rad⁹ per million. Human populations, however, predominantly receive low doses of radiation under acute (short-term at high dose rate) or chronic (protracted at low dose rate) conditions of exposure. On the basis of experimental studies, it is estimated that under these conditions the rate of mutation induction is about one third of the above figure. Consequently, for males, a rate of induction of 30-1,500 mutations per million per rad seems a more realistic approximation. At high acute doses of radiation the risk of mutation in females conceiving shortly after radiation exposure will be about twice as high as in males, whereas at low doses the risk will be reduced to at least one third and with chronic exposure to about one twentieth of that expected after acute exposure to high doses. If the human ovary responds to irradiation as does that of the mouse, which is by no means certain, it can be expected that, if conception occurs after a sufficient interval following irradiation, the resulting frequency of mutations in the descendants of irradiated females might approach zero.

⁸ For details, see annex E.

⁹ 1 rad ~ 10 times the annual dose received from natural sources.

35. Dominant gene mutations are expressed in the first-generation descendants of an irradiated population. There is evidence suggesting that in man about 1,000 genes may contribute to this category. The estimated rate of induction of dominant visible mutations in the human male exposed to low doses of irradiation is two per rad per million descendants.

B. CHROMOSOME ABERRATIONS

36. Spontaneously occurring chromosome aberrations are a source of considerable human hardship, since they are responsible for a large fraction of all spontaneous miscarriages, congenital malformations and mental and physical defects. For instance, the possession of an additional small chromosome (number 21) leads to Down's syndrome, which is associated with severe mental retardation. Extensive data have been collected recently in the mouse on another type of aberration, known as translocation. This involves the exchange of parts between two different chromosomes. It is known that in man it may lead to malformations similar to those associated with the presence of additional chromosomes, or may lead to early pre-natal death. These effects are associated with the presence of translocations in an unbalanced form, in which there may be loss of one of the exchanged segments and gain of the other. In its balanced form, a translocation usually has no detrimental effect for the person carrying it, but half of his or her offspring are likely to have the translocation in unbalanced form.

37. In male mice, the yield of balanced translocations in the generation after exposure is more or less proportional to dose for acute x-irradiation at moderate to high doses, about 30 being induced per million offspring per rad. It is probably similar in female mice, but information is still meagre. The expected yield of unbalanced translocations (causing early death or detectable abnormality) will be 60 per million zygotes per rad after exposure of males and 180 per million per rad after exposure of females.

38. In attempting to deduce from these figures the probable risk for man under usual exposure conditions, a number of different factors have to be considered. First, there is evidence from work on chromosome aberrations in blood cells that man may be twice as radio-sensitive as the mouse in this respect. Second, chronic gamma-irradiation is only one third as effective as acute x-irradiation in inducing translocations in male mice, while acute x-irradiation at very low doses (as used in medical diagnosis) may be only about one quarter as effective per rad as at higher doses. Therefore the probable yield of balanced translocations in the offspring of exposed males is about 7 per million per rad with chronic gamma-irradiation and about 15 per million per rad with low-dose acute x-irradiation. The expected yields of unbalanced translocation products will be about twice these.

39. Information from both man and the mouse suggests that many of these unbalanced zygotes will die at such an early stage in pregnancy that they will lead, at most, to a missed menstrual period. The proportion surviving to produce abnormal new-born babies is difficult to estimate at present, but is likely to be less than 6 per cent. Therefore one to two additional abnormal babies per million would be expected per rad of paternal exposure at low doses or dose rates. Although a similar estimate cannot yet be made with confidence for maternal exposure, it seems unlikely that risks will be much higher.

40. Translocations are only one category of chromosomal aberration. Those occurring spontaneously (in balanced or unbalanced form) represent about one third of all the chromosome aberrations observed in new-born babies. Information from the mouse suggests that very few of the other aberrations (e.g. gains or losses of chromosomes) are likely to be transmitted to the next generation after irradiation of the male because the reproductive cells carrying them will be eliminated before they mature. In the female, however, some are transmitted. Thus evidence from the mouse suggests that irradiation of females at low dose rates results in eight additional zygotes with the XO constitution per million (i.e. with a missing sex chromosome).

41. Most of these cases will die before birth; those surviving will be sterile and will have certain other symptoms (Turner's syndrome). No doubt loss of other chromosomes will also occur, but these are likely to be associated with such early embryonic death that they may not constitute a significant risk to live-born children. Gains of chromosomes form an important component of the human genetic burden. They may be induced by irradiation, especially of females, but positive evidence is lacking so far.

42. Thus in summary, gene mutations are induced at higher frequencies than chromosome aberrations; furthermore chromosome aberrations will be eliminated after a few generations, whereas gene mutations may persist through many more generations thereby affecting a larger number of individuals.

C. ESTIMATES OF GENETIC DAMAGE IN RELATION TO THE SPONTANEOUS INCIDENCE OF GENETIC DISEASE

43. While the above estimates provide assessments of the risk of induction of mutations, they do not necessarily provide a useful method of evaluating the harm which is experienced by society. The Committee feels that it can also present an estimate of risk of mutation per unit of radiation dose in relation to the natural incidence of genetic disorders observed in man. This was first attempted in the Committee's 1958 report, but confidence in the methodology was not sufficiently great to justify its continued use. Recently, however, experimental work with the mouse has suggested that in males five major indices of mutation are increased, under conditions of acute irradiation, by about 3 per cent per rad. For low-dose or chronic irradiation, the expected increase will be about 1 per cent per rad. Because *all* these indices of induced mutation have approximately the same rate of increase relative to the spontaneous rate, the Committee feels it may revive this method of assessment with renewed confidence, although it still recognizes that numerous qualifications are necessary.

44. It has been estimated that about 4 per cent of all live-born children suffer from various forms of genetically determined diseases, of which about 2 per cent appear to follow simple rules of inheritance. The other 2 per cent have a more complex mode of transmission. For computational purposes a figure of 3 per cent will be used. Therefore the natural incidence of hereditary diseases maintained by receiving mutation is estimated at 30,000 per million live births.

45. The mutations responsible for that incidence would increase by about 300 per rad under conditions of chronic exposure of males in a parental generation. Up to 20 of these new mutations would contribute to the incidence of hereditary diseases among the immediate descendants of the irradiated males, while the contribution of the remaining new mutations would be distributed over many subsequent generations of descendants.

Chapter III

EFFECTS OF RADIATION ON THE IMMUNE RESPONSE¹⁰

46. The immune system provides the main defence mechanisms of the body against infectious agents or their products. The system recognizes what is foreign to the body, and responds by destroying or neutralizing it: it does not distinguish between "foreign-good" and "foreign-bad". Sometimes, therefore, it stands in the way of medically desirable objectives, such as the acceptance of needed tissue or organ transplants. Sometimes, too, the net effects of the immune reaction are themselves undesirable, as in allergies and other immunopathological disorders. Sometimes the system goes awry and reacts to the body's own components, producing auto-immune disease.

47. Because of the many values, "good" and "bad", associated with the immune system, affecting it by irradiation has great human significance in numerous contexts. For example, depressing immune responsiveness by irradiation reduces the ability to acquire resistance to bacterial, rickettsial and parasitic infections or to neutralize bacterial toxins, and is therefore an undesirable effect of radiation. But depressing immune responsiveness by some means is desirable, even necessary, if organ transplants are to be accomplished. Suppressing or controlling allergy, hypersensitivity, immunopathological disorder, and auto-immune disease are other important medical objectives.

48. The concept that the immune system evolved only to protect the body against administered foreign agents has been questioned. There is a growing body of data from both experimental animal, and human clinical, studies which indicates that in cancer the malignant cells are recognized as foreign by the individual's own immune system, and that lymphocytes in the host may be directed against tumour cells. The existence of specific serum factors which react with cancer cells has also been recognized, and in some instances these may protect cancer cells from the action of potentially lethal lymphocytes. Most of the recent data in this field have considered the immune response as reacting against an already existing cancer, and in at least some situations it is clear that radiation-induced immune depression permits an increased rate of growth of the cancer. The more critical unanswered

question is whether immuno-suppression may be an important factor in the radiation-induction of cancer.

49. There have been extensive studies of the effects of radiation on the immune response in experimental animals, but relatively few observations have been made on the radio-sensitivity of the cells involved in the immune response in man. Limited data are available from Hiroshima and Nagasaki and from patients given extensive radio-therapy for malignancy. Comparative studies among many animal species indicate that the radio-sensitivity of a given cell type in the immune system is similar for most species studied. The results of many of these studies can probably be applied directly to man. The relatively recent availability of *in vitro* techniques for analysing the immune response may now permit direct dose-effect studies to be made with human lymphocytes and other cell types involved in the human response. However, even if it were determined that similar radio-sensitivities of cell types existed for man and animals, it still could not be safely concluded that the immune response will show a similar dose-effect relationship in animals and man, because many factors are involved that cannot be accounted for at the cellular level alone. These include the extent of previous antigenic exposure of the individual (the secondary response as a whole being relatively more radio-resistant *in vivo*), the type and dose of antigen, and the interval between antigenic challenge and irradiation.

50. The immune system appears to have large built-in factors of safety, so that it can withstand substantial injury and recover from damage. Although effects on human lymphocytes in culture have been noted even at doses of 10 rads,¹¹ the observable damage to the immune system such as changes in antibody formation resulting from whole-body doses of the order of tens of rads is unlikely to be the effect causing the greatest concern. At doses in the range of 100 rads to the whole body, damage to the immune system leads to an increase in susceptibility to infection, and when whole-body doses approach and exceed 200 rads, damage to the immune system is a very important effect of irradiation as expressed, for example, in increased risk of mortality from infection.

¹⁰ For details, see annex F.

¹¹ 1 rad ~ 10 times the annual dose received from natural sources.

Chapter IV

RADIATION CARCINOGENESIS¹²

51. While experiments with animals suggest that malignant transformations may occur in most mammalian tissues if they are exposed to sufficient radiation doses, the number of people exposed to substantial doses is so small that the relationship between dose and incidence of malignancies in man can only be studied for the most radio-sensitive tissues. By far the largest and most informative groups of irradiated subjects continue to be the survivors of the atomic bombings at Hiroshima and Nagasaki. To these must be added several groups of patients treated by radiotherapy and followed up for several decades, and a few groups of workers exposed to radiation in the course of their occupation—especially underground uranium miners. Children exposed while *in utero*, in the course of radiological examinations of their pregnant mothers, form a special category.

52. Leukæmia is the best known of the radiation-induced malignancies. All evidence indicates that the incidence of certain types of leukæmia increases with dose as a result of post-natal irradiation at high dose rate in the 50-500 rad interval.¹³ At higher doses the rise in frequency decreases, possibly because an increasingly large fraction of cells that would otherwise become leukæmic are destroyed by radiation. Radiation-induced leukæmias tend to occur most frequently within a few years after exposure and, after 25 years, the frequency tends to return to the levels expected in the absence of irradiation. By that time some 15-40 cases of leukæmias per rad¹⁴ per million exposed have been observed.

53. Lung cancers appear to have been induced at Hiroshima by doses estimated on the basis of crude assumptions to be equivalent to some 30 rads of external gamma radiation delivered at high dose rate, and to have increased with dose up to a dose of about 100 rads. The higher incidence of this type of cancer among irradiated people has been revealed by other surveys also but it is not yet known whether the increase, which starts some 15 years after irradiation, will be sustained for a long time or will eventually subside. Taken at face value, however, the data indicate that from 10 (at 250 rad) to 40 (at 30 rad) cases of cancer per rad per million exposed develop during the first 25 years after exposure to high-dose-rate gamma radiation.

54. Information is available also on the induction of thyroid and breast cancers. Because those affected by these cancers have long survival times, only in the very long run do mortality data reflect the incidence of these tumours. Thus, while breast cancer mortality at Hiroshima suggests a risk of 6-20 cases per million per rad in the first 25 years after irradiation among

women exposed to between 60 and 400 rads, this is probably an underestimate of the total yield. For thyroid cancers, an average figure of about 40 cases per million per rad in the same range of doses over the same period of time is obtained from more reliable morbidity data, but the estimate has large uncertainties due to the small number of cases observed. As for lung tumours, there is no information as to whether the increased annual incidence of tumours in the irradiated populations will subside and when.

55. Many surveys of externally irradiated people confirm an increase in other types of cancer taken together, although it is not possible at this stage to identify the specific types whose frequency is enhanced. Among the survivors of the atomic bombing at Hiroshima there is a clear trend for mortality from malignancies other than leukæmia and lung and breast cancers to increase with increasing dose, but quantitative estimates of the rate of increase are hampered by our ignorance of the doses to the tissues concerned. Only a tentative estimate of 40 cases of cancers (other than leukæmias and breast and lung cancer) per rad per million occurring during the first 25 years after exposure to 250 rads can be advanced on the basis of crude assumptions about tissue doses. Here also it is not known how many additional cases may develop at times later than 25 years.

56. In considering these estimates it must be clearly borne in mind that they are based on observations made after doses of at least tens of rads delivered at high dose rates. These dose rates, and occasionally these doses, are of the order of those that can be received in the course of certain radiological procedures carried out on medical indications, but much higher than those at which we are irradiated by environmental sources, both natural and man-made. It is a matter of speculation whether doses of the order of those received continuously from natural sources may have similar effects. Animal experiments suggest that the yield of tumours per unit dose should be lower at very low doses, except when the target tissue has a susceptibility to radiation induction of malignancies much higher than has been observed in man. Animal experiments also indicate that radiation given continuously or in several fractions is usually less carcinogenic than if administered in a single dose within a short period of time. The figures given in the preceding paragraphs are therefore likely to be overestimates of the risk of doses and dose rates such as are received from environmental sources.

57. Studies of people exposed to internal irradiation at substantial doses are few. They concern workers and patients contaminated with radium isotopes and miners exposed to radon gas. Radium-226 is deposited in bones, irradiates bone-forming cells continuously at a decreasing rate for decades after being absorbed into the body and gives rise to bone tumours. Radium-224

¹² For details, see annexes G and H.

¹³ 1 rad ~ 10 times the annual dose received from natural sources.

¹⁴ The estimate applies to doses between 60 and 400 rads of gamma rays.

causes similar effects after a shorter period of irradiation.

58. Miners exposed to high levels of radon and its radio-active daughters show a very high incidence of lung cancers. The frequency appears to rise in proportion to the level and duration of exposure. The range of exposures within which the increased incidence has been reported corresponds to doses of at least a few hundred rads of alpha radiation. However, dosimetry is difficult and the role of other carcinogenic factors such as smoking habits has not yet been fully assessed.

59. The effects of pre-natal irradiation have been the subject of much research. A number of large surveys of children that were exposed to radiation for medical reasons before birth, and that must have received thereby doses of at most a few rads at high dose rate, indicate that pre-natal irradiation is associated with a significant increase of the risk of malignancies in the first 10 years of life. The extent to which the increased risk of malignancies in the medically irradiated is due to radiation rather than to an association with the cause that prompted the irradiation must still be considered as open.

APPENDIX I

LIST OF SCIENTIFIC EXPERTS, MEMBERS OF NATIONAL DELEGATIONS

The scientific experts who took part in the preparation of the present report while attending Committee sessions as members of national delegations are listed below.

ARGENTINA

Dr. D. Beninson (Representative)
Dr. D. Cancio
Mr. A. J. Gonzalez
Mr. G. A. Nowotny
Dr. A. E. Placer

AUSTRALIA

Mr. D. J. Stevens (Representative)

BELGIUM

Professor F. H. Sobels (Representative)
Dr. O. B. Zaalberg

BRAZIL

Professor L. R. Carneiro da Silva Caldas (Representative)
Dr. E. Penna-Franca

CANADA

Dr. G. C. Butler (Representative)
Dr. P. J. Barry
Dr. J. S. Haskill
Dr. A. P. James

CZECHOSLOVAKIA

Dr. M. Klímek (Representative)

EGYPT

Professor M. E. A. El-Kharadly (Representative)
Dr. K. E. A. A. Mahmoud (Representative)

FRANCE

Dr. H. P. Jammet (Representative)
Professor M. P. Avarguès
Dr. R. E. Berger
Dr. R. B. Coulon
Dr. M. H. Dousset
Dr. B. H. Dutrillaux
Dr. J. C. Lafuma
Professor J. Lejeune
Professor P. Pellerin

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Dr. A. R. Gopal-Ayengar (Representative)
Dr. K. Sundaram (Representative)
Dr. K. B. Mistry

JAPAN

Dr. K. Misono (Representative)
Dr. R. Ichikawa
Dr. Y. Tazima

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Dr. M. Martínez-Báez (Representative)
Dr. F. Alba-Andrade
Dr. R. E. Félix Estrada
Dr. R. González
Dr. A. Leon de Garay
Dr. Rebeca Magidin de Nulman

SWEDEN

Professor B. Lindell (Representative)
Dr. K. Edvarson
Professor K. G. Lüning
Dr. A. Nelson
Mr. J. O. Snihs

UNION OF SOVIET SOCIALIST REPUBLICS

Professor A. M. Kuzin (Representative)
Mr. G. I. Apollonov
Mr. Y. G. Balasanov
Dr. N. P. Bochkov
Dr. I. L. Karol
Dr. A. Kulak
Dr. A. A. Moiseev
Mr. M. Naidenov
Dr. R. V. Petrov

UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND

Dr. E. E. Pochin (Representative)
Professor P. Alexander
Dr. W. G. Marley
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UNITED STATES OF AMERICA

Dr. R. H. Chamberlain (Representative)
Dr. S. Abrahamson
Dr. B. Bennett
Dr. A. M. Brues
Dr. H. D. Bruner
Dr. J. H. Harley
Dr. R. D. Owen
Dr. W. L. Russell
Mr. G. C. Spiegel
Dr. P. C. Tompkins
Dr. J. Villforth

APPENDIX II

LIST OF SCIENTIFIC EXPERTS WHO HAVE CO-OPERATED WITH THE COMMITTEE IN THE PREPARATION OF THE REPORT

Dr. A. Bouville
Dr. P. M. Bryant
Professor R. E. Ellis
Dr. T. Hirohata
Professor Y. I. Moskalev
Dr. B. J. O'Brien

Dr. G. Persson
Dr. K. Sankaranarayanan
Dr. F. Sella
Dr. F. D. Sowby
Dr. H. E. Walburg Jr.
Dr. N. L. Warner

APPENDIX III

LIST OF REPORTS RECEIVED BY THE COMMITTEE

1. This appendix lists reports received by the Committee from Governments and agencies of the United Nations between 17 May 1969 and 24 March 1972.

2. Reports received by the Committee before 17 May 1969 were listed in annexes to earlier reports of the Committee to the General Assembly.

Document No.	Country and title
A/AC.82/G/L.	
UNITED KINGDOM	
1282	Assay of strontium-90 in human bone in the United Kingdom. MRC Monitoring report No. 16. Results for 1967.
UNITED STATES OF AMERICA	
1283	Spondylolysis following trauma: a case report.
INDIA	
1284	Seasonal variations of radium-D (Lead-210) in ground level air in India.
FRANCE	
1285	Surveillance de l'exposition aux rayonnements ionisants à haute altitude et de la contamination radioactive des avions long-courriers.
UNION OF SOVIET SOCIALIST REPUBLICS	
1286	Количественные характеристики зависимости между уровнями загрязнения внешней среды и концентрациями радионуклидов в некоторых видах сельскохозяйственной продукции
1287	Изучение кинетики десорбции нитратов цезия из цефиевой формы вермикулита
1288	О механизме поступления радиостронция в клубни картофеля
1289	О влиянии условий азотного питания на поступление стронция-90 из почвы в растения
1290	К оценке размеров поступления стронция-90 из почвы в растения и его накопление в урожае
1291	Некоторые количественные характеристики непосредственного загрязнения наземной части растений глобальными радиоактивными выпадениями
1292	Уровни выпадений и концентрации продуктов деления в приземном воздухе Подмосковья в 1962—1967 гг.
1293	Свинец-210 и полоний-210 в приарктических районах Восточного Севера
1294	О динамике накопления продуктов деления в овощах
1295	Влияние внесения в почвы кремнекислого и трехзамещенного фосфорнокислого натрия на накопление стронция-90 в урожае растений

Document No.	Country and title
1296	Накопление стронция-90 разными культурными растениями при его поступлении из почвы в условиях полевого опыта
1297	Концентрация стронция-90 в продуктах питания и поступление его с пищевым рационом населению Армянской ССР в 1963—1967 гг.
1298	Поведение урана в биологической цепочке
1299	Изменение концентрации стронция-90 и цезия-137 в различных продуктах питания в период с 1957 по 1967 гг.
1300	Соотношения между темпами поступления стронция-90 из атмосферы, содержанием его в почвенном покрове и количеством осадков
1301	Изучение аэрогенного поступления плутония-239 в организм человека
1302	Некоторые закономерности распределения важнейших радиоактивных продуктов деления, оседающих из атмосферы в составе глобальных выпадений, в лесах различных природных зон СССР в 1964—1965 гг.
1303	Метод расчета содержания стронция-90 в костной ткани взрослого человека в период стратосферных выпадений
1304	Расчет уменьшения содержания стронция-90 в воде озер и прудов в результате поглощения его дном
1305	Влияние засоления почвы на адсорбцию стронция-90
1306	Использование закономерностей миграции космогенных радионуклидов при изучении распространения радиоактивных загрязнений в атмосфере
1307	Некоторые закономерности выпадения продуктов ядерных взрывов в Армянской ССР
UNITED STATES OF AMERICA	
1308	Fallout program quarterly summary report, July 1, 1969, HASL-210.
1308/Add.1	Appendix to HASL-210.
1309	Chronic lymphocytic leukemia in Hiroshima and Nagasaki, Japan.
AUSTRALIA	
1310	Fallout over Australia from nuclear weapons tested by France in Polynesia from July to September 1968.

<i>Document No.</i>	<i>Country and title</i>
	UNITED STATES OF AMERICA
1311	Fallout program quarterly summary report, October 1, 1969, HASL-214.
1311/Add.1	Appendix to HASL-214.
1312	Radionuclide concentrations in surface air: direct relationship to global fallout.
1313	Fallout program quarterly summary report, January 1, 1970, HASL-217.
1313/Add.1	Appendix to HASL-217.
1314	Index to fallout program quarterly summary reports, January 1, 1970, HASL-218.
1137/Add.3	Health and Safety Laboratory Manual of standard procedures. NYO-4700. Annual changes and additions (1969).
	UNITED KINGDOM
1315	Radioactive fallout in air and rain. Results to the middle of 1969.
	BELGIUM
1316	La retombée radio-active mesurée à Mol. Année 1968. Rapport d'avancement.
	UNITED STATES OF AMERICA
1317	Fallout program quarterly summary report. April 1, 1970. HASL-224.
1317/Add.1	Appendix to HASL-224.
	AUSTRALIA
1318	Strontium-90 in the Australian environment during 1968.
	CZECHOSLOVAKIA
1319	Values of ⁹⁰ Sr in vertebrae and femoral diaphysis of adults in Czechoslovakia in 1969.
1320	Occupational exposure to ionizing radiation in the CSSR.
1321	⁹⁰ Sr content in bones in Czechoslovakia in 1964-1967.
1322	Exposure of the population of the CSSR to ionizing radiation in X-ray diagnostics.
	UNITED STATES OF AMERICA
1323	Delayed radiation effects in atomic-bomb survivors.
1324	Ocean fallout—the Crater Lake experiment
	SWEDEN
1325	Pathologic effects of different doses of radiostrontium in mice. Dose effect relationship in ⁹⁰ Sr-induced bone tumours.
	UNION OF SOVIET SOCIALIST REPUBLICS
1326	Цезий-137 глобальных выпадений в продуктах питания и организме человека
1327	Цезий-137 в цепочке лишайник — олень — человек на Крайнем Севере СССР (1962—1968 гг.).
1328	Поступление стронция-90 с пищевым рационом населению СССР в 1959—1967 гг. в результате стратосферных выпадений

<i>Document No.</i>	<i>Country and title</i>
1329	К обоснованию методов массового контроля за содержанием стронция-90 в организме взрослых людей
1330	Оценка «популяционной дозы» облучения населения СССР от глобального цезия-137
	UNITED KINGDOM
1331	Agricultural Research Council Letcombe Laboratory. Annual report 1968.
1332	Agricultural Research Council Letcombe Laboratory. Annual report 1969.
	UNITED STATES OF AMERICA
1333	Radiographic survey of the upper gastrointestinal tract.
1334	Thyroid carcinoma in Hiroshima and Nagasaki. I. Prevalence of thyroid carcinoma at autopsy.
1335	Editorials—Thyroid Cancer in Japan.
1336	Marine Radioecology. A selected bibliography of non-Russian literature.
	SWITZERLAND
1337	Treizième rapport de la Commission fédérale de la radioactivité pour l'année 1969, à l'attention du Conseil fédéral.
	UNITED STATES OF AMERICA
1137/Add.4	Health and Safety Laboratory Manual of standard procedures. NYO-4700. Supplement.
1338	Neuro-muscular tests of aging in Hiroshima subjects.
	UNITED KINGDOM
1339	Methods of collection and analysis of radioactivity from distant nuclear test explosions. Report AERE-R 5898.
	EGYPT
1340	Strontium-90 fallout deposition and surface air gamma activity in U.A.R. during 1969 and strontium-90 in human bones during 1968 and 1969.
1341	Annual occupational radiation exposure dose levels for U.A.R. atomic energy workers during the period 1962-1969.
1342	Levels of caesium-137 in man in U.A.R. during year 1970.
	INDIA
1343	Studies in the high background areas in Kerala State: definition of the population and preliminary dosimetric data.
	UNITED STATES OF AMERICA
1344	Fallout program quarterly summary report, October 1, 1970. HASL-237.
1344/Add.1	Appendix to HASL-237.
	UNITED KINGDOM
1345	Assay of strontium-90 in human bone in the United Kingdom. MRC Monitoring report No. 17. Results for 1968.

Document No.	Country and title
	NEW ZEALAND
1346	Annual summary 1969. Environmental radioactivity in New Zealand and Measurements on samples from Fiji and Rarotonga.
1347	Report on radiation control and population dose in New Zealand.
	INDIA
1348	Caesium-137 and potassium in Indian whole milk.
	NEW ZEALAND
1349	Environmental radioactivity in New Zealand. Quarterly report April-June 1970 and Pacific Area Monitoring 27 July-9 October.
	UNITED STATES OF AMERICA
1350	Fallout program quarterly summary report. July 1, 1970. HASL-227.
1350/Add.1	Appendix to HASL-227.
	AUSTRALIA
1351	Concentrations of caesium-137 in rainwater and milk in Australia during 1968.
1352	Concentrations of caesium-137 in rainwater and milk in Australia during 1969.
1353	The concentrations of radioactive isotopes in Australia surface air during the period May 1965-December 1967.
	UNITED STATES OF AMERICA
1354	Fallout program quarterly summary report, January 1, 1971. HASL-239.
1354/Add.1	Appendix to HASL-239.
	JAPAN
1355	Radioactivity survey data in Japan. No. 26. February 1970.
	NEW ZEALAND
1356	Environmental radioactivity in New Zealand and results of extended monitoring of fallout from French nuclear tests in the Pacific for samples processed up to 27 July. Quarterly report January-March 1970.
	JAPAN
1357	Radioactivity survey data in Japan. No. 27. May 1970.
	UNITED STATES OF AMERICA
1358	Papillary carcinoma of the thyroid gland.
1359	Humboldt Bay — Environmental radiation survey.
	JAPAN
1360	Radioactivity survey data in Japan. No. 28. August 1970.
	UNITED KINGDOM
1361	Radioactive fallout in air and rain. Results to the middle of 1970.

Document No.	Country and title
	JAPAN
1362	Radioactivity survey data in Japan. No. 29. November 1970.
	UNITED STATES OF AMERICA
1363	Fallout program quarterly summary report. April 1, 1971. HASL-242.
1363/Add.1	Appendix to HASL-242.
1364	Geographic aspects of malignant lymphoma and multiple myeloma.
	NEW ZEALAND
1365	Environmental radioactivity in New Zealand. Quarterly report July-September 1970 and Pacific Area Monitoring 9 October-31 October.
	CZECHOSLOVAKIA
1366	The values of the ratio ^{90}Sr in vertebrae/ ^{90}Sr in diaphysis in different age groups (Czechoslovakia 1969).
1367	Values of ^{90}Sr in vertebrae and femoral diaphysis of adults in Czechoslovakia in 1970.
	ITALY
1368	Data on environmental radioactivity collected in Italy (January-June 1967).
1369	Data on environmental radioactivity collected in Italy (January-June 1968).
1370	Data on environmental radioactivity collected in Italy (July-December 1968).
	UNITED KINGDOM
1371	Disposal of radioactive wastes arising in the United Kingdom from the peaceful uses of atomic energy.
	UNITED STATES OF AMERICA
1372	Estimates of potential doses to various organs from X-radiation emissions from color television picture tubes.
1373	A radiation survey of television repair shops in the Baltimore area.
1374	Estimation of gonadal absorbed dose due to environmental gamma radiation.
	INDIA
1375	Personnel monitoring using TLD in IRE factory at Manavalakkurichy.
1376	On the biological effects of high background radioactivity: studies on <i>Tradescantia</i> grown in radioactive monazite sand.
1377	Short communication. Comparative uptake of thorium-230, radium-226, lead-210 and polonium-210 by plants.
1378	Radioactivity in the diet of population of the Kerala coast including monazite-bearing high radiation areas.
1379	The effect of chelating agents on the absorption of radium by plants.
1380	Biological effects of high background radioactivity: studies on plants growing in the monazite-bearing areas of Kerala coast and adjoining regions.

<i>Document No.</i>	<i>Country and title</i>
	FRANCE
1381	Retombées radioactives à la suite des tirs nucléaires en Polynésie. Mai-décembre 1970.
	BELGIUM
1382	La retombée radio-active mesurée à Mol. Année 1969. Rapport d'avancement.
	UNITED STATES OF AMERICA
1383	Surveys of radium contamination in aircraft instrument repair facilities 1966-1967.
1384	Fallout program quarterly summary report, July 1, 1971. HASL-243.
1384/Add.1	Appendix to HASL-243.
	NEW ZEALAND
1385	Environmental radioactivity in New Zealand. Quarterly report October-December 1970.
	SWITZERLAND
1386	Quatorzième rapport de la Commission fédérale de la radioactivité pour l'année 1970, à l'intention du Conseil fédéral.
	UNITED KINGDOM
1387	Agricultural Research Council Letcombe Laboratory. Annual report 1970.
	JAPAN
1388	Genetically significant dose from diagnostic medical X-ray examinations in Japan, 1969.
1389	Population mean marrow dose and leukaemia significant dose from diagnostic medical X-ray examinations in Japan, 1969.
1389/Corr.1	Corrigendum to No. 1389.
1390	Radioactivity survey data in Japan. No. 30. February 1971.
	UNITED STATES OF AMERICA
1391	Dietary intake of lead-210.
1137/Add.5	Health and Safety Laboratory Manual of standard procedures. NYO-4700. Supplement.
	ARGENTINA
1392	Fallout radiactivo debido a las explosiones en el Pacífico Sur en el período 1966-1970.
1393	Radioestroncio en el hombre en función de la edad.
	AUSTRALIA
1394	Fallout over Australia from nuclear weapons tested by France in Polynesia from May to August 1970.
	UNITED STATES OF AMERICA
1395	Fallout program quarterly summary report, October 1, 1971. HASL-245.
1395/Add.1	Appendix to HASL-245.

<i>Document No.</i>	<i>Country and title</i>
	JAPAN
1396	Population doses from tele-radiotherapy in Japan, 1971.
1397	Radioactivity survey data in Japan. No. 31 May 1971.
	UNITED KINGDOM
1398	Assay of strontium-90 in human bone in the United Kingdom. MRC Monitoring report No. 18. Results for 1969.
	JAPAN
1399	Radioactivity survey data in Japan. No. 32. August 1971.
	NEW ZEALAND
1400	Environmental radioactivity in New Zealand. Quarterly report January-March 1971.
1401	Environmental radioactivity in New Zealand and Pacific area monitoring. Annual summary 1970.
	UNITED KINGDOM
1402	Radioactive fallout in air and rain. Results to the middle of 1971.
	AUSTRALIA
1403	The concentrations of radioactive isotopes in Australian surface air during the period May 1965-May 1970.
1404	Concentrations of lead-210 in rainwater in Australia during the years 1964-1967.
1405	Concentrations of lead-210 in rainwater in Australia during the years 1964-1970.
	JAPAN
1406	Radioactivity survey data in Japan. No. 33. November 1971.
	FRANCE
1407	Retombées radioactives à la suite des tirs nucléaires en Polynésie. Juin-octobre 1971.
	JAPAN
1408	Estimation of genetically significant dose equivalent from occupational exposure to external sources of radiation in Japan.
	AUSTRALIA
1409	Strontium-90 and caesium-137 in the Australian environment during 1969 and some results for 1970.
	UNITED STATES OF AMERICA
1410	Fallout program quarterly summary report, January 1, 1972. HASL-246.
1410/Add.1	Appendix to HASL-246.

ANNEXES

Levels

Annex A

ENVIRONMENTAL RADIATION

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reviewed only man-made radio-activity in the environment (614, 616). In reviewing the latter topic, however, the Committee directed its attention almost exclusively to contamination due to nuclear tests in the atmosphere. With the low rates of injection of nuclear debris now experienced, the importance of this source of contamination has decreased relative to radio-active contamination due to other, rapidly expanding, activities.

4. Hence the Committee has decided to devote considerably greater attention in this report than in previous ones to the contribution that nuclear industry, and the use of nuclear explosions for peaceful purposes, make or may make to radio-active contamination of the environment, and a considerable part of this annex is therefore devoted to reviewing these sources. The reader should be cautioned, however, that the amount of space devoted to discussion of individual sources of environmental radiation does not necessarily reflect their relative importance.

1. *The concepts of average dose*

5. In addition to the radiation doses to *individual* members of the population, that are relevant in assessments of radiation risks, *average* doses are also of interest. Average doses to large populations can be used either to assess the total number of expected injuries in a given population or to compare the risks of two sources of radiation. The latter approach has been used by the Committee in previous reports. Both approaches imply the assumption of a linear, non-threshold relationship between risk and radiation dose.¹ The Committee has stressed that this is a cautious assumption which may or may not be valid.

6. In its evaluation of the environmental contamination caused by nuclear test explosions, the Committee made use of the concept of "dose commitment" as defined in the 1969 report, in order to have a measure of the total future radiation dose to a population caused by the given series of explosions. This concept is described in detail in paragraphs 14-15. Dose commitments may be calculated for different tissues and organs; the Committee has made such calculations for the gonads, the bone marrow and the endosteal cells.

7. The dose commitment is useful in assessing the consequences of any activity per unit practice when significant contributions to the total dose are caused by long-lived nuclides. It is therefore also useful to apply to environmental contamination caused, e.g., by peaceful uses of nuclear explosions and the production of nuclear energy. In these cases the unit practice may be a nominal explosion or one megawatt-year of electrical energy produced, respectively. The concept of dose commitment is particularly useful in the assessment of the trend in a situation before an equilibrium is reached. In such cases the predicted annual dose in a future equilibrium situation is numerically equal to the dose commitment per year of the practice leading to the expected equilibrium.

8. In situations where an equilibrium has already been reached, the actual annual dose (i.e. the dose commitment from each year of practice) is the quantity of immediate interest for assessing the risk to a group

of people. This may be taken to be the case with regard to medical and occupational exposures in technologically developed countries. The quantity which is easiest to calculate is then the *per caput* dose, i.e. the average dose within a given population.

9. If the dose distribution over the individual members of the population is not uniform, it may be that a substantial fraction of the *per caput* dose is contributed by the exposure of individuals which, for biological reasons, are not at risk. This would be the case with regard to genetic effects and carcinogenic effects when doses are received by individuals which, because of their child expectancy or life expectancy, respectively, would not be expected to be able to make the possible biological effect manifest.

10. In such cases weighting procedures are appropriate. Weighting for the individual's child expectancy is part of the calculation of the *genetically-significant dose* (GSD), the procedure being described in paragraphs 7-9 of annex B. A weighting for life expectancy could properly have been an element in the derivation of a leukemia-significant dose although this calculation has not been attempted by the Committee. Instead, the Committee has calculated the population average mean marrow dose without any weighting procedures, this dose therefore being merely a *per caput* mean marrow dose.

11. Weighting procedures are of particular interest when the average dose in a population is composed of contributions from a number of practices each with different weighting factors. The most striking example is the contribution to the genetically-significant dose from a number of different types of diagnostic x-ray examination. Through the appropriate weighting for child expectancy it is possible to assess the relative importance of the different contributions to the GSD, which is of considerable value in planning protection measures.

12. In the case of occupational exposures, the age distribution makes it less important to derive the properly weighted quantities and it will in most cases suffice to make assessments of the *per caput* doses. In this case it is rarely meaningful to assess anything but the *per caput* whole-body dose or the *per caput* gonad dose. In some cases true genetically-significant doses have been reported and seem to be about half the *per caput* gonad dose. Where such assessments have been made they may be considered to give a more representative presentation of the relevant doses.

13. When a whole population is more or less uniformly exposed to radiation from a particular source, the mean dose received from that source, with any appropriate weighting factors for age and sex of those exposed, gives useful information about the relative importance of the exposure. When, however, only part of the population receives exposure from a source, it is important to know the number of people exposed and the doses which they receive from the source. In these circumstances, in order to summarize and to compare the population exposures from different sources it is convenient to express the total exposure from each such source as the product of the number exposed and the dose to which each is exposed, in "man-rads". However, when the term "man-rad" is used in the present report, it is not intended to imply that it is a measure of the total harm from a source, because of the possible influence of factors such as non-linearity of dose re-

¹ This reservation may be unnecessarily stringent in the case of relative risk estimates for dose contributions additional to the natural background radiation, where the *differential* dose increments would be of interest.

sponse, non-uniformity of body radiation, time distribution of the irradiation and radiation quality. With these reservations, the estimate affords a useful comparative indication of the doses delivered to the population, and the quantity may be referred to as the population dose. When based on dose commitment rather than on annual dose, and related to a practice which causes the exposure, it has been used in this report as a measure of the population dose caused by that practice.

2. Assessment of dose commitments

14. When a source delivers radiation at a varying rate, as with radio-active material newly released into the environment, it is necessary to integrate over an infinite period of time the average dose rate to individuals that results from the material released during a given and finite time interval. The quantity thus estimated is called the dose commitment from this release. The dose commitment may, alternatively, be referred to the events or series of events or to the practices that have led to the release.

15. More rigorously, if, at time τ , an individual i born at time t_i is exposed to a dose rate $R_i(\tau)$ arising from a certain release, the dose received up to time t is

$$D_i(t) = \int_{t_i}^t R_i(\tau) d\tau, \quad (1)$$

where $R_i(\tau)$ can assume values other than zero only during the individual's lifetime. If, at time τ , the popu-

lation consists of $N(\tau)$ individuals, then the average dose rate at that time is, summing over all i ,

$$R(\tau) = \frac{1}{N(\tau)} \sum R_i(\tau) \quad (2)$$

and the average dose received up to time t by the population is

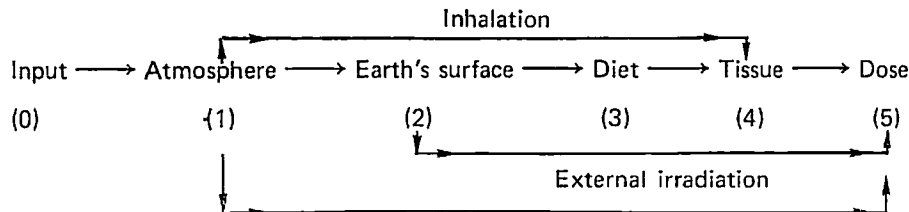
$$D_p(t) = \int_{-\infty}^t R(\tau) d\tau, \quad (3)$$

The use of $-\infty$ as the lower integration limit in equation (3) conveniently avoids the need to define the time scale relative to the exposure. The average dose received by the population, accumulated over infinite time, is

$$D_p(\infty) = \int_{-\infty}^{\infty} R(\tau) d\tau, \quad (4)$$

and is called the dose commitment from the release.

16. The calculation of dose commitments is usually fairly simple, particularly when the radiation is external. With internal radiation from nuclides deposited in the body the problem may become highly complex because of the need to predict changes in the amounts and distribution in the body of the relevant radio-nuclides. In practice, this may involve not only considerations of the metabolism of the nuclides in various organs and tissues but also in food-stuffs. The chain of events leading from the primary release of radio-active material to irradiation of tissues can be represented schematically as follows:



Some of the possible simultaneous pathways are shown in the diagram, indicating the possibility that several steps may be bypassed. Similar schemes could be drawn up for releases into waters or into soil.

17. Since the dose commitment from a given source is the integral over infinite time of the dose rate resulting from that input, steps in the sequence from input to the final dose commitment can be conveniently described in terms of the ratios of the infinite integral of the appropriate quantity in step j of the sequence to the infinite integral of the appropriate quantity in the preceding step i . These ratios define the *transfer coefficients* P_{ij} that appear as links in the pathway from input of radio-activity into the environment to the subsequent radiation dose to man. These transfer coefficients must be expressed in terms of the dimensions of the two quantities they link.

18. The tissue dose from a given source, acting through a given sequence or chain of events, is the product of the input from that source and of all the relevant transfer coefficients. The dose commitment to

the tissue is the sum of the contributions of each sequence. For instance,

$$\text{Dose} = \text{Input} [(P_{01} P_{12} P_{23} P_{34} P_{45}) + (P_{01} P_{14} P_{45}) + (P_{01} P_{12} P_{25}) + (P_{01} P_{15})]$$

19. Transfer functions and the estimation of their parameters were discussed at length for a number of nuclides in the 1969 report. The essential information from that report will be summarized in this annex whenever necessary.

20. Consistent with the practice of the Committee, radiation doses will, in this annex, be given in rads without regard to their biological effectiveness, but the quality of radiation will be indicated whenever necessary. Rems will be referred to in a few instances when doses have been so reported by the original authors. In these cases the quality factor used by the authors will be mentioned where possible. Population dose rates and population dose commitments will be given in man-rads per year and man-rads, respectively.

I. Cosmic rays

21. The high-energy radiations which enter the earth's atmosphere from outer space are known as primary cosmic rays. When they interact with atomic nuclei present in the earth's atmosphere, secondary particles and electromagnetic radiation are produced and these are called secondary cosmic rays.

A. PRIMARY COSMIC RAYS

22. The origin of the primary cosmic rays is still not yet completely determined. However, it is known that most of the observed radiation originates in our galaxy. Moreover, during periods of solar activity the sun produces solar cosmic rays which consist mostly of non-relativistic protons.

1. Primary galactic cosmic rays

23. Primary galactic cosmic rays largely consist of high-energy protons which enter the solar system from

interstellar space. Together with protons are ${}^4\text{He}$ ions in the proportion of about 10 per cent. Smaller proportions of heavier particles are also present, together with electrons, photons and neutrinos (15, 197, 504, 639, 640, 643). The approximate charge composition of primary cosmic rays is shown in table 1. The energy spectrum of the primary-cosmic-ray protons has been measured both in and above the earth's atmosphere by means of instruments carried on balloons and spacecrafts (72, 453, 544). Above about 10^3 MeV, the proton flux density decreases exponentially with increasing energy. The energy spectrum is peaked around 300 MeV per particle and is very broad, extending from about 1 to 10^{14} MeV.

24. Below 10^4 MeV, the primary flux density is modified by two processes. In the first place, it is affected by the earth's magnetic field which deflects lower-energy charged particles back into space. This effect is latitude-dependent so that a greater flux of low-energy protons reaches the top of the atmosphere at the poles than in equatorial regions. Thus the ionization produced in the atmosphere is also latitude-dependent. This latitude effect increases with altitude and is illustrated in figure I (453). In the second place

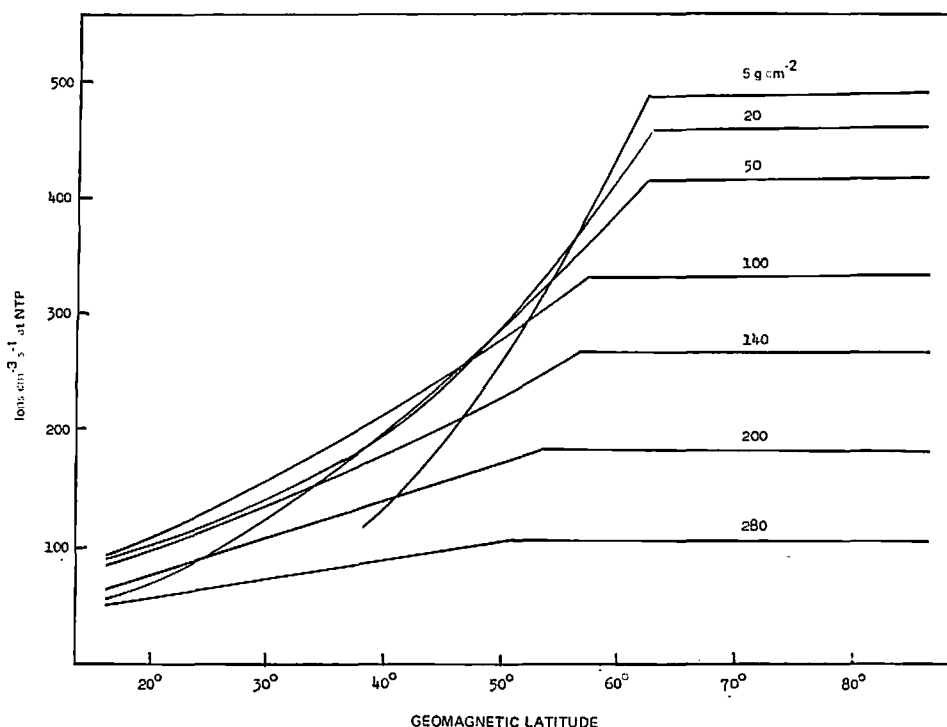


Figure I. Ionization at different latitudes and atmospheric depths (453)

the intensity of the low-energy-proton flux density also varies with the 11-year solar cycle, the density being a minimum during times of maximum solar activity and vice versa; this is known as modulation (453, 455, 456).

2. Modulation of cosmic rays

25. The solar-wind theory, originally put forward by Parker (479, 480), adequately accounts for the measured variation of cosmic-ray intensities during the solar cycle. The solar wind consists of an outward flow of plasma, mainly low-energy protons and electrons, travelling out from the sun at several hundred kilo-

metres per second. This wind gives rise to an interplanetary magnetic field which extends out to some 5×10^9 kilometres and this in turn markedly distorts the dipole pattern of the earth's magnetic field (figure II) (183, 458, 459). The solar wind protons have insufficient energy to penetrate the earth's magnetic field and so do not give rise to radiation doses in the atmosphere.

26. During the 11-year solar cycle the magnitude of the solar wind and of the interplanetary magnetic field and its irregularities undergo a cyclical change, reaching a maximum during increased solar activity and a minimum during the period of the quiet sun.

Because the less energetic cosmic-ray particles are deflected away from the solar system by the magnetic irregularities transported by the solar wind, an 11-year modulation of the galactic cosmic-ray flux density at the earth is produced. Moreover, recent measurements made on space vehicles have indeed detected a permanent gradient in the flux density of cosmic rays, the flux density becoming smaller with decreasing distance from the sun (70, 191, 459).

27. Variations in the solar wind due to changes in solar activity over the 27-day cycle cause similar modulations in the galactic cosmic-ray activity. Changes in the ionization and the neutron flux density over an 11-year period are shown in figure III (310, 513).

28. Solar flares are observed as bright flame-like protuberances on the sun's surface which reach maximum brightness in about 10 minutes and then slowly subside. They tend to occur more frequently during periods of sun-spot maximum. Large amounts of energy in the form of visible, ultra-violet and x radiation are emitted

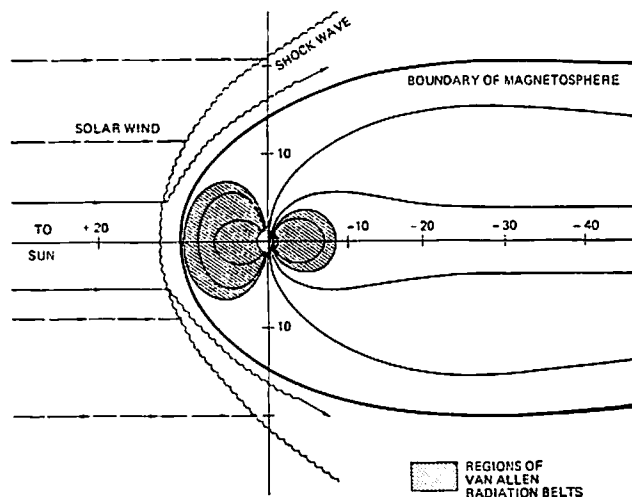


Figure II. Illustration of the intersection of the solar wind with earth's magnetic field (modified from reference 458). The numbers refer to distances in earth radii

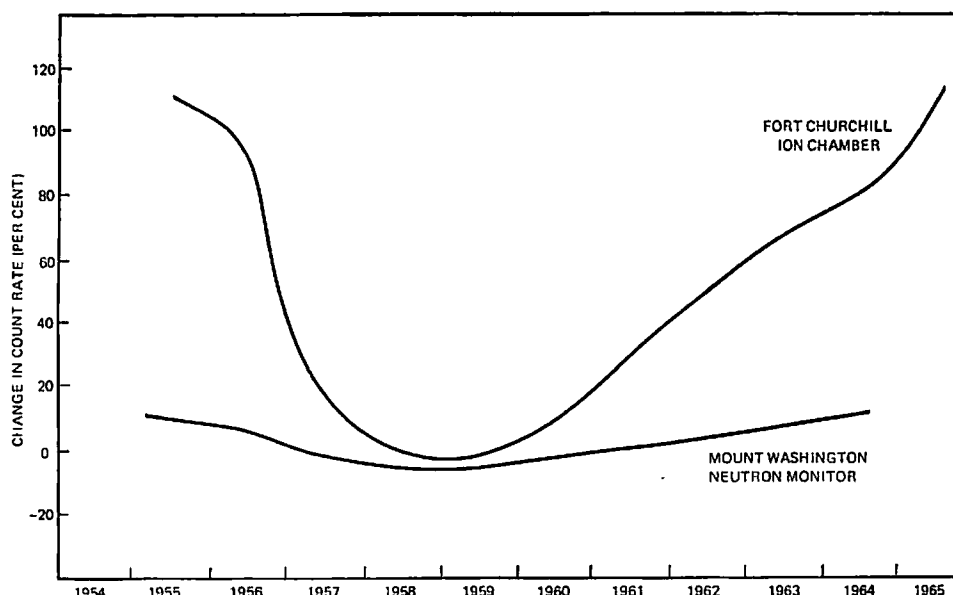


Figure III. Changes in ion and neutron count rates during a solar cycle (310, 513)

and, in the largest flares, large quantities of charged particles, mainly protons and alpha-particles, are also released (544). Measurements indicate that most of the protons have energies in the 1-40 MeV region (72). Because the radiations from solar flares (solar cosmic rays) have relatively low energy, they do not usually cause significant increases in radiation doses at the earth's surface. In fact, only 13 flares produced observable effects in the lower atmosphere between 1942 and 1962 (544). However, large flares can increase the radiation dose rates in the upper atmosphere by a factor of 100 or more for short periods of time.

3. Radiation belts

29. There are two so-called radiation belts, often called Van Allen belts, situated between one and eight earth radii above the equator, the inner belt extending from about 30° N to 30° S, the outer belt extending from about 60° N to 60° S (627). Energetic particles, mainly electrons and protons, are trapped in these belts by the earth's magnetic field. They spiral along

the lines of magnetic force, being reflected back and forth by the increased convergence of the magnetic field towards polar regions.

30. The belts consist of large numbers of electrons and protons with energies ranging from tens of kilo-electron-volts to hundreds of mega-electron-volts. Although these can present a radiation hazard to astronauts travelling in space, they do not result in any radiation dose to the general population.

B. SECONDARY COSMIC RAYS

31. When the primary cosmic-ray particles enter the atmosphere, those with higher energy undergo nuclear reactions, while those with lower energy lose energy by ionization. When reacting with nuclei of atoms present in the air they produce neutrons and protons, in addition to pions and kaons (197, 504). Many of the secondary particles have sufficient energy to initiate whole sequences of further nuclear reactions with nitrogen and oxygen nuclei. The initial high-energy reactions are called spallation reactions and quite a

variety of reaction products are formed, some of the more important being ^3H , ^7Be and ^{10}Be . Three basic types of cascade are produced: the nucleon-nucleon cascade, the nucleon-meson cascade and the photon-electron cascade. The pions rapidly decay into photons or muons. The properties of some of the more important cosmic-ray particles are given in table 2.

32. The nucleonic components, protons and neutrons, are mainly produced in the upper layers of the atmosphere. The protons are formed mainly in spallation reactions, while neutrons are produced both by spallation reactions and by the so-called evaporation of neutrons due to low-energy (p, n) reactions. Neutrons lose energy by elastic collisions and, when thermalized, they are captured by ^{14}N to form ^{14}C . Because nucleons rapidly lose energy through ionization and nuclear collisions, the nucleonic flux density is considerably attenuated in the lower part of the atmosphere and only accounts for a few per cent of the dose rate at sea level.

33. On the other hand, because muons have only a small cross-section for interaction with atomic nuclei, and since they have a mean life of 2.2 microseconds before decay and largely move at relativistic velocities, they penetrate into the lower layers of the atmosphere and are the major cosmic-ray constituent at sea level. The third cascade process, the photon-electron cascade, is initiated from photons produced in the decay of neutral pions. These photons create electron-positron pairs, which in turn produce additional photons by Bremsstrahlung, Compton effect and positron-electron annihilation. Except in the lower layers of the atmosphere, electrons are the main source of ionization (468).

1. Ionization in the atmosphere

34. A number of measurements of cosmic-ray ionization at various altitudes have been reported (191, 192, 376, 453, 454, 517, 552). As can be seen from figure I, the ionization in the atmosphere becomes increasingly latitude-dependent with increasing altitude but at high latitudes, between about 60° and 90° , the ionization is almost constant. The ionization also varies with the solar cycle in general, being greatest during the solar minimum and smallest during the solar maximum (453, 454).

35. Ionization measurements in the upper atmosphere between altitudes of 4 and 35 kilometres have been made by Neher (454) over Thule, Greenland (latitude 76°N). These measurements were made annually between 1954 and 1969 and so cover a complete solar cycle. The 1969 measurements agree closely with those of Raft *et al.* (517) made at 54°N latitude in 1969. George (191) has reported ionization measurements made in 1965, during the solar minimum, from a satellite between altitudes of 400 and 1,500 kilometres in polar regions.

36. At sea level, the atmospheric ionization does not vary greatly with latitude or solar cycle. There is a small variation with atmospheric pressure—about 4 per cent per centimetre of mercury (552). Many measurements have been made of sea level cosmic-ray ionization since those reported by Millikan in 1931. The most recent determinations in terms of ion pairs per second per cubic centimetre of NTP air are: Shamos and Liboff (552), 2.18 ± 0.06 at 42°N ; Lowder and Beck (376), 2.1 ± 0.1 at 50°N ;

George (192), 2.6 ± 0.3 . The inconsistency of many of the early results has been discussed by Shamos and Liboff (552). Lowder and Beck (376) and also George (191, 192) have compared their measurements with the earlier recorded results. There is some discrepancy between the results of George and those of Lowder and Beck and of Shamos and Liboff. Carmichael (103) has reviewed all the atmospheric ionization measurements and concludes that the results of George are inconsistent with respect to the others. In this annex, a value of $2.14 \text{ ions cm}^{-3} \text{ s}^{-1}$ at NTP is taken as the cosmic-ray ionization in the atmosphere at sea level for computing doses.

2. Cosmic-ray neutrons in the atmosphere

37. Most of the dose delivered by low-energy neutrons arises from capture reactions such as (n, γ) and (n, p), while for high-energy neutrons it comes from knock-on protons (443). Since a significant part of the cosmic-ray-neutron spectrum extends from about 0.1 eV to several GeV, some knowledge of its shape is necessary to compute the dose from neutrons.

38. The differential energy spectrum of neutrons at different altitudes and latitudes was computed by Hess *et al.* (243), Lingenfelter (365), Newkirk (462) and by others. The shape and magnitude of the computed spectra agree reasonably well with flux densities that have been reported for different energy ranges (21, 202, 207, 240, 244, 416, 598).

39. More recently, Light *et al.* (361) have computed the neutron spectrum using Monte Carlo methods, obtaining reasonable agreement with spectra measured in the 1-10 MeV energy region. According to these authors, the global average neutron production rate averaged over a solar cycle is $3.9 \text{ neutrons cm}^{-2} \text{ s}^{-1}$. According to the theory of Hess *et al.* (243), about 20 per cent of these are knock-on neutrons produced by high-energy protons, the remainder being produced by evaporation processes. Figure IV shows the differential energy spectrum of cosmic-ray neutrons at sea level.

C. DOSES FROM COSMIC RAYS

40. For computing dose rates at different altitudes, doses from the ionizing and neutron components will be treated separately. The doses from the ionizing component are obtained from measured ionization in and above the atmosphere. O'Brien and McLaughlin (468) have calculated the ionization produced by the different cosmic-ray components at various altitudes. The energy spectrum they obtain for the vertical components of the proton, muon and pion flux density at sea level agrees well with measured values. The computed total ionization at different altitudes also agrees with measured values to within 30 per cent. The contribution of the different cosmic-ray components to the tissue dose five centimetres inside an isotropically-irradiated phantom as computed by O'Brien and McLaughlin is shown on figure V. These results are very instructive for they show that, below five kilometres, most of the dose arises from muons, with electrons making the next largest contribution. Above 10 kilometres, electrons and protons are the major contributors to dose.

1. Ionizing component

41. Assuming that each ion pair in air is equivalent to 33.7 eV, the dose in air per ion pair $\text{cm}^{-3} \text{ s}^{-1}$ is 1.50

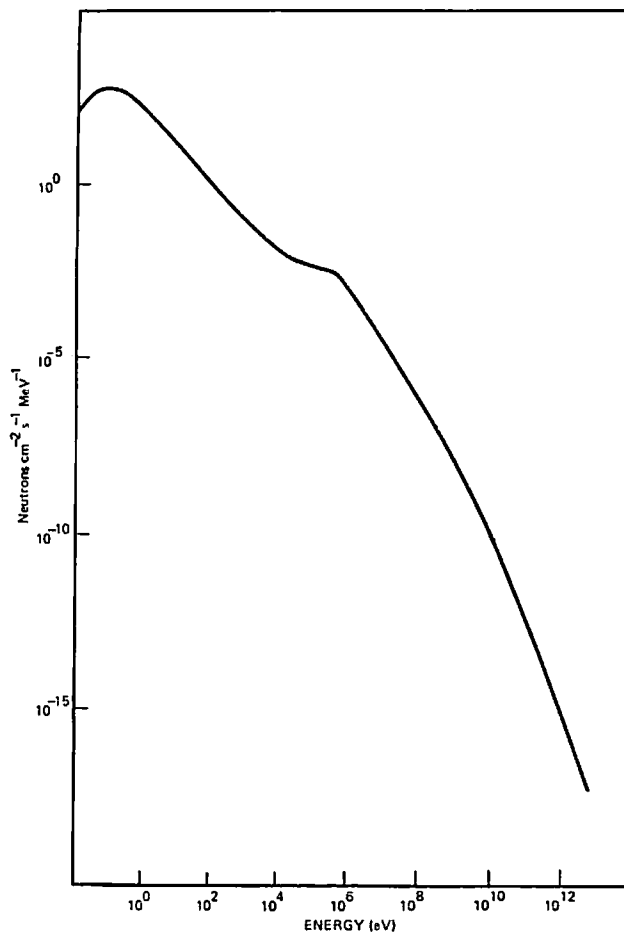


Figure IV. Differential energy spectrum of cosmic-ray neutrons at sea level (219)

$\mu\text{rad h}^{-1}$ (270). The dose rate computed from the measured ionization in the atmosphere for high latitudes is shown in figure VI for altitudes between 1 and 1,000 kilometres. The upper curve for ionization refers to 1965 (solar minimum) and the lower curve to 1969 (solar maximum). Taking the sea level ionization as $2.14 \text{ ion pairs cm}^{-3} \text{ s}^{-1}$ (paragraph 36) the air dose rate is 28 mrad y^{-1} .

2. Neutron component

42. In computing the dose from cosmic-ray neutrons care must be taken in the choice of the geometry used for the dose-rate model. Hajnal *et al.* (219) have computed dose-rate factors for the neutron-irradiation of a 30-centimetre tissue slab, using the fluence-to-dose conversion factors published by Irving *et al.* (274) and Neufeld *et al.* (461). This was done for the neutron-energy spectrum shown in figure IV and for the monolateral and bilateral incidence of normal or isotropic neutrons on the tissue slab. Conversion factors for several depths in tissue are shown in table 3.

43. To compute the dose rate at different altitudes, the bilateral incidence of isotropic neutrons on a 30-centimetre slab was assumed and the dose-rate factor was averaged for a cylindrical geometry over a depth range from 0 to 15 centimetres, resulting in $4.93 \mu\text{rad h}^{-1}$ with a flux density of $1 \text{ neutron cm}^{-2} \text{ s}^{-1}$. This factor is much the same as that for the dose rate at a depth of 5 centimetres in a 30-centimetre slab.

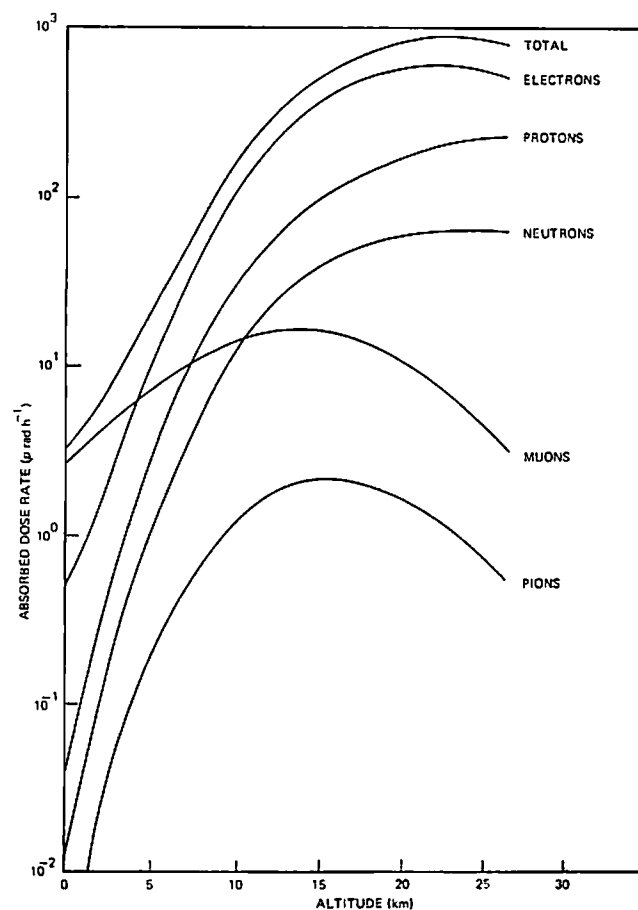


Figure V. Computed dose rate (5 cm inside an isotropically irradiated tissue slab) from the different components of cosmic rays as a function of altitude (468)

44. The measured neutron flux densities of Boella *et al.* (65), Greenhill *et al.* (207), Haymes (240) and Jenkins *et al.* (294) were used to compute the neutron dose. Where necessary, this was done by taking into account the shape of the differential-energy spectrum of figure IV. The data were also normalized to high latitude and to solar maximum or minimum (454, 554). The resulting neutron dose rates are shown in figure VI. The dose rate reaches a maximum value of $30 \mu\text{rad h}^{-1}$ at 20 kilometres during solar minimum. During solar maximum, the dose rate at 20 kilometres is reduced by a factor of two. Extrapolating the neutron dose-rate curve of figure VI to zero altitude gives an estimate of the sea-level dose rate of about 0.48 mrad y^{-1} .

45. A number of measurements of the neutron flux density at sea level have been reported. Some of these results are shown in table 4, together with the corresponding dose rate. At sea level, the flux density is quite small and difficult to measure accurately. Kastner *et al.* (314) found that the flux density was different over water and dry land. In addition, they also found a considerable build-up in the low-energy-neutron flux density due to the moderating influence of water in the soil and the absence of nitrogen, which acts as a sink for thermal neutrons. The most recent flux density measurements, those of Hajnal *et al.* (219), compare well with those of Boella *et al.* (65), Kent (325) and Yamashita (659) and with the computed values of O'Brien (467). A quality factor of 6 is assigned to

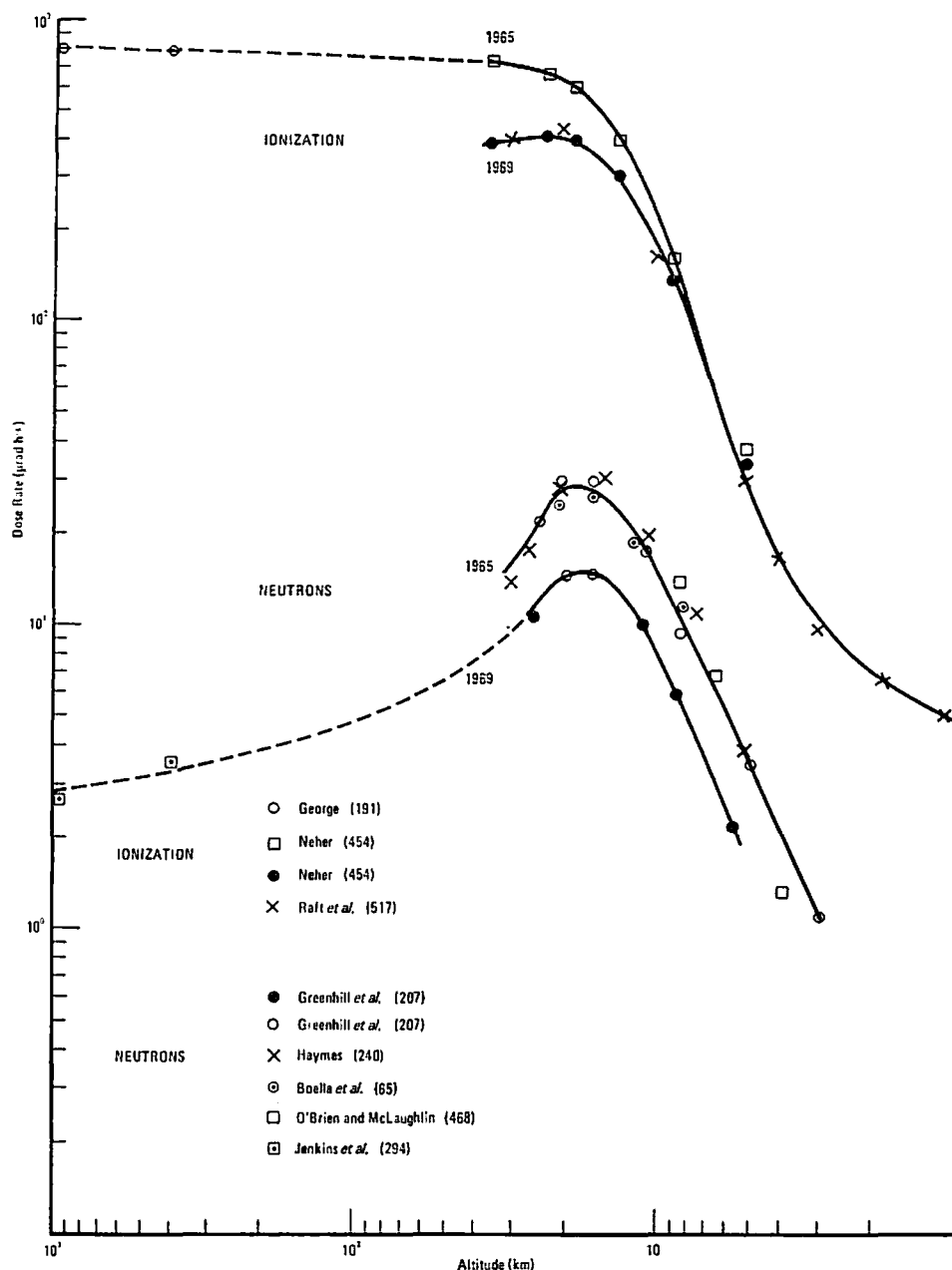


Figure VI. Absorbed dose rates from the ionizing and neutron components of cosmic rays at different altitudes for 1969 (solar maximum) and 1965 (solar minimum)

this radiation, based upon the dose-equivalent and absorbed doses computed by Hajnal *et al.* (219) for isotropic bilateral incidence on a slab averaged to a depth of 15 centimetres.

46. A value of 0.35 mrad y⁻¹ is adopted for the average tissue absorbed dose rate from neutrons at sea level at 40° latitude, but it must be borne in mind that there may be considerable variation due to the effects discussed above. Using the vertical cut-off rigidity data of Shea and Smart (554), the sea-level absorbed dose rate in polar regions is 0.35 mrad y⁻¹, and 0.2 mrad y⁻¹ in equatorial regions. In making the present estimates of dose rates from neutrons, no account is taken of attenuation or build-up due to shielding by surrounding structures.

3. Doses to persons in supersonic transport aircraft

47. The prospect of the development of a supersonic aircraft transport (SST) system on a large scale during the next decade poses the question of the cosmic ray dose rates to which passengers and crews will be exposed and of the contribution of this to the average doses received by the world's population. The first generation of supersonic aircraft will fly at altitudes which may range up to 20 kilometres compared with 12 kilometres for standard jet aircraft. The doses will of course depend markedly on the altitude and latitude of the flight operations. Judging by the ionization densities shown in figure I, the dose rates delivered to persons at these altitudes will be much greater at latitudes higher than 50°.

48. When considering dose rates received by persons exposed at such high altitudes, it is necessary to discuss separately two contributions. In the first place are the background galactic cosmic rays, ever present, which vary in intensity by a factor of about two during the sun's 11-year solar cycle. Secondly, there may occasionally be large short-term increases in the radiation as a result of intense fluxes of solar protons originating from solar flares.

49. Estimates of the dose rates from both the ionizing and the neutron components of galactic cosmic rays at high latitude and at altitudes of 12 and 20 kilometres can be obtained from figure VI. These results for solar minimum are shown in table 5. It should be noted that neutron dose rates determined from whole-body ^{24}Na burdens, compared with dose rates determined from surface monitors, indicate a considerable build-up in neutron flux density inside the human body (80, 546).

50. In order to determine dose rates at altitudes at which an SST might fly, Fuller and Clarke (185) made measurements from balloons at 20 kilometres over Fort Churchill, Canada, in July 1964, near solar minimum. Their measurements indicated a dose rate from the ionizing component of $750 \mu\text{rad h}^{-1}$. An average quality factor of 1.5 was established for this ionizing component from a study of tracks recorded in nuclear emulsion plates. The neutron rem counter indicated a dose-equivalent rate from neutrons of $500 \mu\text{rem h}^{-1}$. O'Brien and McLaughlin (469) concluded that this neutron dose-equivalent measurement corresponded to a surface dose in a phantom irradiated isotropically from above. Since the dose-equivalent rates per neutron $\text{cm}^{-2} \text{s}^{-1}$ for monolateral isotropic incidence on a slab surface and for bilateral isotropic incidence averaged through 15 centimetres are, from table 3, 68 and $29 \mu\text{rem h}^{-1}$, respectively, the $500 \mu\text{rem h}^{-1}$ of Fuller and Clarke reduces to $210 \mu\text{rem h}^{-1}$ for bilateral isotropic incidence averaged through 15 centimetres. With a quality factor of 6, this corresponds to $35 \mu\text{rad h}^{-1}$, in reasonable agreement with figure VI.

51. Fuller and Clarke calculated the absorbed dose rate from nuclear stars recorded in the nuclear emulsion plates as $64 \mu\text{rad h}^{-1}$, with an average quality factor of 8.5. Because of the high quality factor, the dose rate resulting from stars is quite significant and has been included in table 5. The authors were not certain whether all or part of the dose rate from nuclear stars was recorded in the ionization chamber measurements or not. At the most, failure to subtract the contribution of stars from the ionizing component would overestimate the absorbed dose by 10 per cent. Using the maximum estimates for the absorbed dose rates shown in table 5 and assuming a quality factor of 1.0 for solar radiation, the total dose-equivalent rate at 20 kilometres altitude and at high latitude is $1.700 \mu\text{rem h}^{-1}$.

52. The average dose rates from solar particles are listed in the last column of table 5 (267). These estimates were made by the ICRP working group by averaging the effects of solar flares over the period 1952-1960. It can be seen that at these altitudes the average contribution from this source is small compared with that from galactic cosmic rays. Although radiation of solar origin does not contribute significantly to the average dose rate, during an occasional intense solar flare radiation levels at these altitudes may increase by several orders of magnitude. For example, during the

giant solar flare of 23 February 1956, dose rates at 20 kilometres and at high latitude have been estimated to be as high as $0.2\text{--}0.6 \text{ rad h}^{-1}$ (267). For this reason SST aircraft will carry radiation warning devices enabling the pilots to take evasive action by bringing the aircraft to lower altitudes when the dose rate reaches a prescribed action level. These giant solar flare events only last for about 10 hours and occur a few times in each solar cycle, and therefore are not likely to add significantly to the total dose burden.

53. The air speed of SST aircraft will be in the range $2,300\text{--}2,900 \text{ km h}^{-1}$ compared with 800 km h^{-1} for conventional jets. A flight from Europe to North America will therefore take some two to three hours instead of the present eight hours. In a conventional jet aircraft cruising at an altitude of 12 kilometres the dose-equivalent rate is $600 \mu\text{rem h}^{-1}$ or $0.7 \mu\text{rem km}^{-1}$. In a supersonic aircraft cruising at an altitude of 20 kilometres, the dose-equivalent rate is $1,700 \mu\text{rem h}^{-1}$, which also corresponds approximately to $0.7 \mu\text{rem km}^{-1}$.

54. Using the dose rates of cosmic rays given in table 5, the dose for an Atlantic crossing will be about 2 millirads in an SST compared with about 2.6 millirads for present-day jets. The latter figure does not include the dose contribution from nuclear stars. Thus we see, as was noted by Schaefer (546), that the doses per passenger-kilometre will not be very different in SST aircraft than they are at present and may be lower. However, the doses received by the crew of SST aircraft will depend on the number of hours flown and on the flight altitude and latitude, and may range up to a dose equivalent of 1 rem y^{-1} . For the crews of conventional jet aircraft, flying 600 hours per year, the dose-equivalent rate is about 0.5 rem per year.

55. During 1970, some $4.6 \cdot 10^{11}$ passenger-kilometres were flown at an average speed of 580 km h^{-1} , throughout the world excluding China (265). An upper limit to the dose received from cosmic galactic radiation is $2.5 \cdot 10^5$ man-rads which corresponds to an average world population dose rate of about 0.1 millirad per year per person.

56. Schaefer (546) has investigated the contribution to doses at SST altitudes of the heavy-nuclei components of cosmic rays. These particles have a high LET and give rise to a so-called "micro-beam" irradiation. It was concluded that the "micro-beam" part of the heavy flux was virtually extinguished at SST altitudes.

II. Terrestrial radiation

A. INTERNAL IRRADIATION

57. Radio-active nuclides occurring in our natural environment enter the human body mainly through food and water, inhalation being of secondary importance, except for radon daughters. The dose rates to particular body organs are ideally derived from measured tissue concentrations, although an indirect estimation of the dose rates can be made from studies of the distribution of the radio-nuclides in the environment and in diet and from knowledge of their metabolic behaviour. Owing to the varying content of natural radio-active nuclides in the environment and in diet, the levels of radio-active intake, and therefore the corresponding concentrations in the human body, may vary from place to place for elements not subject

to haemostasis. In a given location, time variations also occur as a result of changes in diet. Because of limited geographical representation and of the obvious limitations of sampling, the arithmetic means calculated from the most frequent values will be accepted in this annex, although they may not be strictly representative for the whole world population.

58. The natural radio-active nuclides have been classified into those that are being continually produced by the interactions of cosmic-ray particles with matter, and those that were originally present at the formation of the earth, with their decay products.

1. Cosmic-ray-produced radio-active nuclides

59. A total of twenty radio-nuclides, produced by cosmic rays in the earth's atmosphere, have been detected (table 6). From the point of view of radiation doses, only ^{14}C and, to a lesser extent, ^3H are worth considering.

(a) Tritium

60. Tritium occurs naturally in the surface waters of the earth, being produced in the atmosphere by the interaction of high-energy cosmic rays with atmospheric nitrogen and oxygen (paragraph 31). Recently, its production rate, measured directly (604), has been found to be 0.20 ± 0.05 tritons $\text{cm}^{-2} \text{s}^{-1}$. This figure corresponds to an annual production rate of 1.6 MCi y^{-1} and to a steady-state inventory in the biosphere of 28 megacuries. Since 1954 large amounts of man-made tritium have been released into the environment from nuclear explosions, most of it arising from tritium unused in the thermonuclear reaction. Discharges from the nuclear power industry also contribute to the inventory of tritium. Finally, tritium is widely used as a radio-active luminizing material in products available to the general public such as watches and clocks. Those sources of "artificial" tritium will be discussed later in this annex and in annex D.

61. Prior to its injection into the biosphere from nuclear tests, levels of tritium in waters of the mid-latitude regions of the earth were in the range 6-24 pCi l^{-1} (316, 637). About 90 per cent of natural tritium resides in the hydrosphere, 10 per cent in the stratosphere and only 0.1 per cent in the troposphere (41). The low inventory of tritium in the troposphere is due to the fact that tritium in the form of HTO is rapidly washed out by rain. Early estimates of the half-residence time were 21 to 40 days (42, 359), but more recent work has shown that it is only 10 days (339).

62. The dose rates resulting from natural tritium have been calculated with the assumption that the tritium-hydrogen ratio in the body is essentially the same as that in the surface waters. With an average beta-particle energy of 5.69 keV, the dose rate from natural tritium to soft tissue would be in the range 0.6-2.5 $\mu\text{rad y}^{-1}$.

(b) Carbon-14

63. Carbon is one of the elements that are essential to all forms of life and thus is involved in most biological and geochemical processes on earth. Associated with the stable isotopes (98.9 per cent ^{12}C and 1.1 per cent ^{13}C), there is always a very small but variable amount of ^{14}C , a pure beta-emitting ($E = 50$ keV)

radio-active isotope of carbon with a half-life of 5730 ± 30 years.

64. Natural ^{14}C is produced in the upper atmosphere by interaction of cosmic-ray neutrons with nitrogen, according to the reaction $^{14}\text{N} (n, p) ^{14}\text{C}$. Its production rate is not accurately known, the most recent calculated averages over a solar cycle being 2.5 ± 0.5 atoms $\text{s}^{-1} \text{cm}^{-2}$ (365) and 1.98 atoms $\text{s}^{-1} \text{cm}^{-2}$ (361). A production rate of 2 atoms $\text{s}^{-1} \text{cm}^{-2}$ corresponds to 0.03 MCi y^{-1} and to a steady-state inventory of 280 MCi. The contribution of ^{14}C added to the atmosphere by nuclear and thermonuclear tests will be discussed in paragraphs 167-169.

65. Carbon-14 is present in atmospheric carbon dioxide, in the terrestrial biosphere, and in the bicarbonates dissolved in the ocean. The specific activity of natural radio-carbon in the terrestrial biosphere, as measured in wood grown in the nineteenth century, was 6.13 ± 0.03 pCi (gC)^{-1} but, during the recent decades, it has experienced a slight decrease caused by the artificial combustion of ^{14}C -free fossil fuel (589). The reduction in the specific activity of atmospheric ^{14}C in the absence of nuclear tests has been theoretically estimated at -3.2 per cent in 1950, -5.9 per cent in 1969, and -23 per cent in 2000 (34).

66. The decay rate of natural ^{14}C is equal to the average specific radio-carbon activity before the advent of nuclear tests times the average number of grams of carbon present per square centimetre of the earth's surface. Estimation of those quantities in the different reservoirs of ^{14}C yields a decay rate of 1.81 disintegrations $\text{s}^{-1} \text{cm}^{-2}$ (589). This is less than the production rate but considering the uncertainties in total carbon mass estimates, this is a good agreement. It has been suggested, however, that the present-day inventory does not correspond to the equilibrium value, but is increasing (348, 589). In fact, measurements of wood samples of known age show that variations of atmospheric ^{14}C , amounting to a few per cent, have occurred in the past 6,000 years. Two types of variations have been recognized: one, with a time scale of the order of 100 years, has been explained by the solar wind modulation of the cosmic-ray flux density (589); the other, with a time constant of more than 1,000 years, may largely be due to a variation of the geomagnetic shielding of the earth (208).

67. Assuming that 6.1 pCi (gC)^{-1} is the specific activity of natural ^{14}C in the terrestrial biosphere, 50 keV the average beta energy, and 18 per cent the average carbon content of the whole body, then the average dose throughout the human body is 1.02 mrad y^{-1} . The highest dose is delivered to fat. In soft tissues, the annual dose rate is 0.68 mrad y^{-1} if the carbon content is taken as 12 per cent (613). In bone, the reported values of the carbon content are 13 per cent (266), and 15.5 per cent (577). The average of the two values leads to a dose rate of 0.81 mrad y^{-1} to endosteal tissues. Owing to the Suess effect, the dose reduction was approximately 0.04 mrad y^{-1} in 1969.

2. Primordial radio-active nuclides

68. The primordial radio-nuclides can be divided into those which decay directly to a stable nuclide (table 7), and those belonging to the three radio-active series, headed by ^{238}U , ^{235}U , and ^{232}Th (figure VII). The only non-series radio-nuclides of significance are ^{40}K and ^{87}Rb , which have similar chemical properties.

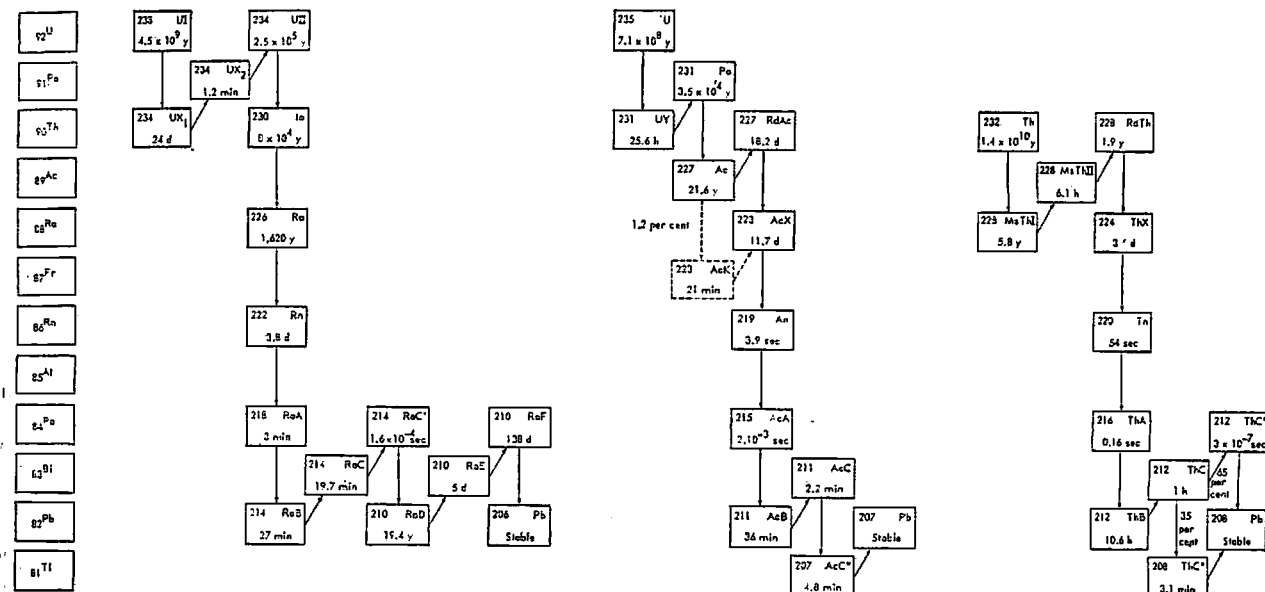


Figure VII. Decay schemes of the natural series^a (boxes show mass number, historical name and half-life)

^a Parallel decay branches of less than 1 per cent are not included

(a) Potassium-40

69. Potassium-40 is the main naturally-occurring source of internal radiation, despite its low isotopic ratio of 0.0118 per cent (40). The activity of ⁴⁰K in soils is on the average an order of magnitude higher than that of ²³⁸U and ²³²Th. In sea-water, ⁴⁰K constitutes the bulk of the activity with a concentration of about 300 pCi l⁻¹ (237).

70. Potassium enters the body mainly in food-stuffs and is under close homeostatic control. Variations in the composition of diet thus have little effect on the radiation dose received, so that knowledge of the behaviour of potassium in food chains is of no practical assistance in the assessment of man's exposure to radiation (540). The potassium content in the body varies considerably from one organ or tissue to another. Some tissues such as muscle, brain, and blood cells contain about 0.3 per cent potassium, blood serum has a normal level of 0.01 per cent and fat contains none (266, 577). In bone, a representative value may be taken as 0.05 per cent by weight for wet bone without marrow (577).

71. The average potassium content of the whole body as a percentage of body weight depends upon body build and is smaller in obese persons. Using whole-body counting techniques, potassium levels as a function of age have been investigated (44) for large populations (figure VIII). Recent results are consistent with those given by the Committee in its 1962 report for individuals of 20 years of age or older, but are up to 15 per cent lower for younger ages.

72. On the basis of a mean potassium content in tissues of 0.2 per cent, the dose rate to the soft tissues can be calculated as 19 mrad y⁻¹, the beta and the gamma doses amounting to 17 and 2 mrad y⁻¹, respectively (577). In bone, the potassium content being about one quarter of that in soft tissues, the annual dose to the osteocytes or to the tissues in the Haversian canals is about 6 mrad y⁻¹. In the active marrow, the potassium content is about 0.2 per cent which leads to an estimated dose rate to the bone marrow and

to the cells near the endosteal surfaces in the trabecular cavities of 15 mrad y⁻¹ (577).

(b) Rubidium-87

73. The isotopic abundance of ⁸⁷Rb, which is a pure beta emitter, is 27.85 per cent. The average concentration of rubidium in the whole body is 17 ppm; in bone, ovaries and testes, the corresponding figures are 10, 4.5 and 12 micrograms per gram of wet tissue, respectively (577). The dose rates to the gonads and to the bone tissues, resulting from decay of ⁸⁷Rb in the body, have been estimated from these concentrations (table 8). The average gonadal dose rate would

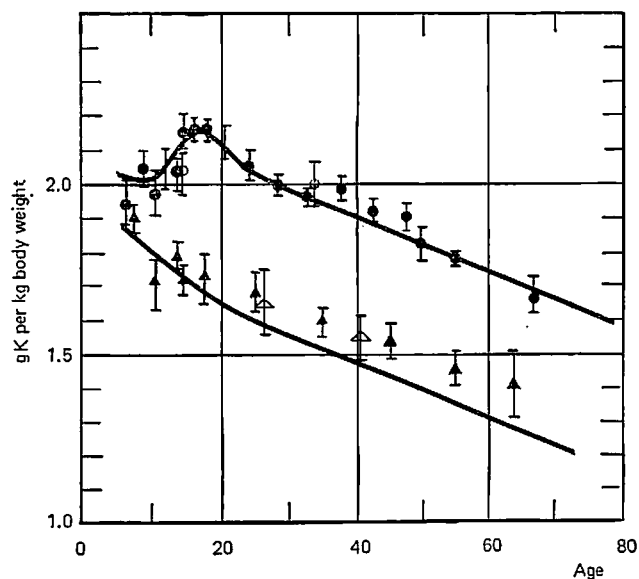


Figure VIII. Potassium concentration in the human body. The upper curve and circles refer to men, the lower curve and triangles to women. The curves represent the results of 10,000 measurements (466), the solid circles and triangles 802 determinations (16) while the open circles and triangles are the results of measurements performed on 57 subjects (44)

be about 0.3 mrad y^{-1} while the dose rate to the small tissue inclusions within bone would be approximately 0.4 mrad y^{-1} . Assuming that the concentration of rubidium in the active marrow is the same as that averaged over the whole body, the dose rate to the bone marrow and to the cells near the endosteal surfaces in the trabecular cavities would be 0.6 mrad y^{-1} .

(c) Uranium and thorium series

74. Uranium and thorium are widely distributed throughout the earth's crust where they present on the average the same activity concentration (225). The radio-active decay chains of ^{238}U and ^{232}Th are presented in figure VII. Uranium and radium enter the biosphere through the soil into plants, and then in herbivorous animals and in man. Further down the chain, radon, as a gas, escapes to a certain extent from the soil into the atmosphere and decays into isotopes of solid elements which are important contributors to radio-activity in the environment.

75. Thus, the ^{238}U series has been classified in four separate sub-series in which the activity of the parent controls to a large degree the activity of the decay products: (a) the isotopes ^{238}U and ^{234}U which can be considered to be in radio-active equilibrium in the environment as they are separated by two much shorter-lived nuclides, ^{234}Th and ^{234}Pa . At high concentrations, these isotopes of uranium present a chemical toxicity problem rather than a radiological hazard (540); (b) ^{226}Ra , as its concentrations in diet and man are not clearly related to those of its long-lived precursor and as the environmental pathways of its decay product, an isotope of a noble gas, are evidently not the same as those of a solid; (c) ^{222}Rn and its short-lived daughters (through ^{214}Po) of significance for inhalation; and (d) the long-lived ^{222}Rn decay products (^{210}Pb , ^{210}Bi , and ^{210}Po) which enter plants mainly by atmospheric deposition.

76. The ^{232}Th series is constituted by different isotopes of the same elements and may be treated in the same way as that of ^{238}U . ^{232}Th will be considered by itself as its decay product is an isotope of radium (^{228}Ra) of sufficiently long half-life to warrant an independent study. ^{228}Ra is the precursor of a sub-series which ends with ^{228}Ac . The gaseous element of the chain is ^{220}Rn , with short-lived daughters. ^{220}Rn does not have any long-lived decay product, as opposed to ^{222}Rn .

77. The decay chain of ^{235}U , also presented in figure VII, will not be dealt with here because the $^{235}\text{U}/^{238}\text{U}$ activity ratio in nature is less than 5 per cent.² Moreover, the very short half-life of ^{219}Rn , the gaseous element in the chain, leads to an atmospheric activity of its decay products which is about 2,000 times less than that of ^{222}Rn (104).

(i) Uranium

a. Concentrations in the environment

78. Soil. The typical content of ^{238}U in the accessible lithosphere has been estimated by the Committee in 1966 to be about 2.8 ppm. In general, igneous rocks and granites contain higher concentrations of uranium than sedimentary rocks such as limestone and chalk. However, some sedimentary rocks of marine origin contain very high concentrations of uranium (540).

² One gramme of uranium contains $0.33 \mu\text{Ci}$ of ^{238}U , assumed to be in equilibrium with ^{234}U , and $0.015 \mu\text{Ci}$ of ^{235}U .

79. Air and water. Uranium is present in the air in minute quantities. The natural debris may be mixed with man-made aerosols such as dust from building materials or smoke from both industrial and domestic sources (222). The concentrations observed in city air range from less than 10 to $1,500 \text{ pg m}^{-3}$ (222, 411, 645). In sea water, the uranium concentration is quite uniform (from 2 to $3.7 \mu\text{g l}^{-1}$), the low values being associated with near-coastal waters (55, 550, 576). On the other hand, concentrations in fresh waters show a high variability, with reported levels ranging from 0.024 to $200 \mu\text{g l}^{-1}$ (433, 525, 645).

b. Intake, levels and doses in man

80. There is very little information concerning the concentrations of uranium in man and in his diet. Values of daily intake of about $1 \mu\text{g d}^{-1}$ seem to be typical in the United Kingdom (224), the United States (645), the USSR (670) and France (550) while it reaches $30 \mu\text{g d}^{-1}$ in one area of the Soviet Union (683). In man, the range of concentrations has been found to be 0.1-0.9 nanogramme per gramme of wet soft tissue, to be compared with 20-30 nanogrammes per gramme of bone ash (224, 645). The corresponding dose rates to bone, calculated by the method of Spiers (577), are small (table 9); in the calculations, uranium was assumed to be uniformly distributed in mineral bone, although that may not be the case (223, 536). The total mass of mineral bone in man has been taken to be 5,000 grammes corresponding to 1,000 grammes of calcium (see paragraph 205). Bone has been assumed to yield 2.7 grammes of ash per gramme of calcium.

(ii) Thorium-232

81. Like uranium, thorium is more abundant in acidic than in basic rocks. It constitutes up to 10 per cent of monazite, which is particularly abundant in certain areas of Brazil and India. Experiments in which plants have been grown in solutions containing thorium show that it is readily adsorbed on roots, largely by physico-chemical processes (492), but that the concentration in shoots is negligible compared to that of radium (147). In the oceans, a very small amount of thorium is found suspended; the thorium-to-uranium concentration ratio is only $2 \cdot 10^{-5}$ or less (315).

82. No information on the intake of ^{232}Th has been found in the literature. Measured levels in rib bone (379) show a linear increase with age. The average value for an adult population would be about one femtocurie³ per gramme of ash, which is about an order of magnitude less than the levels obtained for uranium.

(iii) Radium

a. Concentrations in the environment

83. Soil. Radium isotopes are normally present in any type of soil at varying levels of radio-active equilibrium with their parents. Since, on the average, ^{232}Th and ^{238}U have about the same activity concentration (237) the same can be said for ^{226}Ra and ^{228}Ra , the two isotopes under consideration. The normal content of ^{226}Ra may be slightly increased by the use of phosphate fertilizers (418). The uptake of radium by plant shoots is much higher than that of thorium, lead or polonium (147), but is low in comparison to cal-

³ One femtocurie (fCi) equals 10^{-15} curie.

cium (328). An exception to that rule is constituted by the Brazil-nut tree (*Bertholletia excelsa*) which accumulates radium, along with barium, preferentially to calcium in some tissues of the fruit (494, 540), although the soil on which it has been observed to grow does not have an elevated content of radium.

84. *Air.* The natural background concentration is constituted by the airborne particulate matter picked up from the earth. In city air (222), it can be estimated at around seven attocuries⁴ per cubic metre, if it is assumed that uranium and radium have the same activity in the atmosphere. Fossil-fuelled power plants release very small amounts of radium, which may be detectable in the air around those installations (404). The maximum activity of ²²⁶Ra dispersed each year by the combustion of coal has been estimated at 150 curies (291).

85. *Ocean water.* In ocean surface water, the ²²⁶Ra content is low and relatively constant, with a value of about 0.05 pCi l⁻¹ (83, 597). It is primarily supplied by diffusion from ²³⁰Th-bearing deep-sea sediments (83). Similarly, ²²⁸Ra diffuses from ²³²Th sediments and is relatively abundant in waters in contact with terrigenous sediments (434) but even there it is in a lower concentration than ²²⁶Ra.

86. *Fresh water.* In fresh waters, the ²²⁶Ra content is highly variable, typical figures ranging from 0.01 to 1 pCi l⁻¹ (26, 139, 433). The highest concentrations, ranging up to 100 pCi l⁻¹, are found in mineral waters (139, 245, 508). Those drinking-water supplies drawn from surface waters do not in general contain significant amounts of radium. Flocculation and water-softening processes remove the bulk of the radium activity from water.

b. Transfer to man

i. Areas of normal external-radiation background

87. The average daily intake of ²²⁶Ra in areas of normal radiation background has been found to be about 1 pCi (gCa)⁻¹ in the United States, in the United Kingdom, in Argentina, in India, in the USSR, and in France (table 10). In the Soviet Union, a study conducted in one of the cities of Central Asia showed a high ²²⁶Ra intake of 17 pCi (gCa)⁻¹ explained partly by unusually high levels of ²²⁶Ra in water and in bread (676). Individual intakes are increased when food items which have high concentration factors are consumed; levels of ²²⁶Ra and ²²⁸Ra in Brazil nuts may reach several thousands of picocuries per kilogramme (494) while Pacific salmon, which is eaten in large quantities by Eskimos and North American Indians, contain about 20 pCi kg⁻¹ of ²²⁶Ra (293). The ²²⁸Ra daily intake is not well known but the few existing measurements (table 10) seem to indicate that it is more than half of that of ²²⁶Ra.

88. About 80-85 per cent of radium is contained in the skeleton, the remaining fraction being distributed approximately uniformly in soft tissues. World-wide variations in ²²⁶Ra skeletal burdens in areas of normal rate of intake are not large and show a spread between 4 and 40 fCi (g ash)⁻¹ in different localities (table 11) with an arithmetic average of 14 fCi (g ash)⁻¹ or about 40 picocuries per skeleton. The average ratio between

activities of ²²⁸Th and ²²⁶Ra in bone ash was found to vary between 0.25 and 0.5 (256, 380, 582) which, assuming radio-active equilibrium between ²²⁸Ra and ²²⁸Th in bone, leads to an estimated upper limit of skeletal burden of 20 picocuries of ²²⁸Ra in normal areas.

ii. Areas of high external-radiation background

89. People living on food-stuffs grown in areas of high natural radio-activity have daily intakes well above normal values but indications on their body burdens are very limited. The Indian population along the Kerala coast, including the monazite-bearing high-radiation belt, has an estimated *per caput* intake of ²²⁸Ra of 162 pCi d⁻¹ (424); the corresponding figure for ²²⁶Ra is only 2.85 pCi d⁻¹ (110). The analysis of a femur bone yielded a ²²⁶Ra concentration of 143 fCi (g ash)⁻¹.

90. In Brazil, a survey in the Araxa-Tapira region (495) showed that, out of a population of 1,670 people living in or around the radio-active anomalies of Barreiro and Tapira, only 196 individuals are ingesting alpha emitters at a level five times or more than that of a similar group living in Rio de Janeiro. Their intake of radium ranged from 60 to 240 pCi d⁻¹ of ²²⁸Ra and 10 to 40 pCi d⁻¹ of ²²⁶Ra. The mean concentration of ²²⁶Ra in ashed teeth of the population living in that area is 85 fCi g⁻¹ (496); as the level of ²²⁶Ra in teeth is approximately equal to that in bone (375), the result leads to an estimated skeletal burden of 230 picocuries.

91. In Guarapari, body burdens of ²⁰⁸Tl, a decay product of ²²⁸Ra, are of the order of 10 nanocuries (132). Since the levels in food are normal and the ²²⁰Rn concentrations in breath are elevated, this high burden probably results from inhalation of fine dust particles containing the precursors of ²²⁰Rn.

c. Dose rates

92. The fraction of radon retained by the various organs of the body after decay of radium has to be taken into account when computing the doses. The half-life of ²²⁰Rn is sufficiently short so that most of it decays where it is produced; however, some is detectable in the breath. In the case of ²²²Rn, the Committee adopted, in its 1966 report, an average skeleton retention factor of 0.33, but it has been shown that this factor is not constant at all sites (507). In soft tissues, a conservative assumption is that the ²²²Rn retention is the same as in bone (577). The annual alpha doses from ²²⁶Ra and ²²⁸Ra and their daughters, as calculated by the method of Spiers (577), are presented in table 9.

(iv) Radon-222, Radon-220, and their short-lived decay products

a. Concentrations in the environment

i. Outdoor ground-level air

93. ²²²Rn, ²²⁰Rn and their short-lived decay products constitute the main part of the radio-activity of ground-level air. The continents are the principal source of ²²²Rn and ²²⁰Rn, as the ratio of the emanation rate from the continents and from the oceans is about 500 for ²²²Rn (82, 485), and probably much higher for ²²⁰Rn. The diurnal variation of the atmospheric ²²²Rn concentration near the ground is inversely related to the coefficient of vertical turbulent mixing (398). Con-

⁴ One attocurie (aCi) equals 10⁻¹⁸ curie.

sequently, the typical diurnal ^{222}Rn concentration curve has a maximum in the early morning hours and a minimum in the afternoon (25, 179, 485, 548, 549). The ratio of the maximum to the minimum values is highest in the summer (10 or more) and lowest in the winter (549).

94. The short-lived decay products (^{218}Po , ^{214}Pb , ^{214}Bi , ^{214}Po) are never strictly in equilibrium with ^{222}Rn in surface air because of losses by deposition on the ground and on other obstacles and/or because of rapid diffusion of ^{222}Rn (73, 179). The activity ratio with ^{222}Rn is, in most cases, in the range 0.9-1.0 for ^{218}Po and 0.4-1.0 for ^{214}Po and ^{214}Bi , the lowest ratio occurring in the evenings and during the first half of the night, depending on the local stability conditions in the lower atmosphere. Equilibrium is most closely approached in the morning (179, 398).

95. On a seasonal basis, variations of ^{222}Rn in the air above the continents depend not only upon atmospheric thermal stability (362, 397), but also upon the variation of the rate of emanation from soils (125, 406) and upon local meteorological conditions and distance from coast (442). The average annual values from different parts of the world (table 12) show the high variability of the ^{222}Rn concentrations.

96. ^{220}Rn (thoron) and its daughters behave in the atmosphere in the same way as ^{222}Rn and its decay products. However, their radio-active half-lives are very different and the emanation rate of ^{220}Rn from soils is the main factor controlling ^{220}Rn concentrations in ground-level air. In recent years, the ^{220}Rn -emanation rate from soils has been directly measured by several workers (129, 212, 277, 588). Their results are in the range 2.5-14.0 $\text{fCi cm}^{-2} \text{ s}^{-1}$, which is consistent with Junge's estimated value of 5.6 $\text{fCi cm}^{-2} \text{ s}^{-1}$ based on the world-wide abundance of ^{232}Th (301). Atmospheric ^{220}Rn comes from the top six-centimetre layer of soil (588), and the exhalation is very sensitive to the soil moisture (212, 277, 588). It is much reduced if the soil is frozen and negligible if the soil is covered with snow. In dry weather the rate of emanation is highest at sunset, when convective streams develop in the soil due to the rapid cooling of its surface, and lowest at sunrise (212, 588).

97. In normal emanation conditions, the ^{220}Rn concentrations one metre above ground level are of the same order as those of ^{222}Rn (0.04-0.4 pCi l^{-1}) (179, 276). The distance covered by a ^{220}Rn atom between the point where it emanates from the ground and the point where it disintegrates being less than a kilometre (212), ^{220}Rn levels are determined by the local source and by the degree of stability of the lower layers of the atmosphere. The diurnal variation, as measured by Israel (275), exhibits a primary peak in the evening and a secondary one in the early morning. Because of the long half-life of ^{212}Pb , the daughter products of ^{220}Rn , ^{212}Po excepted, are in much lower concentrations (by a factor of 10 to 100) than ^{220}Rn near ground level (179, 564).

ii. Indoor levels

98. The air concentration of ^{222}Rn and its daughters indoors depends upon the concentration in outside air, upon the ^{222}Rn emanation rate from the walls, and upon the ventilation rate in the room. Table 13 shows the results of measurements carried out in various countries.

99. ^{222}Rn concentrations are usually higher indoors than outdoors; they are expected to be close to the values found outside if the rooms are efficiently ventilated, as in air-conditioned buildings, or if the emanation rate from the walls and the floor is low, as may be the case in wooden houses. High concentrations are found in rooms with very poor ventilation, for example in some basements, where the ^{222}Rn level will be proportional to the emanation rate from the walls, which in turn varies according to such parameters as the origin, nature, and porosity of the building material, and the type of paint or covering layer (649, 680). Between those extremes, average concentrations several times higher than those recorded outside are observed in naturally-ventilated brick, aggregate, or concrete buildings, the measured levels being sensitive to the actual degree of ventilation, which is connected to the individual habits of the inhabitants, and to the emanation rate from the walls (227, 498).

100. The degree of equilibrium of the ^{222}Rn decay products indoors is expected to be ruled by the ventilation rate, the equilibrium being nearly reached in rooms with poor ventilation, and highly perturbed in efficiently ventilated buildings. In naturally-ventilated rooms, the equilibrium conditions should be about the same as outside (555).

101. Indoor concentrations of ^{220}Rn and of its decay products are not likely to be higher than outdoors as papering or painting the walls prevents significant releases of ^{220}Rn on account of its short half-life. However, high concentrations have been observed in houses in monazite sand regions of Brazil (492).

iii. Water

102. Well away from the air-sea and sediment-sea interfaces, the activity concentration of ^{222}Rn in oceans is equal to that of its parent, ^{226}Ra . Even though its emanation rate is small, ^{222}Rn is not in equilibrium with ^{226}Ra near the surface. Its mean concentration at a depth of one metre is around 0.02 pCi l^{-1} (81, 84). In fresh waters ^{222}Rn levels do not show any relation with the ^{226}Ra levels. Their concentrations range from less than 1 pCi l^{-1} in some surface waters to more than $5 \cdot 10^5 \text{ pCi l}^{-1}$ in certain spa waters (111). A few nanocuries per litre seems to be a typical activity concentration for ground water (302, 571, 638). Boiling will remove most of the ^{222}Rn from water.

b. Transfer to man and doses

i. Inhalation

103. The radiation dose to the respiratory tract due to inhalation of ^{220}Rn and ^{222}Rn is negligibly small compared with that due to inhalation of their decay products, which deposit and build up in the respiratory system. The ^{222}Rn daughters are believed to be responsible for the greater rate of lung cancer among the underground uranium miners than among the general population (169). Since the observed lung cancers appear to arise primarily in the bronchi near the hilus of the lung, most authors concerned with the dosimetric aspect of the inhalation of radon daughters assume the relevant biological target to be the basal-cell layer of the bronchial tree and take into account a detailed structure of the deposition pattern along the respiratory tract. In order to calculate the dose received by the different parts of the respiratory system, the fol-

lowing factors have to be assessed: (a) the relative distribution of daughter products inhaled as "free" ions or atoms, or attached to aerosol particles of various sizes; (b) the pattern of deposition in the respiratory system and of translocation before decay; and (c) the distribution in the mucous layer and the thickness of the epithelial tissue separating the alpha particles emitted from their biological target.

(1) Size distribution

104. Radon decay products attach quickly to the aerosol particles present in the atmosphere, forming a radio-active aerosol. The unattached and the attached decay products form two very distinct groups on account of their marked difference in geometric size.

105. The attached ^{222}Rn daughters have a particle-size distribution which depends on the size distribution of the stable aerosols, as the attachment of daughters to particles seems to be related to the surface area of the aerosol particles (514, 626). Among the experimental data available on the distribution of natural radio-activity on aerosol particles (432, 572, 587), those of Mohnen and Stierstadt (432) are representative of the average. According to them, the mean value of the radius of the carrier aerosol is 25 nanometres with a 6-200 nanometre range at a concentration of 3×10^4 particles per cubic centimetre (226).

106. The unattached ^{222}Rn -daughter products which, at their formation, are heavy metal ions, are likely to form molecule clusters with water, oxygen, or carbon dioxide (301). From their observed diffusion coefficient ($D = 0.05 \text{ cm}^2 \text{ s}^{-1}$) it can be inferred (514) that their effective radius is 0.4 nanometre, which is well below the size of the aerosols carrying the attached daughter products. The only measurements of the fraction of unattached ^{218}Po in open air are those of Duggan and Howell (148) who found a range from 7 to 40 per cent with a mean value of 25 per cent. These results agree rather well with theoretical expectations (226, 301, 514).

107. There is no indication that the fraction of unattached ^{218}Po is consistently higher or lower indoors than outdoors (148). As for ^{214}Pb and ^{214}Bi , the unattached fraction is 2 per cent at best, as recent measurements show that there is practically no net removal of attached ^{218}Po from the aerosol (238). In the ^{220}Rn series, the fraction of unattached ^{212}Pb has been found to be about 2 per cent (239) and the size distribution of the ^{212}Pb -carrier aerosol, compared with ^{214}Pb , is slightly shifted toward larger particle sizes (282, 526).

(2) Lung deposition and clearance

108. Figure IX taken from Morrow (436) represents average deposition probabilities as a function of size for a man breathing normally under sedentary conditions. The deposition probabilities for the sub-micronic size range are theoretical. Experimentally, George and Breslin (190) found that the average values of nasal deposition of unattached and attached daughters are 62 per cent and 2 per cent, respectively. Those values agree very well with the theoretical curve and show that the contribution of the unattached ^{218}Po to lung dose is less than what was previously thought (14, 282).

109. Since alpha particles are the main contributor to the dose, regional deposition in the lower respiratory

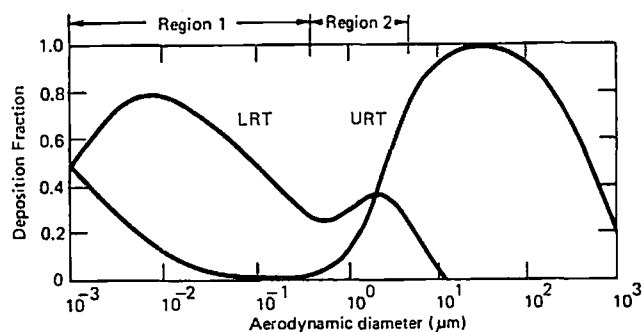


Figure IX. Deposition probabilities for particles from nearly molecular dimensions to those in the visible range. The two respiratory divisions, URT and LRT, denote upper and lower respiratory tracts, respectively; URT is equivalent to the supraglottic airways, whereas LRT is the tracheo-bronchial tree and parenchyma (436). The aerosol carriers of radon daughters are found in region 1; region 2 is the zone of industrial aerosols

tract has to be evaluated and more elaborate models than the one put forth by the ICRP Task Group on lung dynamics (268) have to be used. Landahl's model (350) was used by Jacobi (282) and by Altshuler *et al.* (14) in their extensive studies of the dose to the human respiratory tract from the inhalation of short-lived ^{222}Rn decay products. Improvements on these studies were achieved recently (226, 238): using Weibel's dichotomous lung model (644) (table 14), the depositions in the various parts of the lung were inferred from the equations of Gormley and Kennedy (206). In the range of aerosol sizes considered, the calculations show that the bigger the particle, the less it is deposited in the tracheo-bronchial tree and the lower is the total deposition (238).

110. The use of Gormley and Kennedy's equations implies that the airways are tubes of constant cross-section and that the flow is laminar. In fact, airway diameters are a function of the degree of lung inflation, vary in size from one subject to another, and may not be circular at all (367). As for the assumption of a laminar flow, experiments made with the help of a plastic model of the upper bronchial tree show that turbulent mixing occurs in the trachea and larger bronchi, resulting in a higher deposition probability and in high local deposition values around the branchings (283).

111. Moreover, total respiratory deposition of radon daughters measured in subjects breathing normal laboratory air was found to range from 25 to 45 per cent (190), which is lower than the value of about 70 per cent predicted by the ICRP Task Group on lung dynamics (268). This discrepancy has been partly explained by a rapid growth of the attached decay products in the respiratory tract due to the high humidity present. This effect, which has been found to increase the size of the small particles (up to 60 nm in diameter) by a factor of two, has not been taken into account in the regional deposition studies. The tidal volume also has an influence on the total-deposition value, whereas the respiratory frequency does not (190).

112. The rapid clearance mechanism of the deposited aerosols in the tracheo-bronchial tree is due to the movement of the mucous sheath. Studies of transit times have established that daughters deposited in each region are carried by the mucus, eventually to disinte-

grate at a site nearer to the mouth. However, in terminal bronchioles, the mucus transit time is so long that the decay products are assumed to disintegrate at the deposition site.

113. Because of the long half-lives of ^{220}Rn daughters, lung clearance mechanisms will play an important role. More than 90 per cent of the ^{212}Pb atoms deposited in the bronchial tree are eliminated by swallowing before their decay (436). Those deposited in the pulmonary region are transferred to the blood with a biological half-life of around 10 hours (71, 257, 282) which means that about half of the potential decay energy of ^{212}Pb is expended outside the lung, whereas the corresponding figure for ^{214}Pb is only 4 per cent. In the blood, about one half of the ^{212}Pb atoms are fixed by the circulating red cells and the other half distributed to other tissues (258).

(3) Distance to the biological target

114. The dose rate to the basal cells of the epithelial tissue depends on the distribution of the daughter products in the mucous layer and on the thickness of the epithelial tissue. The alpha-stopping power in tissue, as inferred from measurements of attenuation in polycarbonate or in gas mixtures, shows a remarkable agreement with the theoretical stopping powers and can be considered to be precisely known (238).

115. The distribution of ^{222}Rn daughters within the mucous layer of rabbits and dogs has been recently determined (669). For rabbit trachea the mucous thickness was 10 micrometres. In the dog trachea and bronchus, 30 per cent of the total ^{214}Po activity was found in the first two micrometres of mucus. Activity was estimated to extend throughout the layer with no cut-off point below the surface. Although these data may not strictly apply to the human respiratory tract, they suggest that most of the activity may stay in the top half of the mucous layer, the total thickness of which is about 14 micrometres in man (14).

116. The measured thicknesses of the epithelial bronchial tissues of a single adult man were found to vary considerably in each class of bronchus. In segmental bronchi, an exceptionally low value of thickness was 29 micrometres and the median thickness 56 micrometres. Assuming a distance of 7 micrometres from the basal cell nuclei to the basement membrane, the radon daughter products present in the segmental bronchi are on the average about 60 micrometres away from the basal cell nuclei but may be as close as 22 micrometres if the tissue is exceptionally thin. These dimensions are to be compared with the alpha-particle ranges of ^{218}Po and ^{214}Po , which are 47 and 71 micrometres, respectively.

(4) Doses

117. The models predict that the basal-cell nuclei which receive the highest dose in the tracheo-bronchial tree are those of the segmental bronchi, which is the region of known cancer incidence among uranium miners. Table 15 presents calculated (226) dose rates to the basal-cell layer of that area for various environments as a function of the distance from the basal cells to the ^{222}Rn daughters present in the mucous layer. The values correspond to mouth breathing with an inhalation rate of 10.4 l min^{-1} in the living accommodation and 20.8 l min^{-1} at the working site. Assuming that the average distance from the basal cells to the

^{222}Rn daughters is 60 micrometres, the annual radiation doses, calculated as the sum of the doses received in the living accommodation and at the working site, are in the range $55\text{--}195 \text{ mrad y}^{-1}$, but they might be as high as 520 or as low as 2 mrad y^{-1} if that distance is 45 or 70 micrometres. Therefore, wide variations will occur locally because of the variability in the thickness of the bronchial epithelium and also because of the non-uniform deposition pattern of the radon daughters, but it cannot be stated whether those variations affect the over-all hazard to the tracheo-bronchial tree, as the highest local dose rates are of the order of 1 rad y^{-1} only. It should be noted that the annual dose averaged over the mass of the tracheo-bronchial tree is about 15 millirads.

118. The dose rate to the alveolar region is of the order of 5 mrad y^{-1} ; it is averaged over the mass of the alveolar tissue as the thickness of the walls of the alveoli and the diameter of the blood capillaries are small compared to the range of the alpha particles considered. The doses to organs and tissues outside the respiratory system, presented in table 16, have been measured in guinea-pigs (511); as the ventilation volume and the weight of blood are almost the same for man and for guinea-pig when divided by their respective body weight (510), the results are an estimate of the doses in man. The doses to all organs and tissues are much lower than the dose to the alveoli.

119. The doses received from inhalation of ^{220}Rn and its decay products are much lower than those due to ^{222}Rn daughters and have been the object of less attention. As in the case of ^{222}Rn , the highest dose delivered is that to the segmental bronchi, but the dose to the alveoli is less by only a factor of five (282). Assuming that the mean indoors concentration of ^{212}Pb and ^{212}Bi is 3 fCi l^{-1} , the average dose rate to the basal-cell nuclei of the segmental bronchi is calculated as 4 mrad y^{-1} while the dose rate to the alveolar tissue is 0.8 mrad y^{-1} . The doses to the other organs and tissues, as estimated from experiments on guinea-pigs, are given in table 16 (510).

ii. Ingestion

120. As mentioned by the Committee in its 1966 report, the ingestion of one microcurie of ^{222}Rn dissolved in water leads to a dose to the stomach of about 20 millirads, the doses to the other organs being lower by at least an order of magnitude. Assuming a consumption of 0.3 l d^{-1} of fresh water containing 1 nCi l^{-1} , the annual dose to the stomach is about 2 millirads. Another, but much lower, source of ^{222}Rn is milk, which in Sweden was found to contain about 40 times less ^{222}Rn than drinking water (364, 389).

(v) Radon-222 long-lived decay products

a. ^{210}Pb and ^{210}Po in the environment

121. The main source of ^{210}Pb and its decay product ^{210}Po in the atmosphere is ^{222}Rn which emanates from the ground. The average concentration of ^{210}Pb in ground-level air at a given locality depends on the ^{222}Rn -emanation rate at that point and on the global pattern of air circulation. The observed concentrations are higher above the continents and in the northern middle latitudes, where the proportion of the land surfaces from which ^{222}Rn emanates is greater than in the other latitude bands. For some locations, ^{210}Pb

levels exhibit a seasonal variation with maximum values in winter explained either by the occurrence of long periods of stable air masses (298, 299) or by other climatological factors (557). The $^{210}\text{Pb}/^{222}\text{Rn}$ activity concentration ratios found at a site in the Soviet Union (25) are fairly constant and lie in the range $0.5 \cdot 10^{-4}$ – $1 \cdot 10^{-4}$. The average values of this ratio for other locations vary from $0.2 \cdot 10^{-4}$ to $2.5 \cdot 10^{-4}$ (484). The $^{210}\text{Po}/^{210}\text{Pb}$ activity concentration ratios in ground-level air usually range from 0.05 to 0.30 but ratios greater than unity are found in industrial regions (487), which implies that a significant amount of ^{210}Po is released from coal burning. It is estimated (487) that in the latitude zone between 40°N and 60°N , the quantity of "artificial" ^{210}Po is about 10 to 20 per cent of that arising naturally. Karol (312) calculated that the total contents of ^{210}Pb and ^{210}Po in the atmosphere are from 20 to 26 and from 2.4 to 5.7 kilocuries, respectively. There is no thorough study of the average size of the aerosols to which ^{210}Pb and ^{210}Po are attached. This size has been reported to be intermediate between that of short-lived ^{222}Rn daughters and that of long-lived fission products (371). Skewed distributions have been found with 120 and 160 nanometres as geometric mean diameters (559).

122. The annual rain deposition rate of ^{210}Pb , measured in the United Kingdom (489), in India (299), and in New Zealand (447), is on the average of 3 mCi km^{-2} , which implies an activity of about 80 mCi km^{-2} in the upper layers of the soil under equilibrium conditions. The levels of ^{210}Pb in rainwater are of the order of $1\text{--}5 \text{ pCi l}^{-1}$ (289, 489) while those of ^{210}Po are 5 to 10 times less (96, 399). The mean residence time of ^{210}Pb in the troposphere, calculated from the $^{210}\text{Po}/^{210}\text{Pb}$ -activity-concentration ratio under the assumption that there is no significant ground-level source of ^{210}Po has been found to be of the order of 10 days (181). In surface waters, the ^{210}Pb concentrations are lower by a factor of 10 to 100 than those usually found in rainwater; however, concentrations in ^{222}Rn -rich waters such as mineral waters or some well waters may reach the levels found in rainwater (288, 571).

b. Intake by man

i. Inhalation

123. The average concentrations of ^{210}Pb and ^{210}Po in ground-level air in the northern middle latitudes are around 15 and 1.5 fCi m^{-3} , respectively. Assuming an intake of 20 cubic metres of air in 24 hours, 0.3 picocurie of ^{210}Pb and 0.03 picocurie of ^{210}Po are thus inhaled every day. Using a coefficient of transfer to the blood of 0.30 (437), the amounts of ^{210}Pb and ^{210}Po reaching the blood are less than 0.1 pCi d^{-1} . An additional intake may result from cigarette smoking (171, 250). Both ^{210}Pb and ^{210}Po are present in cigarette smoke, ^{210}Po being more abundant because of its higher volatility. Smoking 20 cigarettes a day leads to a daily intake of 0.3–0.8 picocurie of ^{210}Pb and 0.4–1.4 picocuries of ^{210}Po , corresponding to amounts reaching the blood of 0.2 and 0.3 pCi d^{-1} if the same transfer coefficient as above is used. However, it should be remembered that the conditions of inhalation and possibly the particle-size distributions are very different from those in normal respiration.

ii. Ingestion

124. For non-smokers, food usually represents the main route of uptake of both ^{210}Pb and ^{210}Po by man.

Table 17 shows the values of the daily dietary intake in some countries. In the so-called western-type diet characterized by a high consumption of milk, the ^{210}Pb content is in the range $1\text{--}10 \text{ pCi d}^{-1}$, bread, meat, and vegetables contributing about the same amount. In that type of diet, the $^{210}\text{Po}/^{210}\text{Pb}$ ratio is about one (200, 247). An intake of 5 pCi d^{-1} leads to 0.4 and 0.3 picocurie of ^{210}Pb and ^{210}Po reaching the blood per day, assuming a gastro-intestinal fractional uptake of 0.08 and 0.06, respectively (266).

125. The $^{210}\text{Po}/^{210}\text{Pb}$ ratio may be much greater than one in animal muscle and in sea food (35, 318, 320, 553), and people whose diet consists mainly of meat or fish are expected to ingest relatively large amounts of ^{210}Po . The high ^{210}Po dietary intake of the Lapps is due to the special lichen-reindeer-man food chain, ^{210}Po accumulating in lichens and in reindeer meat. The average intake of ^{210}Po by Lapps is more than an order of magnitude higher than by "non-arctic" populations, while the intake of ^{210}Pb is higher by only a factor of about two or three (317). In Japan, the consumption of sea food accounting for 12 pCi d^{-1} of the ^{210}Pb daily intake, it is likely that the ^{210}Po dietary intake is also much higher than that of ^{210}Pb .

iii. Distribution in man

126. The activity concentration of ^{210}Pb and ^{210}Po in body tissues depends mainly upon the direct intake of those elements. The contribution from other sources, such as decay of ^{226}Ra in the skeleton, decay of atmospheric ^{222}Rn dissolved in the body fluids, and decay of inhaled short-lived daughters of ^{222}Rn is relatively unimportant (249).

127. The major fraction of ^{210}Pb in man is found in bone which contains 70 per cent or more of the body burden (289, 326). In the temperate zone of the northern hemisphere, the ^{210}Pb concentration in wet bone is about 40 pCi kg^{-1} (289). In soft tissues, the highest average concentrations, typically between 5 and 10 pCi kg^{-1} , are found in liver, bladder and gonads (29, 57). An exception is constituted by hair, which, during its period of growth, concentrates ^{210}Pb in amounts higher than bone. It has been suggested that determination of ^{210}Pb in the hair may be used to assess the integral exposure to this nuclide over the previous month in case of occupational poisoning (288, 290).

128. The $^{210}\text{Po}/^{210}\text{Pb}$ activity ratio is close to unity in bone and it is likely that both the amount of ^{210}Po taken up from external sources and that fraction which decays from ^{210}Pb and ^{210}Bi have a long biological half-life in bone compared with the physical half-life (457). In some soft tissues such as the bladder, the $^{210}\text{Po}/^{210}\text{Pb}$ activity ratio is lower than one, whereas it is greater than one in others, for example the lung, the liver and the kidney (29, 57). The reason for the excess of ^{210}Po in those tissues is not clear; it has been suggested (247) that the uptake and the metabolic behaviour of polonium might be related to the chemical form in which the dietary ^{210}Po occurs. Because the concentrations of ^{210}Po in hair, bone tissue and liver of naturally-exposed people show some correlation, hair monitoring has been proposed as a convenient way of assessing the ^{210}Po concentration in bone (18).

129. Comparative studies between smokers and non-smokers (27, 57, 246) show that the concentrations of ^{210}Pb and ^{210}Po in the lungs and ribs of ciga-

rette smokers are about two or three times higher than in non-smokers. In the soft tissues other than lung, the contribution of cigarette smoke to the ^{210}Pb and ^{210}Po content is less important (28).

130. High concentrations of ^{210}Pb and especially of ^{210}Po are to be expected in tissues of arctic populations consuming reindeer or caribou meat. The values observed in samples from Alaskan residents who had not eaten any caribou meat are within the normal range of values reported for unexposed populations while the soft tissue concentrations of ^{210}Po and the $^{210}\text{Po}/^{210}\text{Pb}$ activity ratio were found to increase with consumption of caribou meat (58). However, none of the individuals studied consumed caribou meat daily. The distribution of ^{210}Pb and ^{210}Po in the tissues of such a person, which would be very valuable, has not been measured yet owing to the difficulty of obtaining autopsy tissue samples. However, analyses of teeth of Lapps who breed reindeer showed ^{210}Pb and ^{210}Po concentrations about twice those of southern Finns, who are representative of a non-arctic western population. In blood and placenta, ^{210}Pb and ^{210}Po are 2 and 12 times higher, respectively, in the former than in the latter population (317). It has been assumed that the polonium concentration in gonads would also be 12 times higher in Lapps than in southern Finns.

iv. Doses

131. The radiation dose absorbed by the body tissues from the ^{210}Pb chain depends mainly on the highly energetic alpha particles of ^{210}Po . At equilibrium, the contribution from the beta emission of ^{210}Pb and ^{210}Bi is only 7.5 per cent of that from ^{210}Po and will be neglected here. Because ^{210}Po concentrations in the gonads are higher than once believed, the corresponding dose rates may be higher by a factor of two than those estimated by the Committee in its 1966 report. Lapps might receive an annual genetic dose of 8.5 millirads from this source (317). The annual doses

to the bone tissues of the northern temperate latitudes population (table 9), calculated by the method of Spiers (577), are 4.0 millirads for osteocytes, 2.4 millirads for cells lining Haversian canals, 1.6 millirads for cells lying near the endosteal surfaces in trabecular bone, and 0.3 millirad for the whole marrow, if the concentration activity of ^{210}Po in bone is taken to be 40 pCi kg^{-1} (289). In the lung, the annual average dose is of the order of 0.5 to 1 millirad but ^{210}Po has been found in very high concentrations in the bronchial epithelium of the segmental bifurcations of heavy smokers, implying local doses two orders of magnitude higher than the average (369).

B. EXTERNAL IRRADIATION

132. When present in the top few centimetres of the earth, nuclides of the natural radio-active series, together with ^{40}K (relative abundance 0.01 per cent), give rise to gamma radiation near the earth's surface. The doses from this radiation are lowest on the surfaces of oceans or lakes. The concentration of these natural radio-nuclides varies greatly between different types of rocks and soils, being highest in igneous rocks such as granite and lowest in sedimentary rocks, such as limestone and sandstone (563, 616). These radio-nuclides can also give rise to external radiation doses to man when present in the materials used to construct buildings and to pave roadways. The gamma radiation above the ground can be affected by the moisture content of the soil and, in particular, by snow cover. The effect of snow cover in reducing the natural radiation is illustrated in figure X, which shows the external gamma radiation measured at two sites in Sweden between 1960 and 1971.

133. The dose rate in air from gamma radiation has been determined using both gamma-ray spectroscopy and ionization chamber measurements. In the latter case, it is necessary to subtract the cosmic-ray contribution to obtain the external gamma dose. The

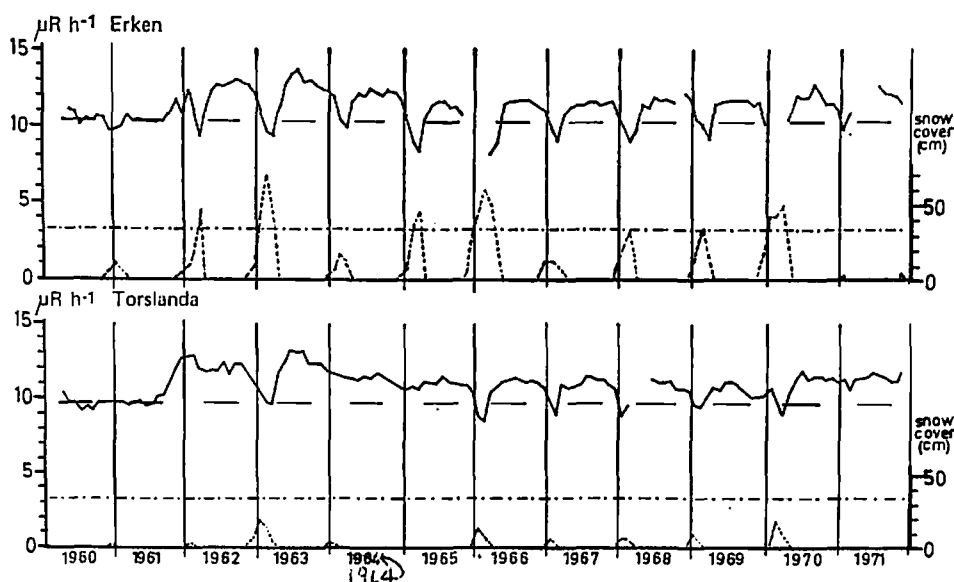


Figure X. External exposure rates at 2.5 metres above ground and monthly averages of the snow cover in Sweden (390, 596)

— Total external exposure
 - - - Exposure level summer 1960 and 1961
 . . . Average exposure from cosmic rays
 - - - Snow cover (scale on the right)

resulting gamma dose rate includes a contribution from radon, thoron and their daughter products present in the air estimated to be from 2 to 3 mrad y^{-1} (563, 615).

134. The dose rates obtained from recent surveys carried out in 12 countries are summarized in table 18, where the results of measurements made both indoors and outdoors are shown. Although individual measurements cover a range up to 400 mrad y^{-1} , the average for the different regions of normal background are much more closely grouped. The average indoor and outdoor dose rates for the three country-wide surveys reported in table 18 show that a representative value would be about 60 mrad y^{-1} .

135. In the United States survey (37), 90 per cent of the populated areas had annual doses ranging between 30 and 95 millirads. The results of this survey also showed that ^{40}K , the ^{238}U series and ^{232}Th series contributed 17, 13 and 25 millirads, respectively, to the average annual dose of 55 millirads.

136. In the United States, the German Democratic Republic and Italy, average dose rates indoors were lower than outside, while in the United Kingdom and the Federal Republic of Germany they were higher indoors. In most other countries, there was little difference in the average indoor and outdoor dose rate. The shielding offered by building structures is often offset by radiation due to natural radio-nuclides present in the building material. In New England, where homes are of wood construction, Lowder *et al.* (378) found that typical radiation levels were about 70 per cent of those outside, while in brick houses in Edinburgh, U.K., Spiers (579) found that dose rates were higher indoors.

137. At certain sites, the terrestrial gamma dose rate is very low. Thus Beck *et al.* (39) have reported measurements over lakes and reservoirs in the United States where the dose rate was less than 4 mrad y^{-1} , while Liboff and Shamos (360) reported levels as low as 0.4 mrad y^{-1} in certain mines in the United States and Canada.

138. There are also several areas of the world where high concentrations of thorium and uranium occur in the surface layers of the earth and result in greatly enhanced gamma dose rates. In the coastal regions of the Indian state of Kerala, there are patches of sand containing monazite, a mineral which may contain high concentrations of thorium and uranium. This mineral also occurs in some coastal areas of Brazil, as well as in China and the United States (563).

139. High radiation exposures are also to be found in the regions of volcanic intrusives in the State of Minas Gerais in Brazil (493).

140. Gopal-Ayengar *et al.* (204, 205) carried out a dosimetric survey on a 55-kilometre-long coastal strip, inhabited by some 70,000 people, in the state of Kerala, India. By issuing thermoluminescent dose-meters, which were worn for two months, the radiation exposures of 8,513 individuals living in 2,374 households were obtained. On the basis of these data, it was estimated that, of the 70,000 inhabitants of that area, 16,600 received annual doses of more than 0.5 rad and that, of these, 4,500 and 470 received more than one and two rads, respectively.

141. In the towns of Guarapari and Meaibe, on the Brazilian coast, it was estimated that some 20,000 inhabitants are exposed to levels of external radiation from monazite sands that vary from 0.2 to 8 rad y^{-1} (493). By issuing 317 inhabitants of Guarapari with thermoluminescent dose-meters for three months, Cullen (131) determined the average dose rate of the group as 0.55 rad y^{-1} with a range of 0.09 to 2.8 rad y^{-1} . Penna-Franca *et al.* (493) also measured external radiation dose rates on a hill near the city of Pocos de Caldas, which presents the highest levels of radiation in the Brazilian volcanic region. The air dose rates were in the range of 0.43 to 25 rad y^{-1} , with many sites having rates of 7 rad y^{-1} . However, this hill has a small area and is uninhabited.

142. All the dose rates quoted so far for gamma radiation are air dose rates. To convert these to dose rates in tissue, say bone or muscle, they must be multiplied by the ratio of the mass absorption coefficient in tissue to that in air. Johns and Cunningham (295) have tabulated this ratio for both hard bone and muscle. For 0.5-10-MeV gamma rays, this ratio is in the range of 1.07-1.11. In order to compute doses to the bone and gonads we will use the value 1.10 given by the ICRU for these energies (270).

143. Bennett (49) investigated the procedures for converting air exposure measurements into absorbed doses to the reproductive organs. He used computed gamma-ray spectra above the ground for both plane and exponential distributions in soil of ^{238}U , ^{232}Th and their daughters and of ^{40}K and ^{137}Cs . In obtaining the gonad dose from a uniform exposure around the body, actual anatomical drawings of body cross-sections were used to account for shielding by overlying tissue and bone. The resulting average conversion factor obtained (gonad/air) was 0.82. It should be noted that this factor already contains the tissue/air dose factor of 1.1 mentioned in the last paragraph. Conversion factors calculated by Bennett (49) and those based upon phantom measurements by Jones (297) are given in table 19 for exposures to gamma rays from natural emitters and from ^{137}Cs . The average conversion factors for testes and ovaries are fairly constant and therefore little error will be involved in applying a uniform factor of 0.8. From the work of Jones (297) it appears that the appropriate screening factors relating the absorbed dose in bone marrow to the free air dose is also 0.8. Since the above factor refers to 2π geometry, it is applicable to gamma-radiation received outdoors.

144. Spiers and Overton (578) determined screening factors using a phantom irradiated in 3π geometry. They obtained values of 0.63 and 0.64 for the exposure of gonads and bone marrow to external radiation. These factors are just screening factors and do not contain the tissue/air dose-conversion factor. Applying the tissue/air dose-conversion factor a value of 0.7 is obtained for the average gonad and bone-marrow dose. By using this factor of 0.7 for indoor exposure and 0.8 for outdoor exposure and assuming that 7 hours per day is spent outdoors, an average conversion factor of 0.73 is obtained. The product of the average air dose rate (60 mrad y^{-1}) and the average conversion factor (0.73) gives a value for the gonad and bone marrow dose rates of 44 mrad y^{-1} . This figure does not differ significantly from the value of 50 mrad y^{-1} previously used by the Committee.

III. Recapitulation of dose rates

145. Table 20 summarizes the contribution of natural sources to the radiation exposure of human populations. The three tissues considered are the gonads, the bone marrow and the bone-lining cells. For comparison, table 20 includes the estimates for the gonads and the bone marrow given in the 1966 report.

146. In addition to the doses included in table 20, yearly doses in the range 50-200 millirads are received by the basal epithelial cells of segmental bronchi from inhaled radon daughters. Their actual values are still uncertain owing to the many assumptions that underlie the estimates.

Part Two. Man-made environmental radiation

I. Nuclear explosions

A. ATMOSPHERIC AND SURFACE EXPLOSIONS

147. More than any other subject, radio-active contamination of the environment by nuclear test explosions has been a matter of continued interest for the Committee. When the Committee prepared its first comprehensive report in 1958, very little was known about the movements of artificial radio-activity through the biosphere and only some of the nuclides released into the environment by atmospheric and surface explosions were being monitored and considered worth studying.

148. The amount of information available has grown over the years, as the pace of atmospheric injections reached its peak in 1961-1962 and declined to its current comparatively low levels. The present review will largely be devoted to an assessment of current radio-active contamination from all tests, and the reader is referred to earlier reports for a record of the situation as it changed with time. However, a certain amount of background information previously discussed by the Committee is included in this review so as to make it reasonably self-contained.

149. After a description of transport mechanisms in the atmosphere, which largely summarizes the discussion in the 1964 report, the transport of individual nuclides in the biosphere and the resulting doses will be discussed, followed by a review of external radiation from radio-nuclides deposited on the ground and by a summary of the dose commitments arising from all nuclear tests.

1. Transport of radio-active debris within the atmosphere

150. After an atmospheric explosion, the fission products and construction material contained within the fireball are initially present in gaseous form. As the fireball rises and cools, particle formation takes place through condensation and coagulation. The resulting particles are small and consist mainly of material from the nuclear device and its carrier.

151. With surface explosions and explosions at such heights that the fireball touches the ground, large amounts of fragmented ground material will be incorporated in the fireball and become melted and partly vaporized. Some of the vaporized material forms par-

ticles by condensation and coagulation, in the same way as with atmospheric explosions, but most of it will condense on the surface of melted ground particles.

152. The dependence on total yield of the altitude of both the top and base of the stabilized cloud (the mushroom) for surface explosions and atmospheric explosions below an altitude of three kilometres is shown in figure XI (506). The initial vertical distribu-

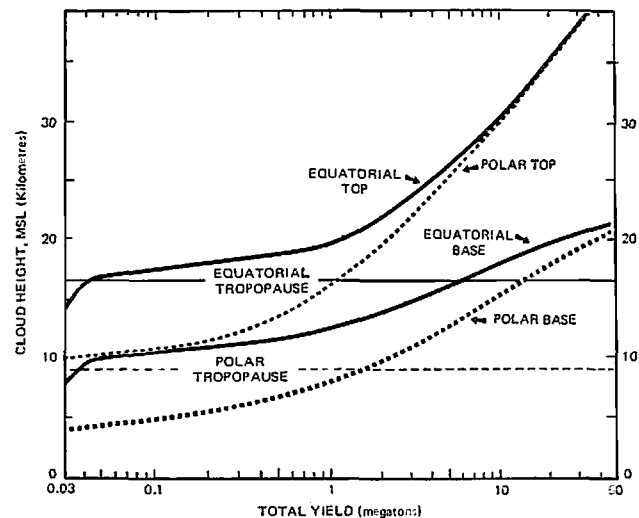


Figure XI. "Mushroom cap" cloud top and base as a function of total yield of device. "Equatorial" refers to 0-30° latitude; "polar" refers to 30-90° (506)

tion of radio-activity within the cloud is shown in table 21 (506). The total amount of radio-activity injected into the stratosphere by a surface explosion is about one half of that from an atmospheric explosion of the same yield.

153. Although our knowledge of air movement in the atmosphere is incomplete in certain respects, particularly at high altitudes, some basic features of this motion are fairly well established. One marked feature of atmospheric circulation is the system of westerly jet streams situated in mid-latitudes at altitudes of about 10 kilometres (figure XII). Velocities of 100-300 kilometres per hour are usual in these regions. In middle and higher latitudes air is carried around the

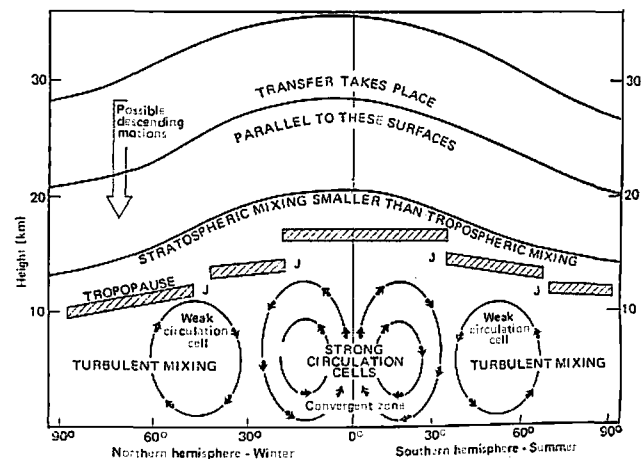


Figure XII. Schematic cross-section displaying characteristics of meridional transport ("J" locates typical jet stream positions) (614)

globe in a week or so and in one to two months in tropical regions (66). Since, in the stratosphere, these times are short compared to transfer times in the meridional and vertical directions, the debris may be considered to be zonally well mixed so that, several months after a test, they will be uniformly distributed around a circle of latitude (66). In the troposphere, vertical motions are rapid but in the lower stratosphere these vertical motions and hence the associated vertical transport are much smaller (66, 509).

(a) *Movement within the stratosphere*

154. Observations of radio-active tracers have contributed greatly to the understanding of air movement within the stratosphere. A schematic representation of the stratospheric circulation features deduced from data on ^{90}Sr , ^{14}C , ^{185}W , ^{102}Rh , ^{109}Cd and ^{238}Pu is shown in figure XIII (368). Tracer data above about 37 kilo-

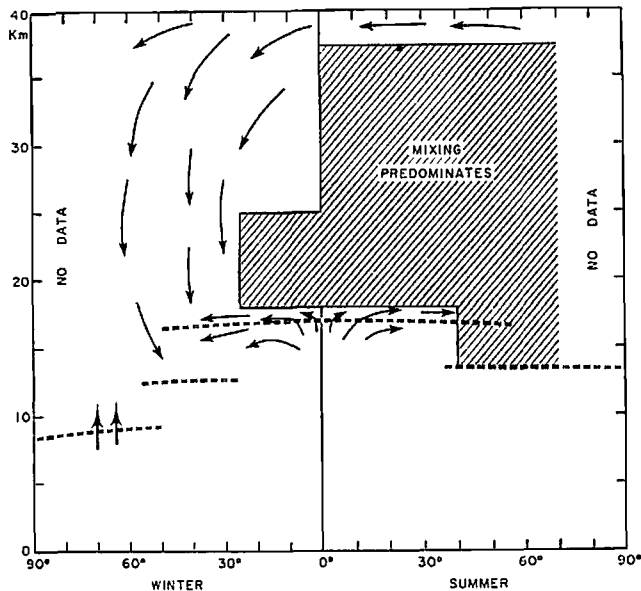


Figure XIII. Schematic representation of the stratospheric circulation as deduced from radio-active tracer data (368)

metres between 25° and 70° indicate a flow from the summer hemisphere to the winter hemisphere and a mean descending motion in the winter stratosphere. Ascending motions occur near the equatorial tropopause and poleward motions in the lower winter stratosphere at latitudes higher than 70°. Virtually the entire summer stratosphere and the winter stratosphere below 25° between 18 and 25 kilometres are dominated by mixing processes with no evidence of organized circulations in the meridional phase.

155. The level of maximum concentration of radio-active tracer material injected into the stratosphere slopes from higher altitudes over the equator to lower altitudes and colder potential temperatures near the pole (386). Six to twelve months after the injection into the lower stratosphere in equatorial, temperate and polar latitudes, the configuration of the levels of maximum concentrations was found to be almost identical irrespective of the latitude and altitude of injection and of the vertical distribution of the debris. Tracers originally injected into the upper stratosphere and aerosphere follow a similar pattern. Machta *et al.* (386) suggest the following genesis of the surface of

maximum concentration as deduced from data on radio-active debris from the nuclear explosion at 40° N of 17 June 1967:

(a) a poleward, essentially horizontal, displacement of most of the air containing the debris by mid-autumn, accompanied by a warming of the order of 0.2° C per day;

(b) a net descending motion during late autumn and winter north of about 55° N at a rate of 1-5 kilometres per month with the air cooling by about 1° C per day;

(c) isolated patches of debris remaining near the source region;

(d) quasi-horizontal diffusion imposed on the mean circulation, smoothing out the gradients and resulting in a surface of maximum concentration sloping downward from about 20 kilometres at 20° N to 15 kilometres at 60° N in spring and summer.

(b) *Transfer to troposphere*

156. Many mechanisms may play a role in the transfer of particulate radio-activity from the stratosphere to the troposphere. Thus, heavy particles can settle through the tropopause but the bulk of the radio-activity in the lower stratosphere is associated with particles too small for gravitational settling to contribute significantly to the downward transport through the tropopause (614). The horizontal transport through the subtropical tropopause gap makes a considerable (and often determinant) contribution in the air mass exchange between the stratosphere and the troposphere and the well-known spring maximum concentration of fall-out in surface air is due to a winter maximum exchange between lower stratosphere and troposphere through the tropopause of temperate and high latitudes (313). Finally, stratospheric radio-activity can be incorporated into the troposphere by diffusive mixing through folds of the tropopause (133-135).

157. The concept of stratospheric mean residence time has been thoroughly discussed in the 1964 report of the Committee. It is defined as the average time spent by the radio-active debris in the stratosphere before it is transferred to the troposphere. Such a definition in no way implies that the material is well mixed within the stratosphere or that it is held up during the transfer to the troposphere (66).

158. The mean stratospheric residence time of radio-active debris produced by an explosion will depend on the explosion's altitude, latitude, and possibly its time of occurrence. Thus, fission products in lower polar stratosphere may have a mean residence time of six months or less, while debris from medium-altitude explosions has mean residence times of perhaps two to three years (300). At much higher altitudes (over 100 km) as illustrated by the ^{102}Rh experiment, the residence time increases to 5 or 10 years (307, 308, 356, 584). The mean residence time for ^{90}Sr is 1.1-1.2 years (122, 167, 337, 629) and seems to be fairly constant for all northern latitudes (167). For excess ^{14}C in the stratosphere the apparent half residence time is between two and five years (605).

(c) *Movement within the troposphere*

159. Once the radio-active debris enters the troposphere it is mixed fairly rapidly within the hemisphere

of entry since mixing by eddy diffusion and convection is much more rapid in the troposphere than in the stratosphere. In the meridional plane there are two circulation cells within each hemisphere, as shown in figure XII. The tropical cells are well developed, with air rising in equatorial regions and descending into the 20°-30° latitude region. The two cells at higher latitudes are weaker with descending air at latitudes of 40°-50° and rising air at higher latitudes. At middle and higher latitudes large-scale eddies give rise to rapid meridional transport (614).

160. In the troposphere, the exchange of particulate radio-activity across the meteorological equator is impeded for two reasons. In the first place the convergence of low-altitude air currents (figure XII) tends to keep air in the same hemisphere and also retards the exchange of gases. The second reason is the scavenging of particulates by showery precipitation in the convergent zone (614). However, several investigators have reported interhemispheric transport of tropospheric nuclear debris from southern to northern hemisphere (97, 98, 172, 216, 448, 522, 523, 542, 574) and vice versa (115, 349, 413, 651).

161. Meridional circulation seems to constitute the main mechanism responsible for this transport. The mean exchange time between hemispheres, defined as the mean time spent in the northern hemisphere by a molecule of air before transfer to the southern hemisphere and vice versa, was estimated from various gaseous tracer experiments to be about 1.5 years (614).

162. The mean residence time of nuclear debris in the troposphere is estimated to be about 30 days (96, 387, 586). Evidence suggests that particulates reside in the lower, rain-bearing, layers of the atmosphere for a period of the order of five days or less (382, 387, 402).

163. A model for predicting the atmospheric content of radio-active material has been worked out by Krey and Krajewski (337). The atmosphere of each hemisphere is divided into three compartments, i.e. the atmosphere above 21 kilometres, that below 21 kilometres, and the troposphere. Transfer between compartments follows first-order kinetics and the transfer constants used are: from above 21 kilometres to the lower stratosphere 0.116 month⁻¹, from the lower stratosphere to the troposphere 0.0693 month⁻¹ and from the troposphere to ground level 0.693 month⁻¹. The debris from an injection well above 21 kilometres is equally partitioned between the hemispheres while for debris injected into the lower stratosphere there is a dynamic exchange between the hemispheres with a transfer constant of 0.0116 month⁻¹. Using this model Krey and Krajewski (337-339) have calculated stratospheric inventory, surface air concentration and deposition and found good agreement with measurements.

(d) Deposition

164. Mechanisms of deposition were discussed in some detail in the Committee's 1964 report. After entering the troposphere from above, fission products are transported down to the level of the rain-bearing clouds mainly by turbulent mixing. This downward movement is enhanced over anti-cyclonic systems and opposed over cyclonic systems (134). Below this level, the radio-active particles are rapidly washed out by precipitation and deposited upon the earth (346). In addition, dry removal of fission products takes place

through several mechanisms. Dry removal by sedimentation requires particles to be larger than about five micrometres and is important only in local fall-out. Dry deposition of world-wide fall-out makes an important contribution to the total fall-out only in areas of low rainfall.

165. Fission products can enter rain-water by processes within the cloud, the so-called rain-out, or can be picked up by raindrops below the cloud, the so-called wash-out. For aerosols of small particle size the wash-out is relatively quite slow so that rain-out is probably the most important wet-deposition process (164, 301). The small contribution of wash-out processes to total deposition probably accounts for the fact that the activity of fission products in ground-level air does not seem to be greatly influenced by precipitation rates (162, 381, 619).

2. Internal irradiation

(a) Tritium

166. Eriksson (165) estimated that 1,900 megacuries of tritium were released into the atmosphere by tests up to 1963, most of them into the northern hemisphere. The dose commitment can be calculated using the relation,

$$D_p(\infty) = \gamma_0 \frac{W}{B}$$

where γ_0 is the dose rate from natural tritium, W is the amount of artificial tritium released into the atmosphere and B is the amount of natural tritium produced annually. The dose rate due to natural tritium of 0.6-2.5 $\mu\text{rad y}^{-1}$ results from an annual production of 1.6 megacuries, that is 0.8 megacurie in each hemisphere (paragraphs 60 and 62). By assuming that all the bomb-produced tritium remains in the northern hemisphere we obtain an upper limit to the dose commitment. This will be in the range 0.6 10^{-3} (1900/0.8) = 1.4 and 2.5 10^{-3} (1900/0.8) = 5.9 millirads. If it is assumed that there is rapid (compared with the half-life) mixing of tritium between hemispheres, a lower limit to the dose commitment is obtained. This is in the range of 0.6 10^{-3} (1900/1.6) = 0.7 and 2.5 10^{-3} (1900/1.6) = 3.0 millirads. Since the movement of tritium from one hemisphere to another appears to be fairly slow the true dose commitment should be closer to the upper limit. In this report, the values used as dose commitments to the populations of the northern and of the southern hemisphere are four and one millirads, respectively.

(b) Carbon-14

167. The activity of ¹⁴C in the CO₂ of tropospheric air of the northern and southern hemispheres is shown in figure XIV, where the ¹⁴C concentrations of surface ocean waters are also shown (464, 518, 614). During 1968-1969, levels in both hemispheres remained fairly constant at about 60 per cent above normal, the ¹⁴C that moved into the oceans having been replenished by the nuclear tests in 1968. The activities in surface ocean waters have risen much less than was expected and now appear to be decreasing.

168. This observation may indicate a much more rapid exchange of ¹⁴C between the surface and deep

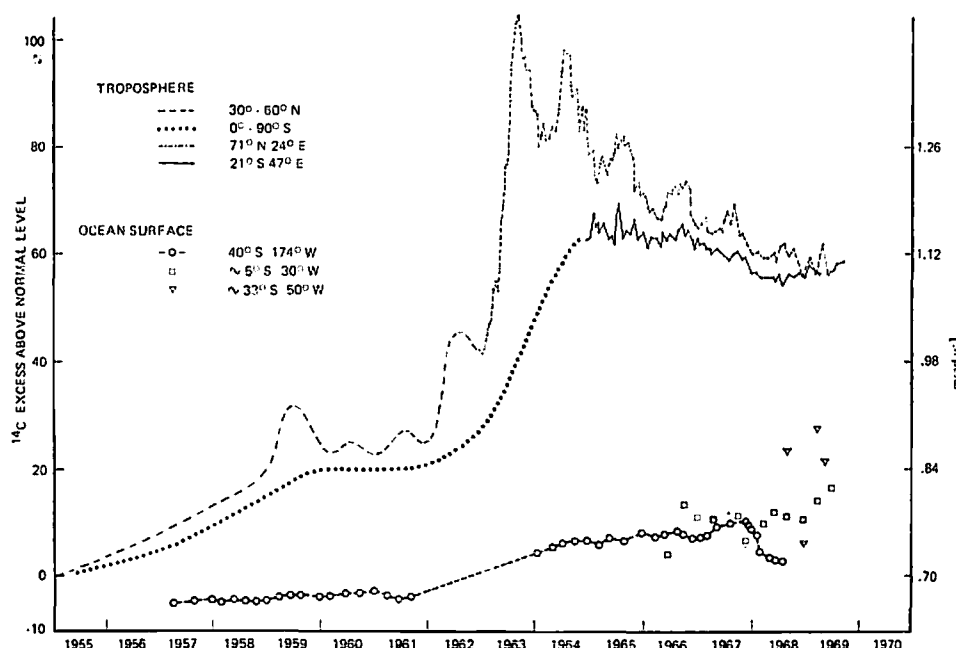


Figure XIV. Radio-carbon in the troposphere and surface ocean (464, 518, 614)

ocean than was originally predicted (518). However, the situation is not simple since the ^{14}C activity of surface ocean waters varies considerably with latitude. The value of the exchange time with the deep ocean will directly affect that part of the dose commitment from ^{14}C delivered up to the year 2000, but at this time there are not enough new data to warrant changing the estimates made by the Committee in its 1969 report.

169. Fairhall *et al.* (168) estimated that the total ^{14}C inventory from atmospheric tests was 6.2 megacuries compared to a steady state natural inventory of 280 megacuries (paragraph 64). Using the dose rates for natural ^{14}C from paragraph 67, the dose commitments, calculated in the same way as for ^3H , are 140 millirads to soft tissue and 170 millirads to endosteal cells.

170. Because of the long half-life of ^{14}C most of the dose commitment is delivered over a period of thousands of years. That part of the dose commitment that will be delivered up to the year 2000 can be estimated from models representing the exchange of ^{14}C between the atmosphere, the ocean and the biosphere (614, 616). The estimates calculated in the same way as in the 1969 report are 12 millirads to the gonads and bone marrow and 15 millirads to cells lining bone surfaces.

(c) Iron-55

171. Iron-55 is almost exclusively man-made and has been one of the major contributors to radioactivity in fall-out since the 1961-1962 series of nuclear tests. This radio-nuclide, which decays by electron capture into ^{55}Mn with a half-life of 2.6 years, is most probably produced from the stable ^{54}Fe isotope by thermal neutrons through the $^{54}\text{Fe} (n, \gamma)$ nuclear reaction and from the stable ^{56}Fe isotope by fast neutrons through the $^{56}\text{Fe} (n, 2n)$ reaction. The total production of ^{55}Fe from tests was estimated as 50 megacuries (248). Its activity in surface air was monitored from 1964 to 1970 at 22 sites in North and South America. Activity fell from about 500 fCi m^{-3} in 1964 to a few femtocuries per cubic metre in 1970 (633).

172. The two main routes of ^{55}Fe intake by humans are the terrestrial food chain from plant to animal to man and the marine food chain from sea-water to fish to man (280, 473). Ocean fish contains a higher concentration of ^{55}Fe than most other food-stuffs (473, 656). In man ^{55}Fe concentrates in the red blood cells, which contain 65 per cent of the body burden (280) although higher concentrations are present in haemosiderin and ferritin—two proteins that store iron (503). The body burden of many people in different parts of the world was determined in 1966 and in 1969; most of the results, which were in the range 20-30 nanocuries in 1966 (473), dropped to the 1-10 nanocuries range in 1969 (352). At Richland, in the United States, the body burden of ^{55}Fe in adults reached a peak level of about 20 nanocuries in January 1967, then started to decrease (474, 475).

173. In Alaska (United States) and in Japan, among people consuming large quantities of fish, body burdens higher than 1,000 nanocuries were observed in 1966 (473), but in 1969 ^{55}Fe in Alaskan fish-eating natives was only 10 times higher than in Richland residents and its level was declining at a more rapid rate, reflecting the much higher turn-over rate of iron in the marine biosphere (351).

174. A body burden of 30 nanocuries leads to annual doses of 1 millirad to red blood cells, 0.5 millirad to the whole blood, 0.15 millirad to the gonads and the cells lining bone surfaces, 0.08 millirad to the red bone marrow and 0.06 millirad to the whole body (503). The dose commitments in the northern hemisphere due to nuclear testing in the period 1954-1962 were estimated by Persson (503). Assuming a maximum body burden of 30 nanocuries in the temperate latitudes, the estimates are 1 millirad to the gonads and bone-lining cells and 0.6 millirad to the bone marrow. A reduction by a factor of four is assumed for the southern hemisphere.

(d) Krypton-85

175. The amount of ^{85}Kr produced by atmospheric nuclear explosions can be estimated at about three

megacuries from the ^{90}Sr production (discussed in paragraphs 178-182) and the $^{85}\text{Kr}/^{90}\text{Sr}$ fission-yield ratio of about 0.06. Since the greatest production occurred in 1961-1962, radio-active decay has resulted in about half the total production remaining in the atmosphere in 1970.

176. Krypton-85 is a beta emitter (maximum energy 670 keV). In 0.4 per cent of the disintegrations, it also emits a gamma photon whose energy is 514 keV. Table 22 indicates the annual doses received by an individual immersed in a cloud of ^{85}Kr with an activity concentration of 1 pCi m^{-3} . By external irradiation, beta rays deliver a dose to the skin and to the subcutaneous tissues only, while the gamma radiation is responsible for whole-body and gonad doses (149, 241). Internal irradiation also occurs as a result of inhalation; lung is then the most exposed organ, and fatty tissues receive higher doses than blood and muscle because of

the greater solubility of krypton in fat than in water (610, 648). From the biological viewpoint, the dose to the gonads from external irradiation (17 nrad y^{-1} per pCi m^{-3}) is the most significant and the internal doses are comparatively negligible.

177. The distribution of ^{85}Kr being almost homogeneous over the surface of the globe and throughout the troposphere (paragraph 396), the estimated three megacuries produced by atmospheric tests correspond to a dose commitment to the gonads of about 0.2 microrad.

(e) Radio-strontium

(i) Inventory

178. The stratospheric inventory of ^{90}Sr in both hemispheres increased temporarily after the tests in 1967, 1968, 1969 and 1970 (figure XV) (340). Apart

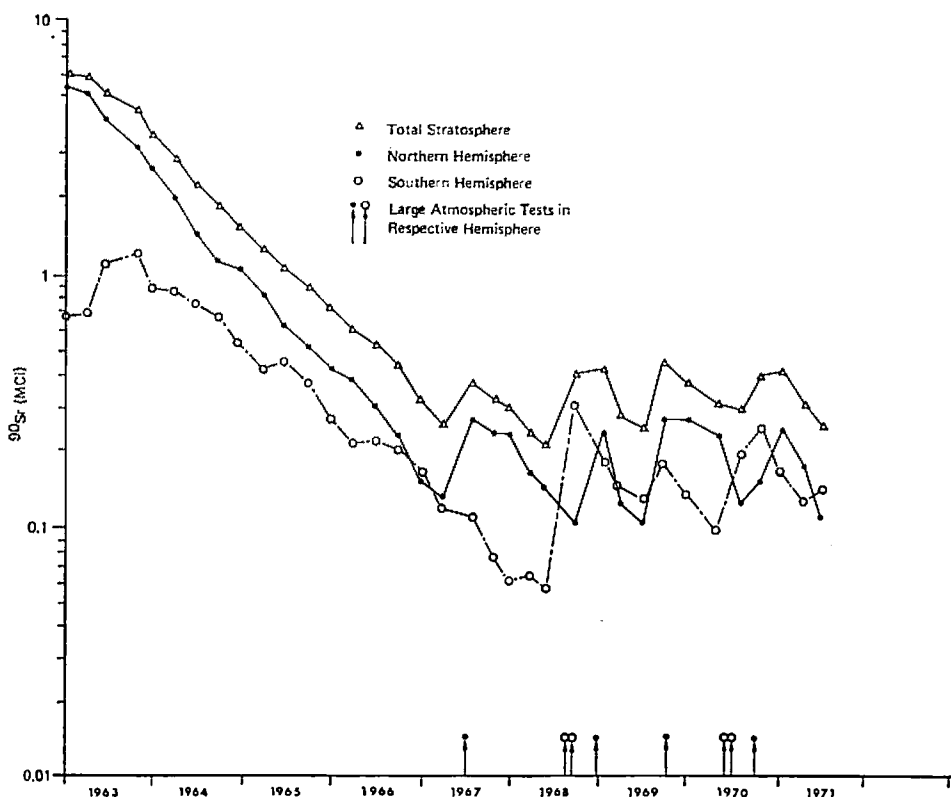


Figure XV. Stratospheric inventory of ^{90}Sr in the northern and southern hemispheres (341)

from those peaks, however, there has not been much change in the stratospheric inventory of ^{90}Sr since 1967 (table 23), the level being maintained relatively steady by the atmospheric nuclear tests carried out during the last three years. In February 1971 the inventories in the stratospheres of the northern and southern hemispheres were estimated to be 0.29 and 0.16 megacurie, respectively, most of this being due to recent tests (340).

179. The annual and cumulative deposition of ^{90}Sr in the northern and southern hemispheres are shown in table 24 for the years 1958 through 1970 (634). The global deposition in 1970 was not much greater than in 1967, 1968 and 1969, reflecting a relatively constant stratospheric inventory. The monthly deposition of ^{90}Sr in both the northern and the southern

hemispheres is shown in figure XVI and the cumulative deposit for both the northern and southern hemispheres for the years 1958 through 1970 are shown in figure XVII. Measurements of the $^{80}\text{Sr}/^{90}\text{Sr}$ ratio in precipitation in the northern hemisphere gave values between one and nine for most of 1969, indicating that much of the radio-strontium was due to recent tests (99, 100, 228). In 1969 the ^{90}Sr deposition was about equally divided between the hemispheres. This is the first time that the annual fall-out in the southern hemisphere has been equal to or greater than that in the northern hemisphere (631). However, the southern hemisphere deposition in 1969-1970 was only about half that recorded in the years 1962-1965 in spite of the recent tests there (634). It can be seen from tables 23 and 24 that the global cumulative deposit of ^{90}Sr has changed little over the last few years, the annual deposition

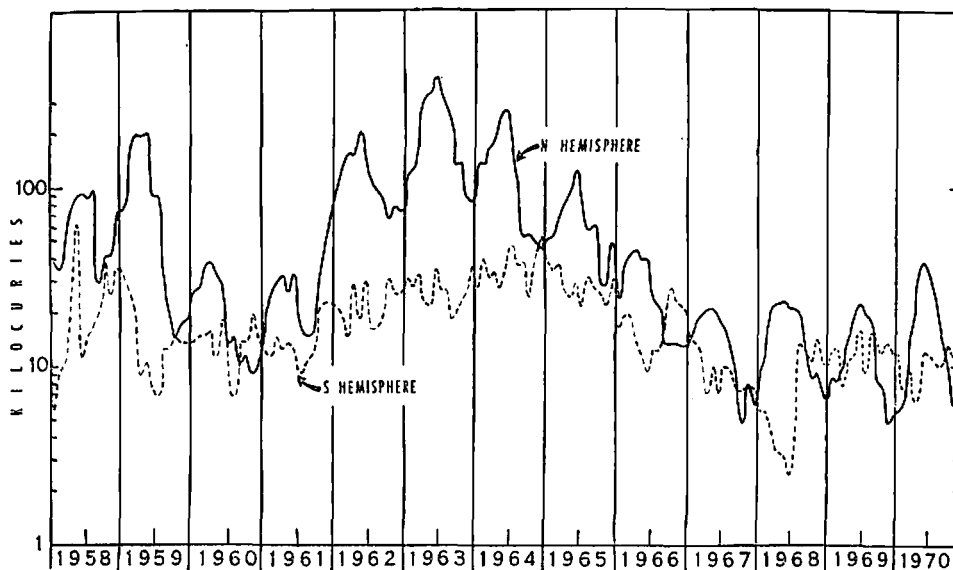


Figure XVI. Monthly ^{90}Sr deposition (634)

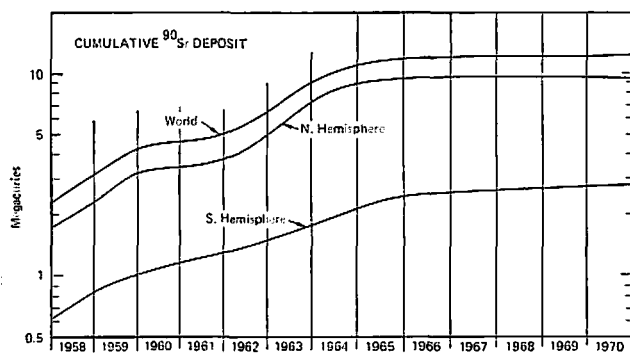


Figure XVII. Cumulative ^{90}Sr deposits (634)

being just sufficient to compensate for ^{90}Sr that has decayed on the ground.

180. It has been estimated that by mid-1969 about 70 per cent of the ^{90}Sr in the surface air of the northern hemisphere was contributed by the tests in central Asia carried out on 27 December 1968. In the southern hemisphere in mid-1969, 75 per cent of the ^{90}Sr activity in surface air is ascribed to the September tests in the south Pacific (99). The global deposition of ^{90}Sr as deduced from the measurements of the United Kingdom network showed that at the end of 1970 the cumulative deposit was 12.4 megacuries and the annual deposit for 1970, 0.21 megacurie (101). The deposition over the world was calculated by integrating the latitudinal distribution of ^{90}Sr concentration in rain weighted by the distribution of rainfall. Much of the United Kingdom data for 1968 was derived from ^{137}Cs measurements using a mean $^{137}\text{Cs}/^{90}\text{Sr}$ ratio of 1.56. These results agree with those reported from the United States network based on ^{90}Sr measurements (table 24). Traces of debris from the 1968 south Pacific tests have been detected (488) as far north as Bombay (India), Hongkong, Chilton (United Kingdom) and International Falls, Minnesota (United States).

181. In table 25 the annual deposition and average concentration of ^{90}Sr in rain is shown for four United States weather stations in the north Atlantic and also for five continental stations and for four island stations.

The annual deposits at each weather station were estimated by dividing the measured deposit by the fraction of the year for which collections were made. Neither the annual deposits nor the average annual concentrations of ^{90}Sr appear to be significantly different on the weather ships and small islands than on the land-based stations. As in previous reports of the Committee, it is assumed that there is no difference between deposition over the oceans and over land.

182. In table 26 are shown the latitudinal distribution of the world's population and of the fall-out of ^{90}Sr and of ^{89}Sr . In order to compute doses to populations it is convenient to know the population-weighted deposition. These have been computed from the data in table 26 and are shown in table 27 for the northern and southern hemispheres.

183. *Strontium-89*. Since ^{89}Sr fall-out is a good indicator of the activity of other short-lived fission products, some deposition data are included in order to extrapolate external doses from the short-lived fission products. The latitudinal distribution of the integrated deposit of ^{89}Sr from 1961 to 1969 given in table 26 indicates that the general shape of the distribution in the northern hemisphere is much the same as that of ^{90}Sr (228). In table 27 are shown the global and the northern and southern hemispheric population-weighted estimates of deposition of ^{89}Sr . The annual deposition in each hemisphere from 1961 to 1969 is shown in table 28.

(ii) Levels in food

184. The annual ^{90}Sr activities of milk during 1966 through 1971 are shown in table 29. Average $^{90}\text{Sr}/\text{Ca}$ ratios in milk of the north temperate latitudes are given in table 30. The rapid reduction in activity observed between 1964 and 1967 has now ceased, there being only a small change in activity between 1968 and 1971. This probably reflects the fact that during the last few years the ^{90}Sr in milk is attributed largely to the cumulative deposit in soils which at present is changing only slowly with time (32, 51).

185. The $^{90}\text{Sr}/\text{Ca}$ ratios in total diet are shown in table 31 for the years 1966 through 1971. As with

milk, there has been little change in the levels between 1968 and 1971. The ratios of $^{90}\text{Sr}/\text{Ca}$ in total diet to that in milk are shown in table 32. Variations within individual countries are apparent, and even greater variations are noted between different countries, particularly between those with different diet types. As shown by Aarkrog (2) and Bennett (51), the relative contribution of ^{90}Sr from different components of the diet, milk, grain products, vegetables, meat, etc., has been changing with time. Changes in the diet-milk ratio are thus expected, particularly following changes in ^{90}Sr deposition, but the ratio should stabilize at later times. From the ratios given in table 32, it appears that an approximate mean constant diet-milk ratio of 1.4 will be an appropriate, useful relationship.

(iii) Transfer from deposit to food

186. A mathematical formalism to account for the transfer of deposited radio-activity to diet and the transfer from diet to the human body was developed in the Committee's 1969 report. The transfer coefficient from fall-out to diet is defined as

$$P_{23} = \frac{IC}{IF_r}, \quad (5)$$

where IC is the integrated level of the radio-nuclide in diet,

$$IC = \int_{-\infty}^{\infty} C(t) dt, \quad (6)$$

and IF_r is the integrated deposition of that radio-nuclide,

$$IF_r = \int_{-\infty}^{\infty} F_r(t) dt. \quad (7)$$

187. The activity in diet at time t , $C(t)$ can be related to the deposition at time τ , $F_r(\tau)$ by the relation

$$C(t) = \int_{-\infty}^t K(t, \tau) F_r(\tau) d\tau, \quad (8)$$

which serves to define the deposit-to-diet transfer function $K(t, \tau)$. In practice data are available on a monthly or annual basis so that the integral in (8) is replaced by a sum, so the activity in diet in year n is given by

$$C(n) = \sum_{i=-\infty}^i K(n, i) F_r(i) \quad (9)$$

where $F_r(i)$ is the deposition in year i . If it is assumed that the weighting function $K(n, i)$ only depends upon the elapsed time ($m = n - i$) since deposition, the integrated dietary level over infinite time is then,

$$\begin{aligned} IC &= \sum_{n=-\infty}^{\infty} C(n) = \sum_{n=-\infty}^{\infty} \sum_{i=-\infty}^i K(n-i) F_r(i) \\ &= \sum_{i=-\infty}^{\infty} \sum_{n=i}^{\infty} K(n-i) F_r(i) \\ &= \sum_{m=0}^{\infty} K(m) \sum_{i=-\infty}^{\infty} F_r(i) \\ &= IF_r \sum_{m=0}^{\infty} K(m). \end{aligned} \quad (10)$$

Thus the transfer coefficient P_{23} is given by

$$P_{23} = \sum_{m=0}^{\infty} K(m). \quad (11)$$

188. In the 1962, 1964 and 1966 reports of the Committee, the following form of transfer function $K(m)$ was used,

$$K(m) = p_r \delta_m + p_d \exp(-\lambda m) \quad (12)$$

where

$$\begin{aligned} \delta_m &= 1, \quad m = 0 \\ \delta_m &= 0, \quad m \neq 0 \end{aligned}$$

Thus the level in diet during year n is

$$\begin{aligned} C(n) &= \sum_{m=0}^{\infty} p_r \delta_m F_r(n-m) + p_d F_r(n-m) \exp(-\lambda m) \\ &= p_r F_r(n) + p_d F_d(n) \end{aligned} \quad (13)$$

where λ is the physical decay constant of ^{90}Sr and $F_d(n)$ the cumulative deposition up to year n . This type of transfer function has been widely used to relate the ^{90}Sr activity in national milk supplies to deposition in previous years. Bartlett (32) found that equation 13 did not adequately fit the United Kingdom data and therefore proposed a relationship of the type

$$\begin{aligned} C(n) &= p_1 F_r(n) + p_2 F_b(n-1) \\ &\quad + p_3 [F_a(n-1) \exp(-1.25\mu) \\ &\quad + \sum_{m=2}^{\infty} F_r(n-m) \exp(-\mu m)] \end{aligned} \quad (14)$$

where $F_a(n)$ and $F_b(n)$ are the deposition in the first and second half of year n , respectively, and μ is a decay constant which combines the physical decay of ^{90}Sr and any increasing unavailability of ^{90}Sr in the soil to plants, which is assumed to be exponential.

189. Since most of the food levels in the world have been reported on a calendar-year basis a relationship of the form

$$\begin{aligned} C(n) &= p_1 F_r(n) + p_2 F_r(n-1) \\ &\quad + p_3 \sum_{m=2}^{\infty} F_r(n-m) \exp(-\mu m) \end{aligned} \quad (15)$$

can be used in an attempt to accommodate the effect of food storage from one year to the next.

190. In fitting by least squares the transfer functions of equations 14 and 15 to milk and deposit data, all the parameters p_1 , p_2 , p_3 , and μ are allowed to vary. Bartlett (32) found that equation 14 gave an excellent fit to the United Kingdom data and obtained a shorter mean residence time in soil of 6.7 years. On the other hand, when both equations are fitted to the data of New York and Denmark, equation 15 gives a better fit. The average $^{90}\text{Sr}/\text{Ca}$ ratios in milk for the northern hemisphere have also been fitted to the fall-out data for the 30°-50° N latitude band using equation 15. The estimates of the parameters thus obtained, together with the value of P_{23} computed from equation 11, are shown in table 33. The values of μ obtained indicate that the effective mean life of ^{90}Sr in soil is between 7 and 10 years which is smaller than reported in earlier Committee reports; however, several more years of

data will be required to determine μ with greater confidence. The fits obtained with data from a number of

areas and with the pooled data from the northern hemisphere are shown in figure XVIII.

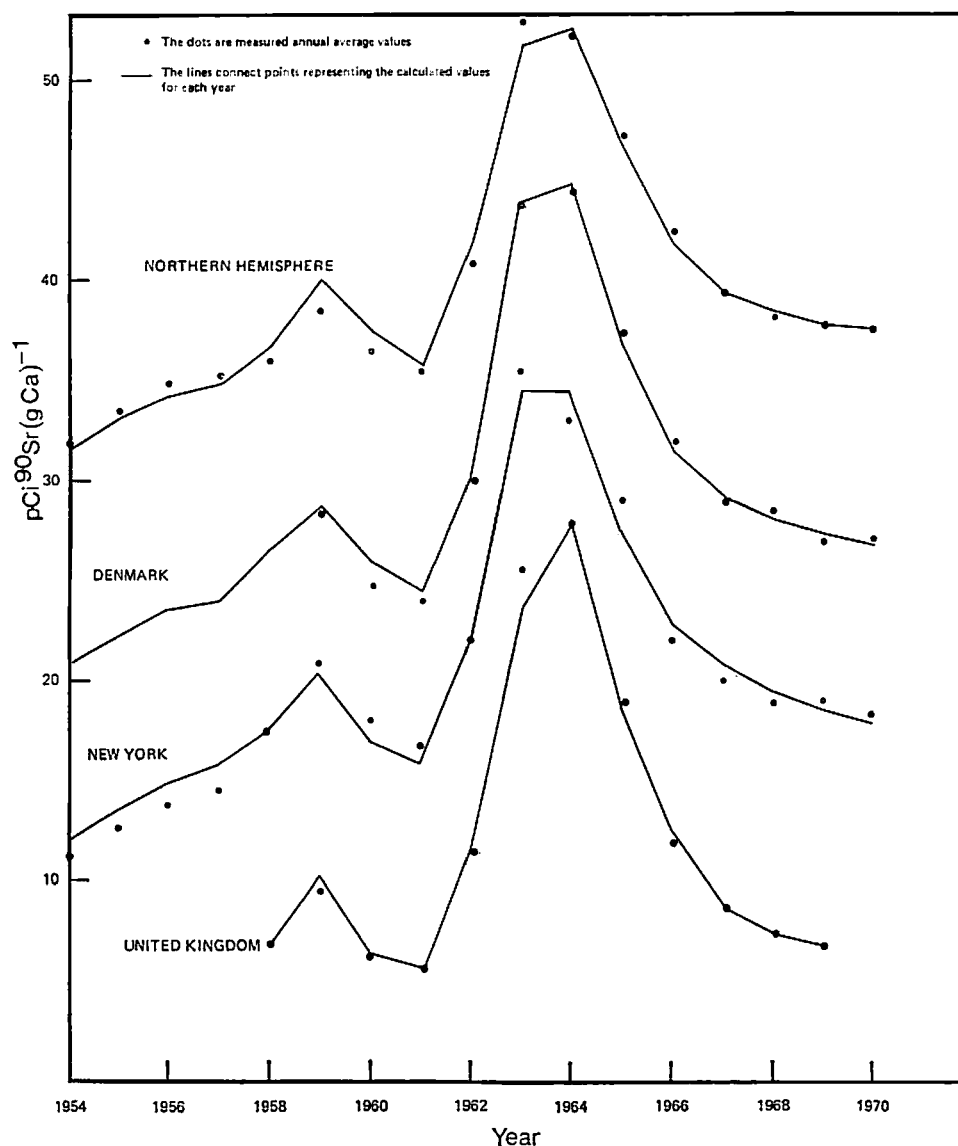


Figure XVIII. Measured and calculated annual average $^{90}\text{Sr}/\text{Ca}$ ratios in milk. The calculated results are based upon deposition data. Equation 15 was used for all results except for those of the United Kingdom for which equation 14 was applied. The curves for New York (USA), Denmark and the northern hemisphere are displaced upwards by 10, 20 and 30 divisions, respectively, for clarity

191. In 1970 the $^{90}\text{Sr}/\text{Ca}$ level in milk in the northern hemisphere was $7.4 \text{ pCi (gCa)}^{-1}$ and the corresponding integrated level $161 \text{ pCi y (gCa)}^{-1}$ (table 30). Assuming an effective mean life in the soil of 10 years (table 33, northern hemisphere) the estimated future integrated level in milk is $74 \text{ pCi y (gCa)}^{-1}$ giving a total integrated level in milk of $235 \text{ pCi y (gCa)}^{-1}$. With an integrated deposition ($40\text{--}60^\circ \text{N}$) up to 1970 inclusive of 80 mCi km^{-2} (table 26) a value of 2.9 is obtained for the deposit-to-milk transfer coefficient P_{23} (milk). From table 33 we can assign a lower limit to the mean life in the soil of 5.5 years, while the upper limit is 40 years. Using these values one obtains lower and upper limits to P_{23} of 2.5 and 5.7. A value of 5 was used in the 1969 report of the Committee. In this report a value of 3.2 is taken (table 33)

for the purposes of computing dose commitments. The deposit-to-diet transfer coefficient is obtained from the corresponding value for milk by multiplying by 1.4, resulting in $P_{23}(\text{diet}) = 4.5 \text{ pCi y (gCa)}^{-1}$ per mCi km^{-2} . The value of this factor is based upon data from countries in northern temperate latitudes which have a western type diet. It may be different for other types of diet or in other geographical regions. However, since there are few data from other regions, the value of 4.5 will be assumed to apply globally, for the purposes of computing doses.

(iv) Levels in bone

192. New data on ^{90}Sr in bone are shown in table 34, including results from the limited bone-sampling programme undertaken by the World Health Organiza-

tion. A definite variation with age in the ^{90}Sr levels in bone appears up to the age of 20 years, values being higher between one and four years. The relative uniformity of levels in adult bone compared to the

variability in deposition of ^{90}Sr must be noted and will be worth detailed consideration when samples from a few further areas are received by the WHO. Table 35 and figure XIX show the time trends of ^{90}Sr levels in

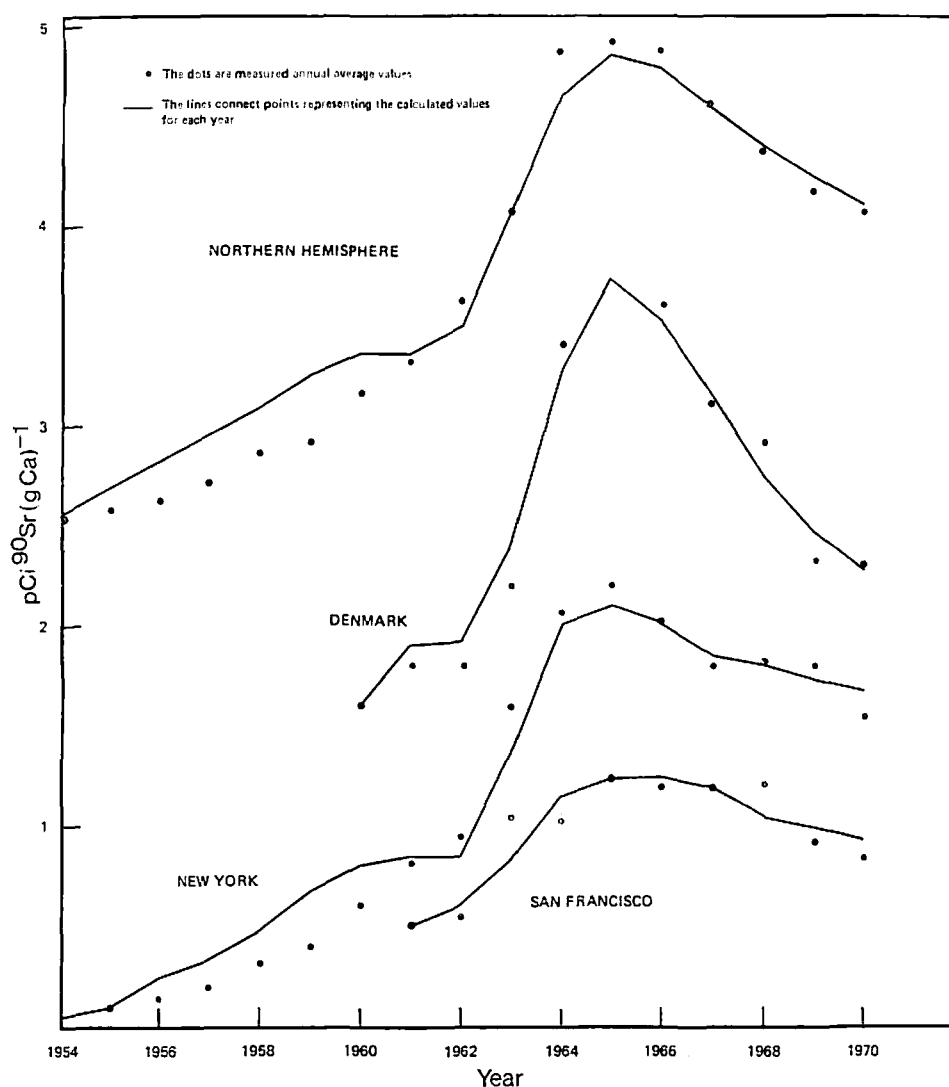


Figure XIX. Measured and calculated annual average $^{90}\text{Sr}/\text{Ca}$ ratios in human adult vertebrae. The calculated values were obtained using equations 26 and 30. For Denmark, New York and San Francisco, the activity of ^{90}Sr in bone was computed from that in total diet but for the northern hemisphere it was computed from the activity of ^{90}Sr in milk. For the sake of clarity the Danish and northern hemisphere results have been displaced upwards by 1 and 2.5 divisions, respectively

adult vertebrae in the northern hemisphere. In general levels have continued to decrease since 1965.

193. Beninson (46) has reported both stable strontium and ^{90}Sr measurements on the bones of a large number of persons whose age at death varied from 0 to 30 years. He found the ratio of stable strontium to calcium in bone to be fairly constant from 1 to 30 years. Much of the variation with age of the $^{90}\text{Sr}/\text{Ca}$ ratio in bone can be attributed to differences in turnover rate which, as has been shown by Beninson (46) and Bennett (50), varies significantly with age. This turnover rate is highest in infants under 1 year of age, falls to a minimum about age 4 years, then rises to a maximum at 8-10 years and then falls again, remaining constant above the age of 20 years.

194. The ratio of ^{90}Sr in vertebrae to that in femoral diaphyses has been determined for adults in Czechoslovakia, where the average value for 51 samples was 2.28 ± 0.22 in 1969 (77) compared with 2.68 ± 0.31 in 1968 (76). In Moscow the corresponding figures were 2.30 ± 0.06 and 2.38 ± 0.04 for 1968 and 1969, respectively (674). When these figures are compared with those reported in the 1969 report it is evident that the ratio has decreased considerably since 1965. In Czechoslovakia the 1969 ratio in males (2.36) appears to be significantly greater than in females (2.06) as was also the case in 1968.

(v) Transfer from food to bone

195. The transfer coefficient P_{34} is defined as

$$P_{34} = \frac{IQ}{IC} \quad (16)$$

where $IQ = \int_{-\infty}^{\infty} Q(t)dt$ and $IC = \int_{-\infty}^{\infty} C(t)dt$

where $C(t)$ is the average $^{90}\text{Sr}/\text{Ca}$ ratio in diet and $Q(t)$ is the population-weighted ^{90}Sr ratio in bone at time t .

196. In the Committee's earlier reports P_{34} was determined using a model developed by Lindell (363). In the 1969 report, P_{34} was estimated from observed levels in bone through the relation

$$P_{34} = (G_t + H_t)/C_t \quad (17)$$

where C_t is the integrated dietary level of ^{90}Sr up to time t ,

$$C_t = \int_{-\infty}^t C(t')dt', \quad (18)$$

and G_t is the integrated level in human bone up to time t averaged over all age groups

$$G_t = \frac{1}{70} \int_{-\infty}^t \int_0^{70} S(t', u) du dt' \quad (19)$$

where $S(t', u)$ is the level in bone at time t' for a person of age u and 70 is the average life span expressed in years. The quantity H_t is the integrated future level in bone due to ^{90}Sr already deposited there, also averaged over all age groups, or

$$H_t = \frac{1}{70} \int_0^{70} S(t, u'') W(u'') du'' \quad (20)$$

where

$$W(u'') = \int_{u''}^{70} \frac{B(u'')}{B(u)} \exp[-k_1(u - u'')] du \quad (21)$$

where $B(u)$ is the mass of calcium in the skeleton at age u , k_1 is the turnover rate of ^{90}Sr in bone. $W(u'')$ is called the integral weighting function. In 1969 about 40 per cent of P_{34} was due to the H_t term. A value of 0.1 y^{-1} was used for k_1 in the 1969 report. Any uncertainty in k_1 will give rise to errors in the estimate of P_{34} .

197. If $Q(t, u)$ is the activity in bone in a cohort of the population whose age at time t is u , then

$$Q(t, u) = \int_{-\infty}^t C(\tau) m(t, \tau, u) d\tau, \quad (22)$$

this equation defines the transfer function $m(t, \tau, u)$ (616). If the transfer function depends only on the time ($v = t - \tau$) elapsed since dietary intake, then

$$\int_{-\infty}^t C(\tau) m(t, \tau, u) d\tau = \int_0^{\infty} C(t-v) m(v, u) dv$$

Assuming a steady population with $N(u)$ people of age u and

$$N = \int_0^{70} N(u) du,$$

the activity in bone averaged over all age groups is

$$\begin{aligned} Q(t) &= \frac{1}{N} \int_0^{70} du \int_{-\infty}^t N(u) C(t-v) m(v, u) d\tau \\ &= \int_0^{\infty} C(t-v) dv \frac{1}{N} \int_0^{70} N(u) m(v, u) du \\ &= \int_0^{\infty} C(t-v) K(v) dv \end{aligned} \quad (23)$$

Therefore $K(v)$ represents a population-weighted transfer function. Now,

$$\begin{aligned} IQ &= \int_{-\infty}^{\infty} Q(t) dt = \int_{-\infty}^{\infty} dt \int_0^{\infty} C(t-v) K(v) dv \\ &= \int_0^{\infty} K(v) dv \int_{-\infty}^{\infty} C(t) dt = IC \int_0^{\infty} K(v) dv \end{aligned} \quad (24)$$

so that

$$P_{34} = \int_0^{\infty} K(v) dv \quad (25)$$

198. In practice, because the dietary and bone data are available on an annual basis, the integrals in equations 23 and 25 are replaced by sums

$$Q(n) = \sum_{m=0}^{\infty} C(n-m) K(m), \quad (26)$$

$$P_{34} = \sum_{m=0}^{\infty} K(m) \quad (27)$$

where $Q(n)$ is the ^{90}Sr level in bone in year n and $C(m)$ is the dietary level in year m .

199. In attempting to fit the adult bone data with a simple equation, the following types of transfer functions were tested on the New York bone-diet strontium data:

$$(a) \text{ exponential } g \exp(-\mu m) \quad (28)$$

$$(b) \text{ double exponential } c \exp(-\nu m) + g \exp(-\mu m) \quad (29)$$

$$(c) \text{ rate term + exponential } c \delta_m + g \exp(-\mu m) \quad (30)$$

$$(d) \text{ power function exponential } g(m+1)^{-b} \exp(-\mu m) \quad (31)$$

The simple exponential function is equivalent to the model used by Rivera and Harley (530) for adult bone. The rate term + exponential is equivalent to the model used by Coulon and Madelmont (124) when applied to adult bone. According to Coulon and Madelmont, the rate term in their model accounts for that part of strontium in bone which is in rapid exchange with that in plasma. The power function exponential model has been found by Marshall *et al.* (401) to give good fits to bone ^{90}Sr levels after a single exposure.

200. All parameters c , g , b , ν and μ were allowed to vary in the least squares fit. The best fit was obtained

with the rate term plus exponential function and in fact the double-exponential reverted to this latter model since the value of ν obtained was greater than 12 y^{-1} and all the other parameters were the same. The parameters obtained by a least-square fit of the rate term + exponential model to the diet-bone data of New York, San Francisco, Denmark and the northern hemisphere are shown in table 36. Also shown in table 36 are parameters obtained from the British data, using an exponential model to fit the ^{90}Sr in vertebræ (478). The northern hemisphere diet data were obtained by multiplying the milk levels given in table 30 by 1.4. The fits obtained for these three sets of data are shown in figure XIX. Since the data for the northern hemisphere are of a composite nature, it is not surprising that the fit is not quite as good as for the New York and Danish data. It should be noted from table 36 that, although the estimates of the mean turnover rate in bone are different for the three sets of data, the values of P_{34} obtained are fairly constant. In general, if the uptake of strontium by bone is governed by linear pro-

cesses, then it might be expected that the integrated level in bone would be fairly independent of the turnover rate.

201. The least-square fit is not very sensitive to changes in μ , so the differences in μ shown in table 36 may not be significant. Marshall *et al.* (401), from a study of the retention by cancellous bone after a single injection of strontium, estimate μ to be 0.10 y^{-1} .

202. It is also possible to estimate P_{34} from the bone and diet data directly, using equations 17 through 21, as was done in the 1969 report of the Committee. The limitation here is that the turnover rate k_1 in bone must be pre-specified. Estimates of P_{34} were calculated for the years 1965 through 1970 assuming three different values of k_1 , notably 0.1, 0.3 and ∞ . The data were taken from table XIII of annex A of the 1969 report and tables 30 and 35 of the present report. The milk levels were multiplied by 1.4 to estimate the total diet levels. The three estimates of P_{34} are plotted against $C(t)/C_t$ in figure XX. The estimates of P_{34} are approximately constant for a turnover rate of

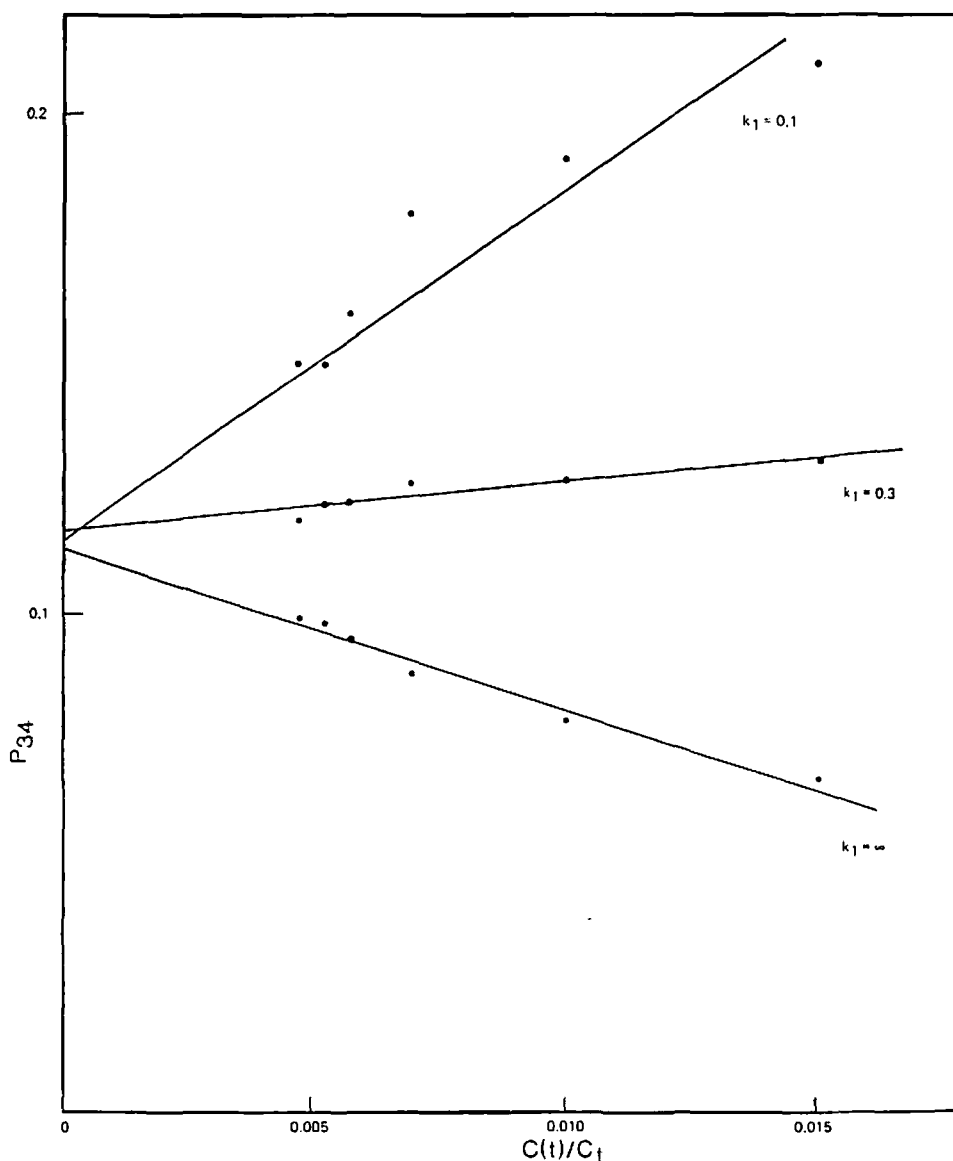


Figure XX. Values of P_{34} calculated from equation 17 assuming three different values of the turnover rate k_1 of strontium in bone. The $^{90}\text{Sr}/\text{Ca}$ ratios in human vertebræ and diet are for the northern hemisphere, 1965 to 1970

$k_1 = 0.3 \text{ y}^{-1}$, indicating that this turnover rate is about correct for the data. If straight lines are drawn through the three sets of points, they intersect the $C(t)/C_i = 0$ axis at about $P_{34} = 0.12$.

203. Thus these estimates of both the turnover rate and P_{34} are in agreement with those in table 36 for the northern hemisphere data. A value of 0.12 will be taken for P_{34} to compute the dose commitment from ^{90}Sr .

204. A transfer function P_{34} for stable strontium can also be determined by the same rate term + exponential model (equation 30) as used for ^{90}Sr . Since there is no radio-active decay, μ must be reduced by 0.025. If this is done for the parameters of the New York and San Francisco data shown in table 36, stable strontium values of P_{34} for New York and San Francisco of 0.14 and 0.18, respectively, are obtained. Rivera (529) reported values of 0.16 and 0.16, respectively, based upon stable strontium measurements in bone and diet.

(vi) Dose commitment from ^{90}Sr

205. For the purpose of dose estimation, it was previously assumed by the Committee that ^{90}Sr is uniformly distributed in the seven kilogrammes skeleton of standard man (616). Committee II of the ICRP has recently qualified the skeletal mass to include five kilogrammes of bone mineral in addition to cartilage and peri-articular tissue (401). Assuming the ^{90}Sr to be uniformly distributed only in bone mineral has the effect of increasing D_o , the dose rate per unit activity to a small tissue-filled cavity in bone. D_o is given by Spiers (577)

$$D_o = N_m \bar{E} (S_T/S_B)_m (K_B/K_T)$$

where $N_m = 1.17 \cdot 10^6 M^{-1} \text{ y}^{-1}$ per pCi (gCa) $^{-1}$ = number of beta particles emitted per picocurie of ^{90}Sr per gramme of calcium; $M = 5$, being the mass, in grammes, of mineral bone per gramme of calcium (401, 650); $\bar{E}$ = the effective energy of beta-rays emitted (1.13 MeV for $^{90}\text{Sr} + ^{90}\text{Y}$); $(S_T/S_B)_m$ = the ratio of the mass stopping powers in tissue and bone = 1.07 (52); K_B and K_T = factors allowing for the effect of scattering on the effective particle range, assumed to be unity here (163). So that $D_o = (1.17 \cdot 10^6 \cdot 1.13 \cdot 1.6 \cdot 10^{-5} \cdot 1.07)/5 = 4.5 \text{ mrad y}^{-1}$ per pCi (gCa) $^{-1}$.

206. Spiers (580) has re-estimated the values of D_m/D_o and D_s/D_o where D_m and D_s are the dose rates in bone marrow and endosteal cells, respectively, per unit activity in bone. The new values are:

	D_m/D_o	D_s/D_o
Cortical contribution	0.055	0.082
Trabecular contribution	0.260	0.352
TOTAL	0.315	0.434

Using these values we obtain:

$$P_{45} (\text{marrow}) = 4.5 \cdot 0.315 = 1.42 \text{ mrad per pCi y (gCa)}^{-1}$$

$$P_{45} (\text{endosteal cells}) = 4.5 \cdot 0.434 = 1.95 \text{ mrad per pCi y (gCa)}^{-1}$$

The values used in the Committee's 1969 report were 0.55 for doses to marrow and 1.1 for doses to endosteal cells.

207. The following values of the transfer coefficients are used:

$$P_{23} (\text{fall-out/diet}) = 4.5 \text{ pCi y (gCa)}^{-1} \text{ per mCi km}^{-2} \text{ (paragraph 191),}$$

$$P_{34} (\text{diet/vertebrae}) = 0.12 \text{ pCi y (gCa)}^{-1} \text{ per pCi y (gCa)}^{-1} \text{ (paragraph 203),}$$

$$P_{45} (\text{bone marrow}) = 1.42 \text{ mrad per pCi y (gCa)}^{-1} \text{ (paragraph 206),}$$

$$P_{45} (\text{endosteal cells}) = 1.95 \text{ mrad per pCi y (gCa)}^{-1} \text{ (paragraph 206).}$$

The deposition from ^{90}Sr from all tests to 1970 in the temperate zones is taken to be (tables 26 and 27)

Northern hemisphere	80.3 (58.4) ⁵ mCi km $^{-2}$
Southern hemisphere	22.1 (13.9) mCi km $^{-2}$

The resulting estimates of dose commitment are shown in table 37.

(f) Iodine-131

208. Eleven radio-active isotopes of iodine, most of them short-lived, originate in nuclear fission. Only ^{131}I , because of its half-life of eight days, is present in significant amount in the long-range tropospheric fall-out shortly after atmospheric nuclear detonations. Iodine-129 (half-life $1.6 \cdot 10^7$ years) is a negligible radiation hazard in fall-out as its activity is very low.

209. Iodine present in diet in soluble form is probably completely absorbed from the gastro-intestinal tract into the blood and is selectively concentrated in the thyroid gland. The stable iodine concentration in the thyroid tissue is of the order of 400 to 500 microgrammes per gramme of tissue while in the rest of the body it is much less than one microgramme per gramme (577). The mass of the thyroid is of the order of 20 grammes in the adults and about 10 times less in 0-1-year-old babies (144, 430). Consequently, young children receive a higher dose than adults from a given intake of radio-iodine. The dose to the whole body is of the order of a thousandth of that to the thyroid (36).

(i) Transfer to man

210. Ingestion and inhalation are the two principal modes of entry of ^{131}I into the body. The transfer to man by ingestion is complex as it depends on a variety of factors including meteorological conditions, agricultural practices and biological variability.

211. Radio-active fall-out is observed to circle the earth in 20-30 days on average (527) which is approximately the mean residence time of an aerosol in the troposphere. It is unlikely that during such a short period the clouds of debris become well mixed. The surface-air concentration of ^{131}I at a particular station will fluctuate according to meteorological conditions and will not necessarily be representative of a larger region nor of a latitude band (486).

212. Information on the physical and chemical nature of fall-out ^{131}I is very limited. In the United Kingdom, late 1961, an average 75 per cent of the activity was in particulate form, the rest being in the gaseous state (152), but in the United States in 1962 the particulate fraction was found to vary from 10 to 90 per cent (500). These large variations are thought to be

⁵ Figures in brackets refer to the whole hemispheres, the others to the northern and southern temperate zones (40°-60°).

due both to the origin of the fall-out and to the history of the air masses undergoing physical and chemical transformations during the travel.

213. Radio-iodine is deposited on the ground and on vegetation by dry and wet processes. The rate of dry deposition is characterized by the deposition velocity which, for ^{131}I fall-out, is of the order of $5 \times 10^{-3} \text{ m s}^{-1}$ (107). When precipitation occurs, ^{131}I is deposited at a much faster rate than in dry weather, essentially by rain-out, or in-cloud, mechanisms rather than by wash-out, or below-the-cloud, processes (614). For instance, during the period June-September 1970, owing to the frequent occurrence of rain in Cape Town, South Africa, the deposition-to-surface-air concentration ratio was an order of magnitude higher in that city than in Pretoria, where it rained only four days (624). On the other hand, rain will wash the surfaces of the leaves and thus remove some of the radio-iodine (156). Chamberlain and Chadwick (107) calculated that, from September to December 1961, only about half of the ^{131}I falling out in rain was retained on herbage. Other processes, such as mechanical disturbance and re-volatilization, enhance the decrease of grass contamination. Evidence from laboratory experiments and nuclear industry releases shows that the effective half-time of ^{131}I on herbage is 3-6 days, most estimates lying around 5 days (53). Unfortunately, the results of measurements of ^{131}I in world-wide fall-out cannot be used to test the foregoing estimates as quantitative observations are usually obscured by the rapidly changing pattern of fall-out (189).

214. Fresh milk is usually the main source of ^{131}I in food because of the concentration achieved by the grazing animal and the short storage period of milk. The extent to which ^{131}I is transferred from vegetation to milk varies widely depending mainly upon density of the herbage and on feeding practices. The animal may feed partly only, or not at all, on contaminated grass and the milk produced may be diluted with uncontaminated milk at a dairy. Garner and Russell (189) suggested that from laboratory experiments the maximum level in cow's milk from continuous grazing after a single deposition of 1 pCi m^{-2} might be 0.15 pCi l^{-1} , corresponding to an integrated level of 1.5 pCi d l^{-1} and mentioned that ^{131}I in tropospheric fall-out might be reduced in availability because of its physical form. This hypothesis seems to be confirmed by fall-out results from Argentina, where the relationship between integrated milk level and deposition is $0.23 \text{ pCi d l}^{-1}$ per pCi m^{-2} and shows little variation from year to year (47). On the other hand, the transfer coefficient from deposition to diet for ewes and goats is probably much higher as a considerable fraction of their ^{131}I intake is secreted in milk (189).

215. Milk dominates as a source of ^{131}I ingestion in areas where it is a major dietary component, but vegetables are probably the main source of intake where little milk is consumed (657). However, only milk will be considered here because of its important world-wide contribution in the diet of infants. It should be noted that there are three sources of milk in infants' diet: human milk, fresh milk from animals such as goats and cows, and dried or evaporated milk. Only fresh milk of animal origin contributes ^{131}I to their diet to a significant extent. In the United States, infants of more than six months of age consume mainly this kind of milk and their daily milk intake from six months to two years is about 0.7 litre (150). This figure has

been assumed to be representative of many areas of the world.

(ii) Doses

216. The Committee, in its 1964 report, estimated at 16.5 rads the dose to the thyroid of a baby of less than two years of age resulting from the ingestion of one microcurie of ^{131}I . Similar results can be found in recent publications. Morley and Bryant (435), using values of parameters revised by the United Kingdom Medical Research Council in 1968, obtained a value of 15.5 rads per microcurie for a six-month-old baby while, according to Neil and Robinson's data (457) the corresponding figure for a 6-11-month-old baby is 18.5 rads.

217. Adopting average values for the parameters discussed above (table 38), the dose from ^{131}I fall-out to the thyroid of infants can be estimated at 4.0 mrad per pCi d m^{-3} . The corresponding dose to adults should be at least an order of magnitude lower because their average milk consumption is much less (620) and the mass of their thyroid is approximately 10 times larger.

218. Inhalation is another possible mode of exposure which can only be predominant when deposition of ^{131}I does not result in the contamination of the diet. Assuming that the blood uptake after inhalation is 0.75 of the uptake from ingestion and that six cubic metres of air are inspired daily by an infant (86), an integrated air concentration of 1 pCi d m^{-3} would lead to a thyroid dose of about 0.07 millirad.

219. Because ^{131}I deposition patterns are unpredictable, doses can only be calculated if the local deposit and transfer coefficients are known or if milk levels are measured. Since these are often not available from large areas of the world, it is not possible to estimate dose commitments on the global scale but only those to local groups whose milk supply has been adequately monitored.

220. During the period from 1951-1958, the pattern of weapons testing was such that copious tropospheric fall-out was produced, but neither interest in ^{131}I nor the proper tools for measuring it existed at that time (156). Integrated milk levels, crudely derived from beta air concentrations, were estimated to be of the order of one microcurie day per litre in certain areas of Utah, United States in 1952, 1953 and 1957 (491). Milk contamination from atmospheric tests during the period 1961-1968 was examined by the Committee in its 1964, 1966 and 1969 reports. In the northern hemisphere, the highest levels in milk were observed in Alaska in 1962 ($37,800 \text{ pCi d l}^{-1}$), while in the southern hemisphere, the highest values were reported in Argentina in 1966 ($27,000 \text{ pCi d l}^{-1}$).

221. Integrated milk levels resulting from the atmospheric tests conducted in 1970 and 1971 in the southern hemisphere are presented in table 39. The milk contamination pattern was clearly different in the two years but the values obtained in the same location are in general smaller than in 1966. There has been no report of significant milk contamination arising from the atmospheric tests performed in the northern hemisphere from 1969 to 1971.

(g) Caesium-137

222. Caesium-137 produced by nuclear explosions in the atmosphere is transported to the earth's surface

without fractionation with respect to ^{90}Sr , as shown by the relative uniformity of the observed $^{137}\text{Cs}/^{90}\text{Sr}$ ratios in air and deposit, which lie around 1.6. Caesium-137 enters plants mainly through surface contamination and is absorbed readily in the human body where its biological half-life is about 100 days.

(i) *Transfer from deposit to diet*

223. The transfer from deposit to diet is normally characterized by high uptake during the first years after deposition and by a relatively small uptake subsequently. The main dietary sources of ^{137}Cs are milk, meat, vegetables and cereals. A large number of milk analyses from different countries have been reported (table 29). Milk levels show a pronounced yearly cycle depending on deposition rates and agricultural practice, but the yearly mean level is representative of the dietary intake in that year. Milk being locally produced in most areas of the world, its levels are representative of the contamination of the regional agricultural production.

224. In a given country, variations of an order of magnitude from one region to another are common. Low concentrations predominate in the temperate regions where caesium is fixed in the solid phases of the soil and milk levels are strongly dependent on the deposition rate of the same year and of the preceding year. In those regions, the annual ^{137}Cs concentrations were fairly stable from 1968 to 1971. On the other hand, high concentrations, explained by a significant uptake from soils low in potassium and high in organic content, are mainly dependent on the ^{137}Cs cumulative deposit (2. 655, 673). From 1968 to 1970, the milk levels in those regions decreased with a half-time of about five years. The highest reported levels in 1970 (620 pCi l^{-1} with a range $70\text{--}1,600 \text{ pCi l}^{-1}$) were found in some forest areas of the Byelorussian SSR, where an increased uptake of ^{137}Cs from the soil into plants was most common in areas of peaty bog and clayed podzolic sandy soils with a high water-table, high moisture content and low pH (673).

225. On a world-wide scale, high milk levels are predominantly found in the high latitudes of the northern hemisphere but tracer experiments indicate that uptake of ^{137}Cs from red, lateritic and alluvial soils common in the tropics and subtropics might also be considerably higher than uptake from the clay soils of temperate regions (182). Unfortunately, measurements in local food products or people in the tropics are scarce.

226. Yearly averages of ^{137}Cs dietary intakes in various countries, summarized in table 31, are not closely related to milk levels for various reasons. Widespread distribution of grain products and meat, which provide about half of the ^{137}Cs intake, tend to smooth out the local variations observed in milk contamination. Furthermore, the grain products are often stored and may thus be representative of an earlier fall-out situation. This also applies to meat when live-stock is fed with grain products prior to marketing.

227. Levels in such dietary items as fish or mushrooms depend strongly upon cumulative deposition. In the case of fresh-water fish, the activity concentrations are inversely related to the potassium content of the water (334), so that the activity of fresh-water fish can be one hundred times that of ocean fish, with a maximum value of a few nanocuries per kilogramme in

fresh-water fish (166, 213). In 1968, fish accounted for 7 per cent of the ^{137}Cs dietary intake in Denmark. Mushrooms were shown to concentrate very effectively ^{137}Cs from soils with a high organic content (211, 296). Typical levels are several tens of nanocuries per kilogramme so that a single meal of mushrooms may increase the normally incorporated ^{137}Cs content to a considerable degree. As a result of these factors, the relative contribution of the individual food-stuffs varies from year to year and levels in diet have decreased between 1968 and 1970.

228. In its 1969 report, the Committee estimated at $4.1 \text{ pCi y (gK)}^{-1}$ per mCi km^{-2} the transfer coefficient P_{23} from deposition to diet. This value has been confirmed by studies conducted in Denmark and in the Soviet Union. In Denmark (2), the influence of the soil uptake on the levels in diet was so small that reliable determinations of the soil factor have been impossible and the dietary intake was related to the annual deposition in the same year and in the two preceding years, yielding $4.1 \text{ pCi y (gK)}^{-1}$ per mCi km^{-2} as P_{23} .

229. In the Soviet Union, the territory has been divided in two zones according to the importance of the soil factor which, although much greater than in Denmark, has not been calculated precisely (684). Assuming that the daily intake of potassium is 3.8 grammes and that the half-residence time of ^{137}Cs in the soil is equal to its physical half-life, the coefficient P_{23} lies in the range 3.8–7.3 and the contribution of the soil uptake is from 40 to 180 per cent of that of the surface uptake. If no major series of atmospheric tests takes place in the next few years, the contribution of the soil uptake will probably be more precisely determined.

230. Exceptionally high values have been observed in caribou and reindeer meat which is the staple food of the populations living in arctic regions. Levels of ^{137}Cs in caribou and reindeer are high because the lichens, which are an important food for these animals during winter, effectively entrap a substantial proportion of the deposit falling on to them, and retain it with an apparent half-life of a few years due to grazing and leaching. Two other food chains participate in the accumulation of ^{137}Cs in man more effectively in those regions than in the middle latitudes: fresh water–fish–man and fresh water–plants–milk–man (519).

(ii) *Transfer from diet to body*

231. Caesium-137 ingested by man is rapidly distributed in the body, about 80 per cent being deposited in muscle and 8 per cent in bone. About 10 per cent is eliminated with a biological half-time of about one day, and the remainder is excreted at a slower constant rate (577). The observed half-life in adults varies between less than 50 and more than 200 days. Even within a relatively homogeneous group, the variability in half-life is considerable. The half-life in children is shorter than in adults and is of the order of ten days for new-born infants. Based on published data, McCraw (410) gave the empirical equation $T_{1/2} \text{ (days)} = 12.8 (u^{1/2} + \exp(-u))$ where u is age in years.

232. Table 40 and figure XXI present ^{137}Cs levels in man in several countries. The average body content of ^{137}Cs in a population at a given time varies with individual values of the biological half-life and with

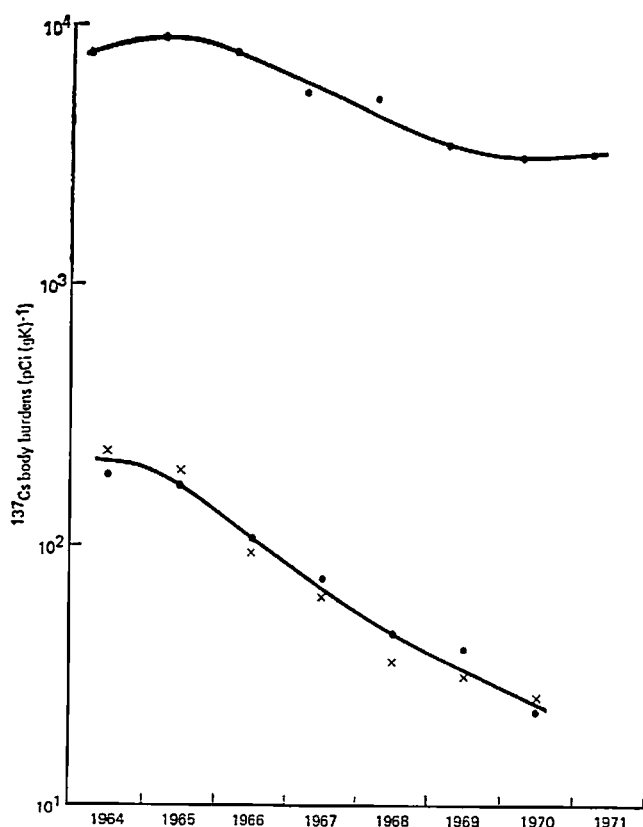


Figure XXI. ^{137}Cs body burdens (pCi (gK)^{-1})

Upper curve: Inari male reindeer herders (Finland) (519-521)

Lower curve: Denmark (●) (5)

France (x) (490)

dietary habits. The variation with time of the average body burden of reference groups located in three cities of the Federal Republic of Germany shows three different slopes which probably reflect variations in the composition of the diet (92). The observed ^{137}Cs levels (in pCi (gK)^{-1}) are 20-30 per cent lower in women than in men. Levels in children are, in general, lower than in adults. However, in the areas of the Byelorussian SSR where high levels in milk were reported, the concentrations in children under 10 years of age were about the same as in adults (about $800 \text{ pCi (gK)}^{-1}$) as a result of their higher consumption of milk (673). For estimating the dose commitment, it will be assumed that the ^{137}Cs level (in pCi (gK)^{-1}) in children is the same as in adults, an assumption which probably leads to a small over-estimate of the population average.

233. Levels in subarctic populations are two orders of magnitude higher than in the middle latitudes. The highest values have been found in a small group of Lapps in the Murmansk region of the Soviet Union (679). For reindeer herders in Finnish Lapland, about 70-90 per cent of the total amount in the body comes from reindeer meat, about 5-15 per cent from cow's milk, and about 5-20 per cent from fish (519).

234. The short residence time of caesium in the human body implies that the ratio between integrated body content and total dietary intake over a few years will be a good estimate of the transfer coefficient P_{34} . The available data (tables 31 and 40) for the period 1968-1970 for diet and body content expressed in pCi

$(\text{gK})^{-1}$ yield an average of 2.9 which is the value adopted by the Committee in its 1969 report. As recent values of P_{23} and P_{34} are consistent with the figures given in the 1969 report, there is no need to change the value of P_{234} which will be taken as $11 \text{ pCi y (gK)}^{-1}$ per mCi km^{-2} .

235. However, there has been some indication that a small part of caesium might be fixed in bone with long residence time and this would increase the value of P_{34} . Both in Denmark and in the Soviet Union, the long-term component is much higher in the equation of transfer from deposit to man than from deposit to diet suggesting that a fraction of the body burden has a long residence time (2, 684). However, the Danish data from 1969 to 1971 seem to be less in agreement with the model and a significant trend is not apparent in the relative variations of ^{137}Cs in diet and man in the other countries during the period 1968-1970. If in the future the studies from Denmark and the Soviet Union prove to be representative of the situation in the other countries as well, then the upper limit for P_{234} would be about $25 \text{ pCi y (gK)}^{-1}$ per mCi km^{-2} .

(iii) Dose commitments

236. If the ^{137}Cs body content is expressed as pCi (gK)^{-1} , the dose-rate factor is approximately independent of age. It will be assumed as in the 1969 report that $P_{45} = 18 \text{ } \mu\text{rad per pCi y (gK)}^{-1}$ which, combined with the estimate of $P_{234} = 11 \text{ pCi y (gK)}^{-1}$ per mCi km^{-2} , gives $P_{2345} = 0.20 \text{ mrad per mCi km}^{-2}$.

237. The average integrated deposits of ^{137}Cs in the north and south temperate latitudes, obtained by multiplying the ^{90}Sr values by 1.6, are 128 and 35 mCi km^{-2} , respectively. The corresponding dose commitments are 26 and 7 millirads. The upper limits, calculated from the studies conducted in Denmark (2) and in the Soviet Union (684) are about twice those values. An extensive study taking into account the variations in the demographic structure of the population and in the dose-rate factor as a function of age yielded a dose commitment for the Soviet Union of 19 millirads for all atmospheric tests before 1963 (687). This result is in good agreement with the above estimate for the north temperate latitudes from all tests before 1970. If the dose commitments are calculated from the population-weighted deposition of ^{90}Sr over the whole hemispheres, the results are 19 millirads for the northern hemisphere and 4 millirads in the southern hemisphere.

238. In the arctic and subarctic regions where people include reindeer and caribou meat in their diets, the dose commitment is much higher. In Finnish Lapland, the body burdens were estimated to decrease with an effective half-time of about four years from 1967 to 1969 leading to a dose commitment of approximately one rad (521). In different arctic regions of the USSR the dose commitment for the native population varies from 0.45 to 1.7 rads (677). A value of one rad is probably representative of other arctic regions. As those populations constitute a small fraction of the world's population, the enhanced doses that they receive do not contribute significantly to the world-wide dose commitment.

239. The external dose commitments from ^{137}Cs deposited on the ground are discussed in paragraphs 261-264.

(h) Plutonium

(i) Levels in the environment

240. Plutonium is a fissile element that has received the greatest attention as a possible source of biological hazard mainly in occupational work. It enters plants from the soil only to a very small extent (539) and less than one thousandth of that ingested in diet is absorbed through the gastro-intestinal tract, but when inhaled it is one of the most toxic of radio-active materials (145, 408). In recent years, the plutonium content of surface air has therefore been carefully monitored.

241. Plutonium-239, an alpha emitter with a physical half-life of 24,000 years, is a man-made radio-nuclide produced by neutron irradiation of ^{238}U . As a component of global fall-out, it is found in surface air (138, 140, 342, 471, 633, 686) (figure XXII)

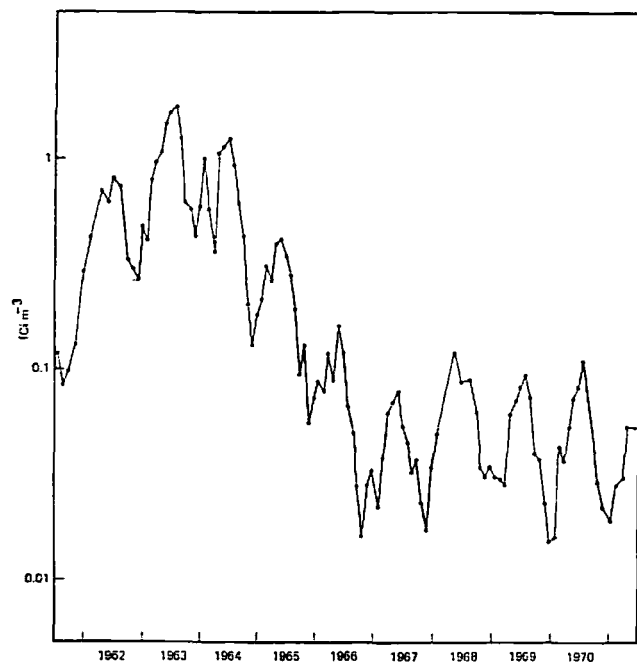


Figure XXII. ^{239}Pu concentration in surface air at Ispra, Italy (120, 133, 140)

where it is accompanied by smaller quantities of ^{240}Pu , from which it cannot be distinguished by alpha spectrometry (558), of ^{238}Pu in the ratio of 0.02 to 0.04 (1, 140, 344, 428) and of ^{241}Pu .

242. The total amount of ^{239}Pu produced in nuclear tests can be inferred from the ^{90}Sr corresponding value, since the $^{239}\text{Pu}/^{90}\text{Sr}$ activity ratio is about 0.02 both in stratospheric and in surface air (3, 235, 428, 429, 630). If the local fall-out is not taken into account, the production of ^{90}Sr by nuclear tests amounted to 15.5 megacuries in January 1971 (table 24) and the corresponding value for ^{239}Pu was 0.3 megacurie.

243. Appreciable amounts of ^{239}Pu were released locally to the environment when airplanes carrying nuclear bombs crashed in the vicinity of Palomares, Spain, in January 1966 and of Thule, Greenland, in January 1968 (3, 272). Near Palomares, the nuclear fuel of two thermonuclear weapons was burned out and an area of about two square kilometres was contaminated with plutonium and uranium particles. Contaminated vegetation and the top five centimetres of soils in

areas with alpha-emitting levels above 320 pCi m^{-2} (about 8 per cent of the total contaminated area) were removed and stored as radio-active wastes. The rest of the area was plowed over down to a depth of about 25 centimetres, so as to dilute the concentration of radio-active elements in the soil. However, the combined action of dry climate, high wind velocities and farming of the soil have resulted on a few occasions in a significant resuspension of particles of plutonium oxides. A station located in a farming area recorded in 1967 a yearly average air concentration of 12 fCi m^{-3} , that is two orders of magnitude higher than the fall-out level (273).

244. Near Thule, the high-explosive components of four weapons detonated and resulted in contamination of about 0.2 square kilometre. An amount of about 200 curies was recovered in the surface layer of the snow pack and about 20 curies were estimated to be trapped in the ice (353). A radio-ecological investigation conducted during the summer of 1968, when the ice had broken up, showed that the plutonium levels in the collected samples in no instances were such that they could be considered harmful to man or to higher animals in the Thule district or in any other part of Greenland. Nevertheless, the accident measurably raised the plutonium level in the marine environment as far out as approximately 20 kilometres from the point of impact. The highest concentrations were found in bottom sediments, in bivalves and in crustacea. Larger animals such as birds, seals and walrus showed plutonium levels hardly different from the fall-out background (1, 3).

245. The amount of ^{238}Pu produced by nuclear tests can be estimated at about 10 kilocuries, if the $^{238}\text{Pu}/^{239}\text{Pu}$ and the $^{239}\text{Pu}/^{90}\text{Sr}$ ratios are assumed to be 0.03 and 0.02, respectively. An additional quantity of 17 kilocuries was injected into the stratosphere as a result of the burning on re-entry of a satellite that used this nuclide as a power source (233). Figure XXIII shows the changes of the $^{238}\text{Pu}/^{239}\text{Pu}$ activity ratio in surface air that followed that event (636). In November 1970, about 0.9 kilocurie, that is only 5 per cent of the original burden, remained in the stratosphere; the residence half-time of the total stratospheric inventory was 14 months during the period 1967-1970 (329).

246. A similar device re-entered the atmosphere and fell into the Pacific Ocean in April 1970. Another generator fell into the waters off the coast of California in May 1968 when a weather satellite exploded during launching. It was recovered in October 1968 (236).

(ii) Doses

247. The report of the Task Group on lung dynamics (268) of Committee II of the ICRP presents models of the deposition of particulate material in, and clearance of this material from, the respiratory tract. For a highly retained dust, such as plutonium dioxide, slow removal processes from the pulmonary region by direct translocation to the blood or by ciliary-mucous transport to the gastro-intestinal tract take place with a half-time of 360 days. Of this, 10 per cent is introduced into the systemic blood (half-time 360 days) and 90 per cent is presumed to be permanently retained in the lymph nodes.

248. Using these values, Voilleque (628) computed the doses to various tissues resulting from the inhala-

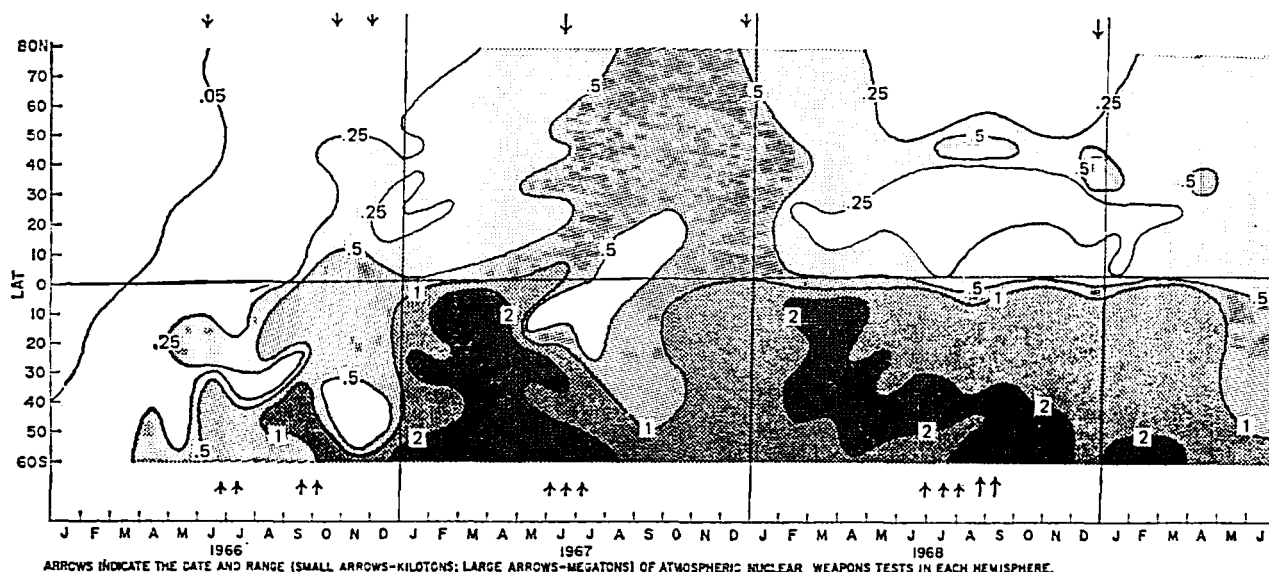


Figure XXIII. $^{238}\text{Pu}/^{239}\text{Pu}$ ratio in surface air (631)

tion of one microcurie of PuO_2 for the three mean particle sizes shown in table 41, which cover the range found experimentally. According to his calculations, the integrated doses over 50 years, corresponding to the inhalation for one year of air containing 1 fCi m^{-3} of $^{239}\text{PuO}_2$ distributed on aerosols of 0.5 micrometre AMAD,⁶ are 0.43, 96, 0.20 and 0.04 millirad to the pulmonary region, the lymph nodes, the liver and bone, respectively.

249. Integrating the curve shown in figure XXII by adding the average annual concentrations for the period 1962-1970 gives an integrated level 2.6 fCi y m^{-3} . From the ^{90}Sr annual deposition values (table 24), the integrated level prior to 1962 can be estimated at 1.5 fCi y m^{-3} . The total integrated level from the beginning of the nuclear tests through 1970 would thus be of the order of 4 fCi y m^{-3} , which corresponds to integrated doses over 50 years of about 2, 400, 0.8 and 0.2 millirads to the organs and tissues cited above. It should be noted that the ICRP does not consider the lymphoid tissues to be critical in irradiation resulting from inhalation because experimental evidence has shown pulmonary rather than lymphatic tissue to be at risk (575).

250. The few measurements of ^{239}Pu in man (table 42) confirm the accumulation in respiratory lymph nodes, lung, liver and bone but seem to show that the concentrations in lymph nodes are probably overestimated whereas those in liver are underestimated. Results of analyses of tissue aliquots from a plutonium process operator who had been exposed for six years to ^{239}Pu largely via chronic low-level inhalation in an approximately known way have been published (180). The assumption that 90 per cent of the plutonium which reaches the lymph nodes is retained permanently leads in that case to an over-estimation by a factor of 13 of the concentration in those tissues relatively to that in the lungs. The correct value is obtained assuming a residence half-time of about two years. However, this result is based on only one individual. It is to be hoped that the National Plutonium Registry

(137) established in the United States will contribute to the verification of the values of the parameters given by the Task Group on lung dynamics.

3. External irradiation

251. Several of the artificial radio-nuclides that are present in fall-out emit gamma rays and thereby give rise to an external radiation dose. In addition to various short-lived radio-nuclides, the most important of which are ^{95}Zr — ^{95}Nb , the main contributor to external gamma radiation is ^{137}Cs which has a mean life of 43 years.

252. In principle it should be possible to calculate the external doses from the short-lived radio-nuclides using the deposition data for each nuclide and appropriate dose-rate conversion factors. Gustafson and Brar (215) determined dose-rate conversion factors for a plane distribution of fission products on the ground. More recently, Beck (37) and Beck and de Planque (38) have calculated dose-rate conversion factors, both for natural emitters and for fission products, using gamma-ray transport theory. These were computed both for plane and exponentially-distributed sources. Dose-rate factors based upon these calculations are shown in table 43. For ^{137}Cs the distribution is assumed to be exponential with a mean depth in the soil of three centimetres. For the short-lived fission products a plane distribution is assumed.

253. For the short-lived fission products, there is little leaching into the soil before they decay, but for ^{137}Cs , Gale *et al.* (187) found there was a rapid movement into the soil during the first few years and henceforth the distribution remained fairly static. The amount of penetration depended upon the soil type, but in all cases most of the ^{137}Cs remained in the top 10 centimetres of soil. The dose rate in air from ^{137}Cs was found to fit the following expression, where $D(t)$ is the dose rate in air in mrad y^{-1} per mCi km^{-2} of ^{137}Cs deposited:

$$D(t) = 0.12 [0.63 \exp(-1.15t) + 0.37 \exp(-0.03t)] \quad (32)$$

⁶ AMAD = Activity Median Aerodynamic Diameter. The aerodynamic diameter is the diameter of a unit density sphere with the same settling velocity as the particle in question (268).

254. It is debatable whether, to allow for weathering, it is preferable to use a fixed exponential distribution in the soil or a dose rate that changes exponentially with time. There may also be some reduction in the gamma dose rate due to roughness of the terrain. In any case, large sections of the population live within paved cities, where a large fraction of the fission products would run off into the drainage system. Therefore, dose commitments calculated using the above models would probably give an upper limit.

(a) *Dose commitment from short-lived fission products*

255. In order to compute the dose commitment from the short-lived fission products it would be necessary to know the integrated deposition of each from 1950 until 1970. Although some data are available on the deposition of these fission products, they do not cover a long enough period to make an accurate estimate of the dose commitment possible. As in the previous Committee reports, we will rely on direct measurements.

256. The external dose in air from fission products in Tokyo, measured at one metre above a paved surface between 1958 and 1967 was 121 millirads (445, 446, 658). Between 1962 and 1967, the dose one metre above a grassed plot in Chiba City, Japan, was 122 millirads (445, 446).

257. Gibson *et al.* (195) have reported results on the gamma radiation from deposited fall-out at Grove, United Kingdom, for the period 1951-1967. These results, which are shown in figure XXIV, are based

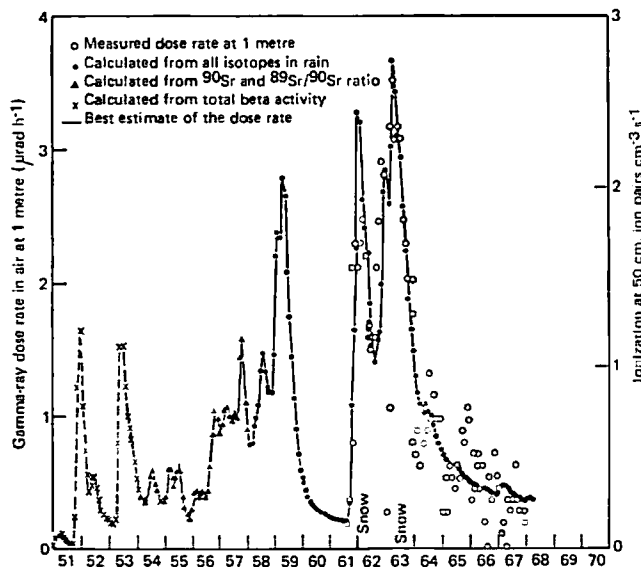


Figure XXIV. Gamma-radiation from deposited fall-out at Grove, UK, from 1951 to 1968 (195)

upon direct measurement and on calculation from deposition data. There was excellent agreement between the computed and measured dose rate. In 1967, the dose rate had fallen to about 15 per cent of that prevailing in 1962-1964. The annual dose from fission-product gamma rays reached a peak of 22.7 millirads in 1963, and for the period 1951-1967 the integrated dose was 131 millirads, of which 16 millirads were estimated to be from ^{137}Cs . Of the 1967 annual dose of 3.5 millirads, about 2.5 millirads were from ^{137}Cs .

258. At Grove, United Kingdom, the dose delivered between 1951 and 1967 from short-lived fission products deposited in the same period was $131 - 16 = 115$ millirads, and if the small contribution to be delivered after this time is neglected, we can consider 115 millirads as the dose commitment.

259. In order to compute the population-weighted dose commitment for the northern hemisphere, we use the ^{90}Sr deposition up to 1967 at Abingdon (near Grove) of 43.2 mCi km^{-2} compared with the population-weighted mean for the northern hemisphere for the same period, 54.2 mCi km^{-2} . The dose commitment for deposition up to the end of 1967 is $115 (54.2/43.2) = 144$ millirads. From table 28, it can be seen that in the northern hemisphere 1.3 megacuries of ^{89}Sr deposited in 1968-1969 compared with 51.7 megacuries in the period 1961-1967. Using this as a guide, the contribution to the dose commitment from deposition in 1968-1969 is at most 2.5 per cent. Adding this to 144 millirads, we obtain 148 millirads for the population-weighted dose commitment in the northern hemisphere for all deposition up to 1969. In the same manner, the dose commitment in the northern temperate latitudes (40° - 60°) is estimated to be 203 millirads.

260. To estimate the dose commitment for the southern hemisphere, we use the deposition of ^{89}Sr in the northern and southern hemispheres for the period 1961-1969 (table 27), 260 and 71 mCi km^{-2} , respectively, as a guide, and assume the dose commitment to be proportional to these. The dose commitment in the southern hemisphere from short-lived fission products is thus $148 (71/260) = 40$ millirads. In the temperate regions it is 60 millirads.

(b) *Dose commitment from ^{137}Cs*

261. Using 93.4 and 22.2 mCi km^{-2} as the total population-weighted deposition of ^{137}Cs in the northern and southern hemispheres, respectively, together with the dose-commitment conversion factor of 1.44 mrad per mCi km^{-2} from table 43, the dose commitments in the northern and southern hemispheres are 134 and 32 millirads, respectively.

262. It is possible to estimate the dose commitment from ^{137}Cs by another method. At Grove, United Kingdom, the dose from ^{137}Cs up to 1967 was 16 millirads and in 1967 the annual dose was 2.5 millirads (see paragraph 257). Assuming that the ^{137}Cs was already permanently distributed in depth within the soil, only the second term of equation 32, which has an effective mean life of 33 years, applies. Thus, the dose commitment at Grove for ^{137}Cs deposited up to 1967 is $16 + (2.5 \times 33) = 99$ millirads. Using the ^{90}Sr deposition at Abingdon up to 1967 of 43.2 mCi km^{-2} and the population-weighted deposition in the northern hemisphere of 58.4 mCi km^{-2} from all tests to 1970, the dose commitment for the northern hemisphere is 134 millirads, in agreement with the estimate made in the last paragraph.

263. To estimate average doses to the population it is necessary to consider the shielding afforded by buildings. A reduction factor of 0.2 will be taken as a world average for shielding by buildings (613). Also assuming an average time of 17 hours is spent indoors, the over-all reduction of dose due to shielding is 0.4.

264. In addition, in order to obtain the gonad and bone-marrow tissue doses, we must multiply by the (tissue/air) conversion factor of 0.8 discussed in paragraph 143. This factor allows for conversion from air dose to tissue dose in addition to screening by intervening body tissues. The combined factor to convert air doses to gonad and bone doses is thus 0.32. The dose commitments resulting from short-lived radio-nuclides and from ^{137}Cs for all tests up to the end of 1970 are shown in table 44.

4. Summary of dose commitments

265. Estimates of dose commitments from nuclear tests carried out before 1971 are summarized in table 45. For comparison, the estimates given in the 1969 report for tests conducted before 1968 are also included. Although no major series of tests occurred during the period 1968-1970, there are significant differences between the two sets of estimates for the internal dose commitments from ^{90}Sr to the bone-lining cells and for the external dose commitments to all tissues. As a result, the ratios of the external to the internal dose commitments for all tissues are found to be markedly higher in this report than in the 1969 report. Most of the changes are a consequence of improved information becoming available.

266. In the case of ^{90}Sr , the transfer coefficient from deposit to diet has been estimated as $4.5 \text{ pCi y (gCa)}^{-1}$ per mCi km^{-2} instead of $9 \text{ pCi y (gCa)}^{-1}$ per mCi km^{-2} , and the transfer coefficient from diet to vertebrae has been taken as 0.12 instead of 0.2. A reassessment of the dose-rate factors (P_{45}) resulted in changes from 1.1 to 1.95 mrad per pCi y (gCa)^{-1} for bone-lining cells and from 0.55 to 1.42 mrad per pCi y (gCa)^{-1} for bone marrow.

267. Estimates of doses from external radiation are higher, mainly because the ratio of the tissue dose to outdoor air dose is now taken as 0.32 instead of 0.2. However, the ^{137}Cs dose-rate factor used in this report is $0.033 \text{ mrad y}^{-1}$ per mCi km^{-2} compared with 0.04 mrad y^{-1} per mCi km^{-2} used in the 1969 report. In addition, a small difference results from an incorrect use in the 1969 report of the cumulative rather than the integrated ^{90}Sr deposit to estimate the ^{137}Cs deposit. Doses from short-lived radio-nuclides have been estimated from actual measurements and the new tissue/air dose conversion factor was applied.

268. As a result of the combination of higher dose commitments from external radiation and lower dose commitments from ^{90}Sr , the relative importance of ^{90}Sr has decreased and ^{137}Cs appears to be the main contributor to the total dose commitment.

B. UNDERGROUND AND CRATERING EXPLOSIONS

269. During the last decades, in addition to the development of nuclear devices for military purposes, there has been an increasing interest in the peaceful applications of nuclear explosions. The inherent advantage of using nuclear explosives for peaceful applications lies in the huge energy source available in a small package at a relatively low cost per unit of energy released.

270. There are two basic types of explosions: *cratering explosions* in which nuclear explosives are

potentially useful as an earth-breaking and moving tool for, e.g., uncovering of mineral deposits, canal construction, construction of earth and rock-fill dams, reservoir construction, creation of cuts and embankments for railways and roads, harbour construction, creation of craters for the disposal of mining and processing wastes; *contained explosions* in which the devices are potentially useful to break up or increase the permeability of the underground resource strata so that the resource can be recovered and used by man or to provide storage cavities. Examples are intensified exploitation of oil and natural gas deposits, stimulation of geothermal heat, creation of underground cavities for the storage of natural gas, gas condensates and oil products, creation of underground cavities for the burial of biologically dangerous industrial wastes, underground working of ore deposits, and stopping oil and gas blow-outs.

271. Both types of explosions present certain hazards. This report is only concerned with those arising from radiation exposure which may occur through (a) *release of radio-activity to the environment*. This is a primary concern with cratering explosions where some radio-activity is unavoidably released, but it is also relevant to contained explosions where the probability of accidental venting exists and where contamination of ground-water may occur. Of special concern are such nuclides as ^3H , ^{14}C , and ^{85}Kr because of their long half-life and high mobility in the environment; and (b) *the use of products recovered from "contained type" of explosions*. When nuclear energy is used to increase the availability of oil, natural gas, etc., the resulting products will be contaminated to some extent with radio-nuclides. These products could be used at locations far removed from the explosion.

1. Sources of radio-activity

272. There are two sources of radio-activity from a nuclear explosion, the direct products of the nuclear reactions (the fission fragments and tritium) and the radio-active products which result from activation of the surrounding medium (both inside and outside the explosive device).

273. The two design extremes are the pure fission device producing about $2.9 \cdot 10^{23}$ fission fragments per kiloton and the pure fusion device which would produce no fission products but approximately from 10^{23} to 10^{24} atoms of ^3H per kiloton (depending on the efficiency and kind of thermonuclear fuel) (606). The excess neutrons produced (about $2 \cdot 10^{23}$ neutrons per kiloton escape both from an unshielded fission explosive and from a fusion explosive) are captured either in the device or in its immediate environment (358). In this way, a variety of induced radio-active products are formed.

274. A fully contained one-megaton explosion (10 kt fission) surrounded by borated material would, if exploded in a medium with the average chemical composition of the earth's crust, produce radio-nuclides in the amounts shown in table 46 (583). The relative activities of the total fission products and the induced activities at various times after the explosion are shown in figure XXV. After one year the activity is entirely dominated by ^3H , ^{60}Co , ^{90}Sr and ^{137}Cs , tritium being the most abundant nuclide. After 10 years, tritium is still the most abundant nuclide and its activity is three orders of magnitude greater than that of ^{60}Co or ^{90}Sr .

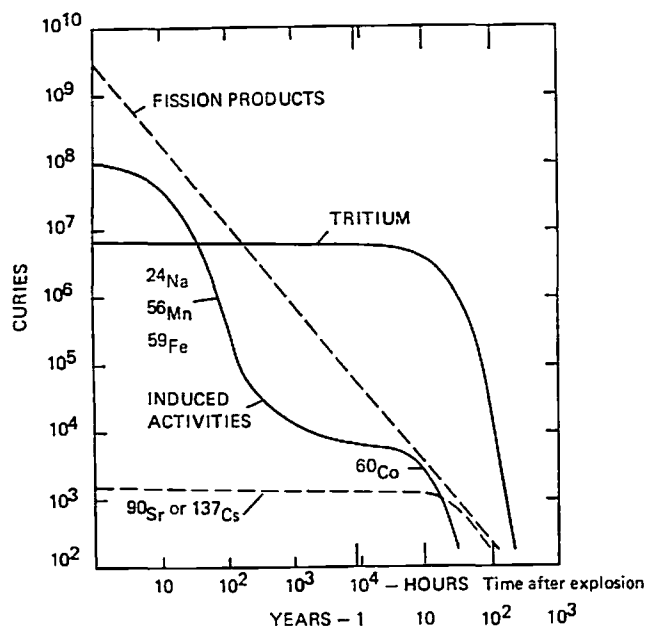


Figure XXV. Activities of radio-nuclides at various times after a nominal one-megaton explosion (10 kton fission) in average crustal material (583)

For peaceful applications, the explosive can be selected so as to minimize the potential hazard of the associated radio-activity.

275. For cratering explosions, Kelly (322), based on past experience, assumes that largely because of (a) the amount of scavenging during the venting process: (b) the effect of special emplacement techniques: and (c) the use of low fission explosives, the sum of fission products airborne in the radio-active cloud and in the fall-out for each nuclear explosive detonated may be expected to be as low as the equivalent of 20 tons. Further, the tritium release may be less than 20 kilocuries per kiloton of total yield. The inventory of selected products expected in the radio-active cloud and in the fall-out are shown in table 47.

276. For underground engineering, fission products (except ^{85}Kr) do not generally appear to be troublesome, but tritium, either from the explosive or from neutron reactions with trace lithium in the soil, gives rise to potential difficulties. Where hydrocarbons are involved, approximately 3 per cent of all neutrons that escape into the soil will produce tritium in typical shales (209). In addition, tritium might be produced in second-order reactions if boron is used as shielding material. Thus, a fission explosive with no neutrons allowed to leak to the soil should be used for hydrocarbon applications (209).

2. Contained experiments

277. The initial result of an underground nuclear explosion is the release of all its energy and of a large number of neutrons within less than a microsecond (463). The neutrons are thermalized and captured in the surrounding material, producing a variety of induced nuclides. The extreme pressures and temperatures ($> 10^6$ atmospheres and $> 10^7$ degrees) that are generated vaporize some of the surrounding material and give rise to a strong shock wave that propagates outwards. Initially this shock wave is sufficiently intense to vaporize additional rock and add its mass and

volume to the cavity formed. In contained explosions the cavity reaches its peak size in a few hundredths (or tenths) of a second (667). At this time the pressure is approximately balanced by the lithostatic pressure and the shock wave breaks away from the cavity. While still in the neighborhood of the cavity the shock wave crushes the rock. Further out, fractures are produced whereas, at greater distances, the medium behaves elastically in response to the pressure wave. The resulting cavity stands for a period of time which depends upon the type of rock, the depth of burial and the explosion yield. When and if collapse occurs, it generally progresses upward at about the same diameter as the cavity until the limit of the fracture zone is reached. The resulting roughly cylindrical volume of broken rock and rubble is called the chimney. The time history of an underground explosion is shown in figure XXVI.

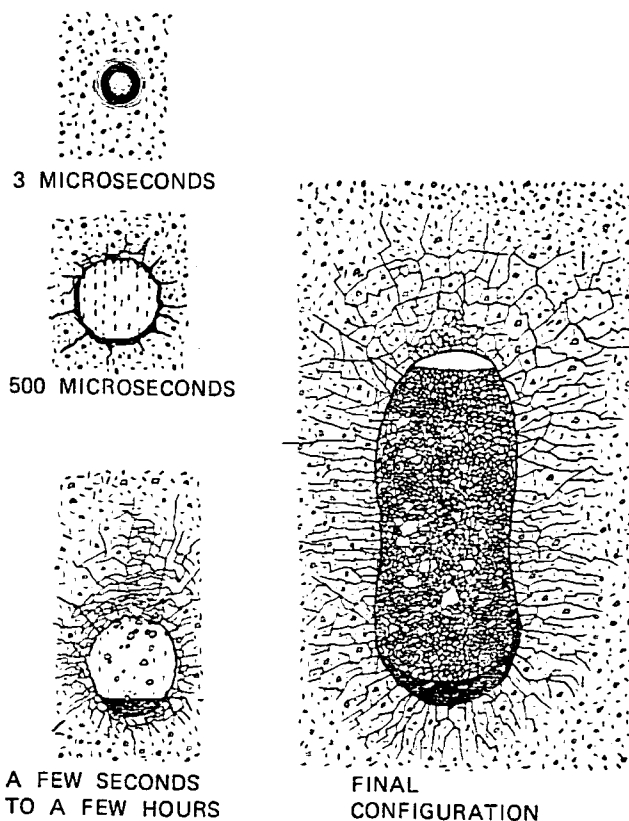


Figure XXVI. A typical sequence of events after a nuclear explosion is detonated underground (538)

278. If the explosion occurs at great depths,⁷ all the radio-active products will remain underground. However, the crushing of rock and the formation of fissure systems may create channels from the cavity through the overlying layers to the surface and radio-activity may be released into the atmosphere. This process would usually require considerable time (of the order of an hour or more). This means that only the isotopes of inert gases or volatile elements (e.g., halogens) could escape into the atmosphere. The isotopes ^{85}mKr , ^{87}Kr , ^{88}Kr , ^{133}Xe , ^{135}Xe , and ^{138}Xe would be the ones most efficiently released (278). If, however, the release were to begin a few minutes after

⁷ The minimum depth for total containment depends on explosion yield and is approximately $140 \text{ m kt}^{-1/3}$.

the explosion, the short-lived ^{89}Kr , ^{90}Kr and ^{137}Xe might escape (278) and their decay products would settle on atmospheric dust particles, forming so-called secondary aerosols. It should be noted that this type of release is not likely to occur if the site of the explosions is determined after a careful study of its geology. It has not been observed after any United States contained explosion for peaceful purposes.

279. *Gas stimulation.* One of the most important possible applications of contained underground explosions is for recovering gas from known reservoirs from which gas may not be produced as efficiently by conventional methods. In these attempts to stimulate gas reservoirs, the chimney and fracture regions serve as a gathering system for the natural gas (251). In the Plowshare programme two gas stimulation experiments, Gasbuggy and Rulison, were performed. Data on these experiments are shown in table 48. These experiments demonstrated that the principal radio-nuclides remaining in the gas several months after the initial explosions were ^3H and ^{85}Kr (568, 569). From table 48 it is evident that the concentration of tritium in the Rulison gas is down by a factor of four compared with Gasbuggy, and that its total amount in the gas is also less by a factor of about two. However, neither of the devices used in those tests are specially designed for gas stimulation (209). The amount of residual ^3H per kiloton of yield will be considerably less in future United States gas stimulation experiments owing to the use of an explosive specially developed for that purpose (358). The only other activities observed in the Gasbuggy gas were due to ^{133}Xe , ^{37}Ar , ^{39}Ar and ^{14}C (252). The concentrations of the long-lived ^{39}Ar and ^{14}C in the early samples were about 0.1 and 1 pCi cm^{-3} , respectively.

3. Cratering experiments

(a) Formation of crater

280. When the explosion takes place at a relatively shallow depth,⁸ there is a breakthrough of the cavity to the surface and ejection of radio-active products into the atmosphere (667). The size of the resulting crater, the shape of the explosion cloud and the particle properties of the airborne debris depend not only on the depth of burial and the explosion yield but also on the strength and water content of the ground material.

281. Explosions in dry hard rock result in a fast drop of the cavity pressure and the cratering will be caused mainly by the shock wave. The material overlying the expanding cavity will act as a filterbed through which the radio-active material must pass. As a result only a base-surge cloud (see figure XXVII) is formed which contains small particles mixed with finely-distributed ground material and enriched in volatile radio-active products. When the water content of the ground is high, the cavity pressure will drop more slowly and overpressure will contribute to the crater formation (330) causing a "dynamic venting" of gases and of primarily-formed particles. Besides a base-surge cloud this dynamic venting results in the formation of a main cloud (see figure XXVII) which reaches substantially higher into the atmosphere. Although at very early times the airborne activity is not grossly fractionated, the smallest particles are strongly enriched in volatile products.

⁸ The minimum depth for cratering depends on explosion yield and is approximately $60 \text{ m kt}^{-1/3.4}$.

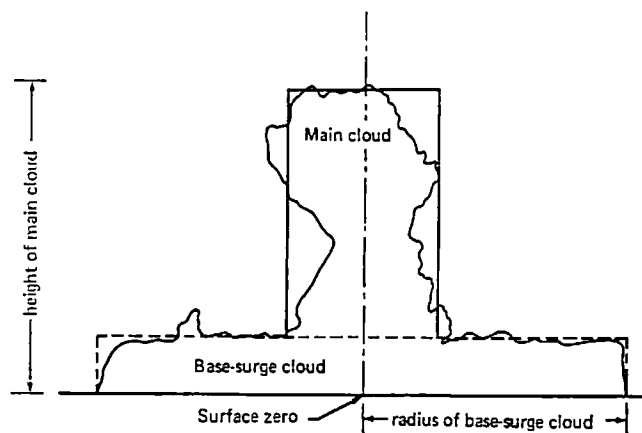


Figure XXVII. Definition of cloud dimensions (333)

282. At greater explosion depths, the ground between the cavity and the surface is lifted by the shock wave but falls back again so that no real crater is formed. A certain amount of dynamic venting may occur and release a small part of the still volatile products as well as some of the smallest particle fraction. Later on a slow seeping out of gaseous products (mainly noble gases and tritium) may occur through fissures in the ground material.

283. Probably the most widely known potential application of nuclear cratering is the construction of canals and specifically that of a sea-level canal across the American Isthmus. Of the four considered routes involving nuclear excavation techniques, a route through Colombia appears to be the least expensive by a considerable margin (210). It would require a total of 148 devices, amounting to a yield of approximately 120 megatons. The channel would be excavated in sections by about 20 separate rows of explosions, each consisting of from 5 to 16 nuclear devices which would be exploded simultaneously (271). According to an early estimate, about 115 million tons of dust would be airborne at one time or another as a result of the explosions (606).

284. In the Soviet Union, plans have been developed for the transport of additional water to the Caspian Sea which has been drying up in the past 15 years (668). The proposal is for the northward flowing Pechora River to be intercepted by a series of dams and canals, the water being diverted into the southward-flowing Karna River. One canal would be 112 kilometres long and would be built over 65 kilometres by nuclear means (250 charges). Up to 20 charges would be detonated simultaneously with a maximum explosive yield of three megatons.

(b) Release and transport of debris

(i) Cloud geometry

285. At the time of stabilization, the geometry of the cloud from a nuclear cratering explosion depends on explosion yield, explosion environment, depth of burial of the device and meteorological conditions during cloud formation (331). Figure XXVII shows the form of the main cloud and base surge cloud at the time of stabilization (333). Figures XXVIII and XXIX give the radius of the base-surge cloud and the main-cloud height, respectively. On increasing the water content of the medium surrounding the explosive, one can

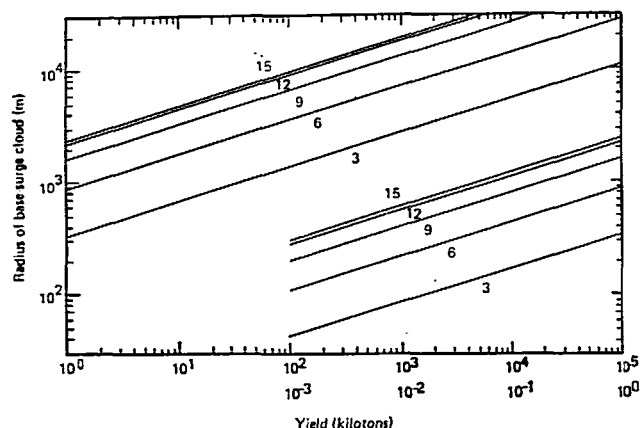


Figure XXVIII. Radius of base-surge cloud versus yield at scaled depth of burial of 3 to 15 m $\text{kt}^{-1/3}$ in alluvium (333)

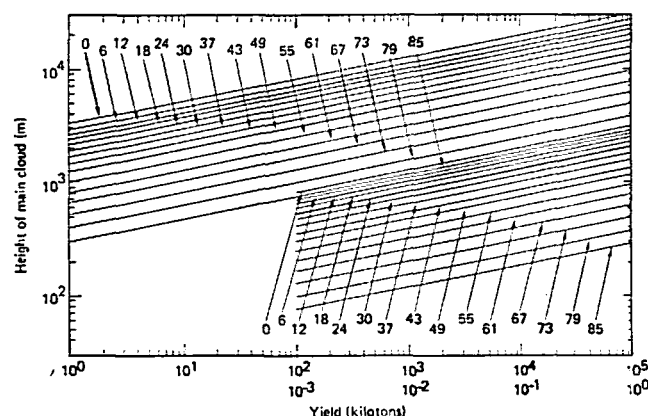


Figure XXIX. Height of main cloud versus yield at scaled depths of burial of 0 to 85 m $\text{kt}^{-1/3}$ in alluvium (333)

expect that the stabilized base-surge cloud would be larger (661) and that the main cloud and the vented fraction of refractory radio-nuclides would increase (333).

286. Lack of experimental data makes it difficult to predict the sizes of the resulting clouds from the explosions of nuclear row charges. However, the individual main clouds may be treated separately and their heights may be obtained from figure XXIX (333). At any rate, it is essential to follow up the evolution of the cloud. The radius of the resulting base-surge cloud would be about the same as that of a base-surge cloud formed in a single explosion with the same total yield and the same scaled depth.

(ii) Deposition

287. *Crater and lip.* A large part of the radio-activity produced in a nuclear cratering explosion is carried down by the fall-back which descends into the initial crater and its immediate vicinity. Figure XXX shows the exposure rate as a function of time for five different explosion yields (600). The exposure rate in the crater and lip area decreases as the explosion yield increases. This decrease is due to lower concentrations of radio-nuclides in the fall-back and ejecta. This in turn results from (a) a decrease with increasing yield (constant fission trigger) in the amount of radio-activity produced per unit yield; and (b) the increase in direct proportion to yield of the amount of material

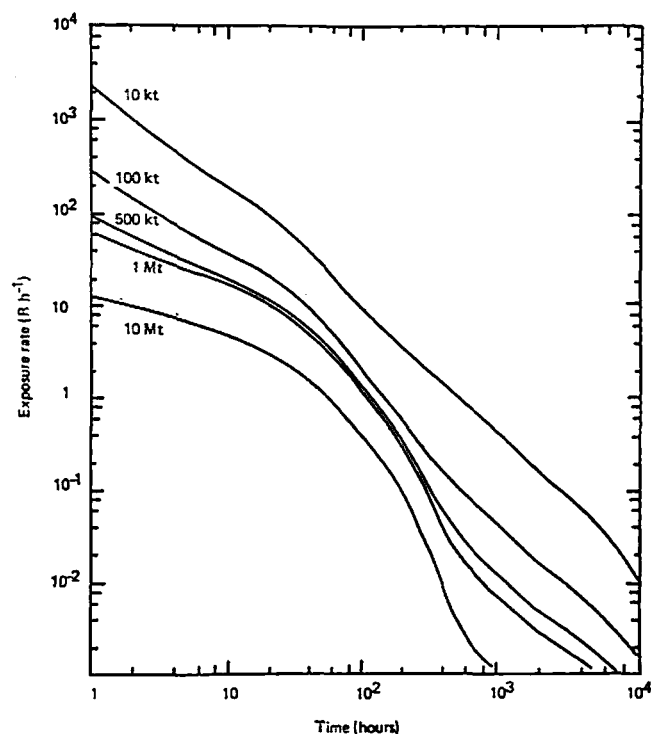


Figure XXX. Time variation of the exposure rate in the crater and lip area from 3 kt-fission explosions of different total yields detonated at a scaled depth of burst of 44 m $\text{kt}^{-1/3.4}$ (600)

which contains the radio-activity. The shapes of the curves change with yield because, as the yield increases, so does the relative contribution from the induced radio-nuclides (600).

288. *Local fall-out.* The large particles in the base surge and the main cloud descend within the first day and form the local or close-in fall-out. Figure XXXI shows, for explosions at different scaled depths, the percentage of the radio-active products deposited as

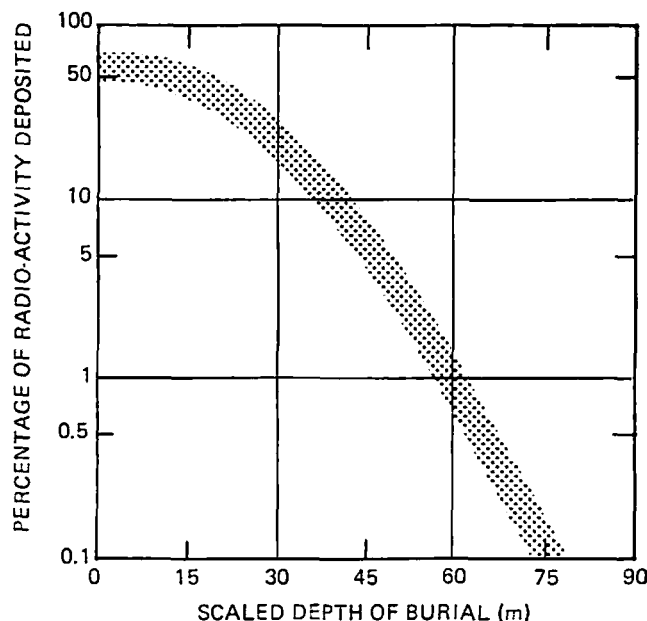


Figure XXXI. Percentage of radio-activity deposited as local fall-out in cratering tests (198)

local fall-out (198). The medium surrounding the explosive, and especially its water content, plays an important role which is reflected in the breadth of the band that describes the relationship in figure XXXI. Once the fraction of radio-active products present in the local fall-out is predicted, it is possible to calculate a fall-out pattern which can be used in planning safety measures. This is accomplished by using appropriate meteorological data (turbulence and wind speed as a function of altitude), distribution of debris of different particle sizes and initial cloud configuration (333).

289. *Long-range fall-out.* The very small particles may remain suspended in the air for considerable times before they reach the ground as long-range fall-out. The cloud dimensions continually increase as a result of turbulent diffusion. The cloud can thus be very large and the particles be brought to great distances by the wind before they descend to earth either by impact or by precipitation. With regard to the radio-activity present in the long range cloud, Crawford (333) has developed a diffusion model which enables the cloud concentrations to be estimated as a function of time and which also provides a means for determining the deposition of material from the cloud over considerable distances from the epicentre. Experimental findings indicate that the basic constituents of the long-range fall-out from cratering explosions are ^{89}Sr , ^{140}Ba and ^{91}Y which after about 10 days account for more than 80 per cent of the total activity (279). This distribution of fission products is due to the fact that among the precursors of these products in the mass chains are isotopes of krypton and xenon with half-lives ranging from 10 seconds to several minutes. Similar isotopic composition of long-range fall-out has been reported elsewhere (319, 336, 501). Devices of different designs may result in different distributions of radio-nuclides in long-range fall-out. Thus, ^{181}W and ^{185}W were reported to predominate in the long-range fall-out from the Schooner cratering explosion (table 49) (62, 99, 126, 141, 502).

(iii) Ground-water contamination

290. For contained underground explosions, the concentrations of radio-active products in ground water are dependent on several factors such as radio-nuclide production and initial distribution, radio-active decay, sorption on geologic material, and dispersion during hydrologic transport. For cratering explosions other aspects of the hydrologic cycle, particularly rainfall and the characteristics of the water table, must be considered (646). For contained explosions, where the cavity may collapse either completely to form a subsidence crater or partially to form a chimney, there are indications that the ground water close to the explosion point will flow inward toward the cavity for a considerable time, possibly years (583). After the restoration of the pre-explosion ground-water flow, the radio-nuclides will be transported away from their initial deposition by ground water along the regional hydraulic gradient. Tritium, which is readily available for transport and whose exchange with the rock matrix is negligible, is the only radio-nuclide in ground water likely to appear in significant concentrations at some distance from the explosion point. ^{90}Sr will be significantly retarded in its ground-water transport in practically all geologic environments; the rate of movement of ^{90}Sr will rarely be more than a few per cent of the average rate of ground-water flow (583). The small amount of ^{14}C produced may be considered

insignificant when distributed in the large volume of material around an underground explosion. ^{137}Cs tends to be even more firmly held by sorption than is ^{90}Sr (583), while ^{60}Co is insignificant in comparison with the longer-lived ^{90}Sr .

4. Doses

291. Nuclear explosives for peaceful applications are still in the experimental stage. Cratering events have been conducted in isolated areas on a scale small by comparison to that of the projects to which they might be applied. A few practical applications of contained explosions have so far been made, all of them in the Soviet Union (table 49). Up till now, the doses received by the public have been extremely small. This section will review the doses received so far, and also indicate those that might be expected if some large-scale applications were carried out with the help of nuclear devices of current design.

(a) Contained explosions

292. An underground explosion successfully contained does not lead to any release to the environment, but if its purpose is to enhance the availability of oil or natural gas, the resulting products are likely to be contaminated to some extent. Four such experiments have been reported so far, two in the Soviet Union (321) and two in the United States (table 48).

293. In the Soviet Union, three charges were detonated several years ago in an oil deposit to increase the extraction of petroleum. The explosions produced no general radio-active contamination of the atmosphere or ground site, and the outputs of the wells which were increased over the entire field by 27-60 per cent over its normally-expected yield, showed no traces of non-gaseous radio-active contamination. The data regarding the second explosion, which was set off in a gas field, have not yet been reported (321).

294. The two United States experiments (Gasbuggy and Rulison) were conducted in natural gas formations. The only significant long-lived radio-nuclides found in the dry gas product were ^3H , ^{14}C and ^{85}Kr (568, 569). The contaminated gas was burned at the surface, instead of being marketed. The results of the off-site radiological surveillance for project Gasbuggy indicated that the project did not result in the introduction of any device-related radio-activity into the existing natural-gas distribution system (409). Future contamination of water supplies following hydrological transport of radio-nuclides is also very unlikely (573).

295. Although none of the gas from the Gasbuggy well had been introduced into the distribution system, theoretical evaluation of the potential radiation exposure from hypothetical domestic and commercial utilization of the contaminated gas have been reported (33, 285). The most important radiation exposures from ^3H and ^{14}C are likely to occur after combustion transforms CH_3T and $^{14}\text{CH}_4$ into HTO and $^{14}\text{CO}_2$, whereas ^{85}Kr is merely carried along with the natural gas. Table 50 presents the whole-body doses resulting from hypothetical distribution of all the Gasbuggy gas in the Los Angeles basin, where natural gas is used for fueling steam plants to generate electricity and for a wide variety of industrial and commercial applications, as well as for domestic consumption (33). Tritium would practically be the only contributor to the dose despite the fact that most of the amount produced

by the explosion was bound with water in the cavity where it did not seem to exchange appreciably to methane (252). The most critical pathway would be domestic consumption for space heating and cooking. For a given consumption rate of contaminated gas in a conventional dwelling, the dose from domestic use depends upon the fraction of combustion products vented inside the home, i.e., upon the relative amounts of gas used in nonvented and vented appliances and upon the efficiency of the venting system. The weighted average dose assumes that, in 10 per cent of the houses, the heating and other appliances making use of gas are unvented and that, in the other 90 per cent, only the kitchen range is unvented (33, 647). The dose resulting from ingestion of food and water that have been exposed to the combustion products has not been included, but experimental results indicate that it would only amount to 2 to 7 per cent of the total (285).

296. As the consumption of gas in the Los Angeles basin is much larger than the production of the Gasbuggy well, the contaminated gas was assumed to be diluted before distribution in that region. The hypothetical dose commitment resulting from the exclusive domestic use of *undiluted* Gasbuggy gas, in an area where the annual heating requirement is 2,800-degree Celsius-days (average value for the United States) (286) is 40 millirads. Assuming a production rate of $28 \times 10^3 \text{ m}^3 \text{ d}^{-1}$ (285), more than 99 per cent of the dose would be received in the first year.

297. The population dose commitment would be about 200 man-rads if the contaminated gas were distributed in the Los Angeles basin and thus, to a certain extent, used for industrial purposes. The maximum population dose commitment would occur if all the gas were used for domestic consumption; in that case, it would be 700 man-rads if the gas were distributed in the Los Angeles basin (population 7 million) and 550 man-rads if the gas were distributed in an area where the annual heating requirement is 2,800-degree Celsius-days. After use, the tritium would be released to the atmosphere and would give rise to an additional dose commitment to the world population. This, however, would be quite small, as it corresponds to a population dose of the order of 10 man-rads.

298. From the radiation protection point of view, the analysis of the Gasbuggy experiment led to the conclusion that efforts should be directed to the reduction of production of ^3H by the explosion. From $1,400 \text{ Ci kt}^{-1}$ in the Gasbuggy event, the ^3H production decreased to 250 Ci kt^{-1} in the Rulison event and is expected to be less than 20 Ci kt^{-1} in future gas-stimulation applications which would use a new explosive design (358). For the purpose of comparison, table 50 presents the whole-body doses which would be expected if the Gasbuggy experiment had been shot with the specially developed explosive and if the contaminated gas had been marketed in the Los Angeles basin. Those explosives have been envisioned to develop a field of 28 wells in Wyoming in the United States (647). Four 100-kiloton explosions would be used per well and the 28 wells would be drilled over a six-year period. The gas from this field would supply about 10 per cent of the demand in the Los Angeles basin, where the average whole-body dose commitments to the population of users would be 0.6 millirad from $^3\text{H} + ^{85}\text{Kr}$, the dose from ^{85}Kr being about 10 times less than that from ^3H .

299. The lower limit of tritium production in a gas-stimulation explosion is estimated at 2 Ci kt^{-1} (209). If that limit were reached, the radiation exposures from ^3H and ^{85}Kr would be about equal.

(b) Cratering explosions

300. The nuclear clouds formed by the few cratering explosions which have been detonated did not reach the stratosphere (figure XXIX) and, as a consequence, the radio-activity produced, with the exception of long-lived gases, was deposited in a matter of weeks in inhomogeneous patterns particularly sensitive to scavenging by precipitation.

301. The doses to the public could best be derived from the knowledge of the deposition pattern of the radio-active debris following each cratering experiment. The United States and the Soviet Union have independently developed prediction methods to that purpose (332). Unfortunately, the published data on actual explosions do not indicate if the nuclear clouds crossed densely populated areas a few days after the explosion and are not sufficient to calculate the population doses.

(i) Dose contribution from short-range fall-out

302. In certain circumstances, milk contaminated with ^{131}I appears to be at least a rough indicator of the whole-body doses which might have resulted from cratering experiments. Table 51 presents levels observed around the Nevada test site where the six United States cratering events took place. Five tests gave rise to detectable levels in the local milk network surrounding the test site. This network samples mostly farms or dairies located in eleven western states of the United States. Only Sedan and Palanquin gave rise to detectable levels in the national network which analyses weekly composite samples pooled from farms dispersed over hundreds to thousands of square kilometres.

303. Study of milk contamination around the detonation site provides some information on the population doses resulting from the intermediate fall-out. Analysis of the potential radiation exposures to a child from nuclear excavation projects shows that, for deposition at one day after detonation, the thyroid dose from ^{131}I ingested via the forage-cow-milk pathway would be the most important (127, 175). However, since 1963, the cratering experiments were intentionally conducted during the colder half of the year with wind blowing towards the north to take advantage of the fact that dairy cattle were on dry food (384). As a crude approximation, the total external whole-body dose to man can be expected to be equal to the ^{131}I thyroid dose to infants.

304. Using the pessimistic assumptions that the milk contaminated at the maximum concentration level observed in the local network would be distributed to 5,000 people and that the concentrations reported by the national network would be representative of the milk levels in the whole state, the population dose to the thyroids of infants six months to two years old were roughly estimated from population and birth-rate data (541, 617). The population whole-body dose commitment, then calculated as the product of the total population thyroid dose to infants ($1,200 \text{ man-rads}$) by the ratio of the total population to the infant population (about 40 in the United States) is estimated at $4.6 \times 10^4 \text{ man-rads}$. Dividing by the world population (3.5×10^9) yields an average whole-body dose of 14

microrads. Owing to lack of data, the dose arising from the intermediate fall-out of the Soviet Union cratering tests has not been taken into account.

(ii) Dose contribution from long-range fall-out

305. In order to estimate the doses from long-range fall-out, the inventories of selected isotopes present in the main cloud and the base surge in the Schooner experiment (332) were assumed to be homogeneously diluted in the 40-50° N latitude band. The dose commitments were then estimated from the transfer coefficients and other data given in the section on atmospheric and surface explosions. Results are summarized in table 52. Besides ^3H , only ^{90}Sr and ^{137}Cs have been considered for internal irradiation because the transfer coefficients from deposit to diet are not sufficiently known for the other radio-nuclides listed in table 52.

306. Although it is realized that, as a result of continuous improvement in explosive design and differences in fission yield and conditions of explosion, the activities released by the tests varied widely, if it is tentatively assumed that the Schooner event is representative of the nine nuclear cratering experiments conducted so far, then the total dose commitments from long-range fall-out may be estimated by multiplying the results of table 52 by nine. The total population integrated external dose commitment is thus found to be of the order of 10^4 man-rads. Dividing by the world population yields a world average dose of three microrads.

307. Regarding the internal doses, the major contribution is furnished by ^3H . For a 170-kiloton explosion, the amount of ^3H expected to be released to the environment is estimated at two megacuries (table 47). Assuming that the amount of ^3H released is proportional to the total yield, the cratering experiments gave rise to a world-wide distribution of about three megacuries, which corresponds to an average dose commitment of six microrads, much greater than the contribution of ^{90}Sr and ^{137}Cs .

308. There is a significant potential for using nuclear explosives to accomplish large-scale construction projects at considerable savings in cost and time as compared to use of conventional construction techniques. The most documented project is the construction of a new Atlantic-Pacific interoceanic canal (paragraph 283). If the route through Colombia were to be adopted, an area of about 8,000 square kilometres would have to be evacuated mainly to guard against short- and intermediate-range fall-out. Recent estimates show that approximately 10,000 persons live within this area (271). If those people were not evacuated, they would receive estimated lifetime doses ranging up to 300 rads from external radiation alone.

309. Concerning the long-range fall-out, the trajectories of the clouds are expected to be such that most of the radio-activity would be deposited over the Pacific Ocean and that only a small fraction of the base surge would branch towards the Colombian mainland (127). However, ^3H and ^{85}Kr would eventually be distributed world-wide. The amount of ^3H released would be 1,400 megacuries—slightly less than the quantity produced by atmospheric testing (paragraph 166). The dose commitment to the world's population would be of the order of three millirads. The production of ^{85}Kr has been assumed from table 48 to be in the range 12-23 curies per kiloton of fission. If the

fission yield of the explosive device, assumed constant regardless of the total yield, is taken as 90 tons (smallest fission yield reported in the nuclear experiments), then the total fission yield is 13 kilotons; the production of ^{85}Kr would then be in the range 150-300 curies and the corresponding whole-body dose commitment would be of the order of 10 picorads.

5. Conclusion

310. There is a wide spectrum of potential peaceful applications for nuclear explosives. In any nuclear cratering explosion, some radio-activity is inevitably released into the environment. Nuclear cratering techniques have been developed to the point where they can be used for relatively small projects, such as formation of water reservoirs, as demonstrated in the Soviet Union. Dose commitments from past events have been tentatively estimated and should be considered as merely indicative. They would probably have been lower if current explosive designs had been employed. For large scale projects, problems involving safety of the population living in the proximity of the explosion site seem to be strong limiting factors.

311. The future of contained explosions looks more promising as some applications would not result in a release of radio-activity to the biosphere. For example, elimination of a runaway gas well was safely conducted in the Soviet Union and the prospect of storing industrial radio-active wastes in cavities formed by contained explosives has attracted interest. In other applications, the release of radio-activity would be small and could be controlled to a large extent. The only significant contamination of the natural gas recovered after the gas stimulation experiments carried out in the United States was that due to ^3H and ^{85}Kr .

II. Power production by nuclear fission

A. INTRODUCTION

312. The increasing use of nuclear fission in power production calls for assessment of potential environmental contamination at present and in the future. Estimates of the growth of nuclear power vary but the highest given in table 53 indicate that the world generating capacity, which was about 20 GW(e) in 1970 (264), may increase to about 1,600 GW(e) by 1990 and to about 4,300 GW(e) by the year 2000 (581). This increase is partly due to the predicted rise in power demand and partly to the higher percentage (just over 60 per cent in 2000) of electrical power expected to be produced by nuclear fission.

313. An IAEA survey (264) lists 361 research reactors and 127 power reactors as being in operation in 1971. About half of the power reactors are either experimental with output below 20 MW(e) or have relatively low outputs of 20-100 MW(e). The remainder of the power reactors, which accounted for more than 90 per cent of the installed capacity in 1970, have outputs in the range 100-800 MW(e) and are in operation in a total of 12 countries.⁹ There are many power reactors under construction with outputs up to 1,200 MW(e) and 319 are expected to be in operation by 1977.

⁹ These are Canada, France, the Federal Republic of Germany, India, Italy, Japan, Spain, Sweden, Switzerland, the Soviet Union, the United Kingdom and the United States.

314. The nuclear power generated in 1970, calculated from the figures published by the IAEA (263), was 8.6 GW(e) y to which must be added the contribution (1.1 GW(e) y) from power stations for which the installed capacity is known and the load factor assumed to be 0.65. This load factor is an average value for power stations fully operational before 1970 (263). Other reactors which were not fully operational contributed 5 GW(e) to the total installed capacity of 20 GW(e). The total nuclear power generated during 1970 was thus estimated to be 9.7 GW(e) y corresponding to an over-all load factor of 0.5. This is assumed to apply also in the year 2000, although a substantial number of nuclear power reactors may then be operated only during periods of high energy demand.

315. The Committee noted that the largest part of the information on which it bases its conclusions comes from a very small number of countries among those in which nuclear power plants are used to generate electricity. The Committee does not discuss, in this annex, reactors used in other applications of nuclear power, for example, district heating, ship propulsion or experimental projects.

316. In common with other industries, the nuclear power industry gives rise to wastes which may occur in airborne, liquid and solid forms. Environmental contamination resulting from leakage or discharge of radio-nuclides in wastes will be discussed here step by step, from the mining of ore to the reprocessing of spent fuel. Dose commitments from current practice, and those expected to be incurred in the future as a result of the industry's expansion, will be estimated. The dose commitments considered here will be those which are related to normal conditions of operational variability and not to accidents leading to uncontrolled discharges to the environment.

B. ENVIRONMENTAL PATHWAYS INVOLVING RADIATION EXPOSURE OF MEMBERS OF THE PUBLIC

317. Radio-nuclides discharged in airborne, liquid and solid wastes may be transferred along environmental pathways which depend upon the physical and chemical nature of the nuclides. These radio-nuclides may then give rise to radiation doses which are either external, e.g. from radio-nuclides in air, on the ground or in sediments, or internal, e.g. from radio-nuclides deposited in tissues following intake into the body. Estimations of doses from discharges by the nuclear power industry are more likely to require consideration of local situations than those from weapons tests fall-out because members of the public are likely to be relatively near such installations. As a result of this, short-lived nuclides, e.g. certain isotopes of krypton and xenon, and radio-nuclides whose properties may make them of significance to man in a particular environment, e.g. water-borne ^{106}Ru , give radiation exposures to defined population groups following pathways that are not relevant to fall-out from weapons tests.

1. Atmospheric pathways

318. Radio-nuclides in airborne wastes may be discharged by the nuclear power industry in gaseous, vapour or particulate form. Dispersion of a plume of airborne materials in the atmosphere has been described by a gaussian distribution (593), and working methods for quantitatively predicting dispersion have been

evolved (e.g. 85, 481, 482, 565). The basic methods apply to level ground in open country during meteorological conditions ranging from substantial solar heating of the ground, resulting in considerable turbulence, to inversion conditions when temperature rises with height above ground and turbulence is suppressed. Modifications of the basic methods may be necessary to take account of the presence of obstacles, e.g. buildings or trees, or of discharge from a stack.

319. Airborne radio-nuclides may be deposited by dry deposition resulting from very small-scale turbulent diffusion processes which lead to impaction and/or adsorption of radio-nuclides on surfaces (106). The dry-deposition velocity varies with the physical and chemical form of the radio-nuclide; an outstanding example of this variation occurs with iodine which may be discharged from the nuclear power industry in several different forms (22, 30, 107, 196). Radio-nuclides may also be deposited by means of wash-out by rain falling through contaminated air at a rate which depends on the rainfall rate and on the form of the airborne material (160, 161).

320. If iodine is deposited on pasture grazed by dairy cows, a proportion is transmitted to milk (paragraphs 214-215) which may subsequently be consumed by infants. This pathway is not important, however, for heavy elements such as uranium and plutonium, which are not absorbed significantly from the gut into the cow's bloodstream (116) and, hence, are not transmitted to milk. Nor is the pathway important in the many countries where milk is either not produced near nuclear power sites or does not contribute significantly to diet. Other pathways which may lead to internal radiation exposure of man involve deposition on growing crops and soil, and on pastures used for animals providing meat for human consumption. An additional pathway leading to internal irradiation is inhalation of radio-nuclides in the plume of airborne wastes from the stack; in the special case of tritiated water, intake also occurs by absorption through skin (472) (paragraphs 362 and 395).

321. Beta and/or gamma emitting radio-nuclides in the plume or deposited on the ground may give rise to external radiation exposure of man. Many of the fission-product noble gases emit both types of radiation, the beta component usually irradiating only the skin. The shorter-lived kryptons and xenons mainly irradiate populations which may be described as local (paragraph 359) in contrast to the longer-lived ^{85}Kr which irradiates local populations as the plume is dispersed downwind, and subsequently irradiates the world population when the ^{85}Kr is dispersed in the global atmosphere (652) (paragraphs 392 and 396).

2. Pathways involving the aquatic environment

322. Radio-nuclides may also be discharged by the nuclear power industry in liquid and solid wastes and enter the aquatic environment by mixing and leaching processes. Water-borne radio-nuclides may be further dispersed, or be re-concentrated on sediments or in biota (paragraph 323), as local and general movement of surface and ground water proceeds. This pathway leading to radiation exposure of man is more important for the nuclear power industry than for weapons tests, which have taken place mainly in the atmosphere. Mixing and exchange processes in the sea with special reference to radio-active waste disposal were reviewed in 1961 (261).

323. Re-concentration of radio-nuclides on inanimate matter or in biota depends critically on the specific nuclide involved, its chemical form, which may change with time due to reaction with other constituents of the water, and the presence or absence of a stable homologue acting as a carrier. It also depends on metabolic and/or physical characteristics of the biota and sediments. Whilst concentration factors ranging from just under one to about 10^5 have been observed in particular circumstances, these should not be applied in the course of dose estimations to situations where the conditions are unknown or different from those in which the factors were measured (109, 184). Measurements of ^{134}Cs and ^{137}Cs in environmental materials provide evidence of the complex situation involving the interdependence of contamination of biota and inanimate matter as a result of fall-out from weapons tests and discharges of these nuclides by the nuclear power industry (paragraphs 355-357).

324. Utilization of fresh and sea water provides many environmental pathways for internal radiation exposure of man. Exposure of local (i.e. not global) populations may result from consumption of contaminated fish caught recreationally (paragraphs 356, 357, 386, 390) or commercially (paragraphs 356 and 390), or of an edible seaweed marketed commercially (paragraphs 387-389). Tritiated water discharged in liquid wastes may result in radiation exposure to local populations who ingest contaminated water or locally-produced food-stuffs (paragraph 391), or to the world population when ^3H is dispersed in the water of the globe (paragraph 397). Radio-nuclides re-concentrated on estuarine silt may result in external radiation exposure of a few persons using the area for fishing (paragraph 390).

C. ASSESSMENT OF RADIATION DOSES TO MEMBERS OF THE POPULATION

325. Doses incurred by the population can be assessed either by an adequate knowledge of the quantity discharged and of the transfer parameters involved (dispersion, re-concentration factors, etc.), or by means of a programme of environmental monitoring which is usually related specifically to pathways selected as being of greatest importance.

326. It should be recognized that both approaches have serious shortcomings for the dose assessments required in this report. Calculations based on transfer models are subject to considerable uncertainty due to the complexities involved in field conditions. In many cases, the simplified models available are unrealistic. Monitoring routines, on the other hand, are frequently geared to ensure compliance with accepted limits and therefore provide insufficient information on the very low doses which may be incurred by members of the public. An additional difficulty in the interpretation of monitoring results may be due to the presence of fall-out nuclides in considerably larger amount than that of the same nuclides discharged from the nuclear industry. Furthermore, in many instances the discharges are so small that the resulting environmental levels are too low to measure by usual techniques. In view of the small contribution by the nuclear power industry to total dose commitments to members of the public, there has been no requirement to date for more sensitive methods of analysis and dose estimation.

D. EXPOSURES FROM MINING AND MILLING

327. The first stage in the nuclear power industry is mining of uranium-bearing ores. As explained in Part One of this annex, the isotope ^{238}U , which constitutes about 99.3 per cent of natural uranium, is the radio-active parent of a long chain of daughter products, of which ^{226}Ra , ^{222}Rn and ^{210}Po are the most important from the radiation protection point of view (paragraphs 74-75). The mining processes give rise to liquid wastes which may be of local interest.

328. Most of the uranium is leached from the ore during milling and recovered in the subsequent chemical treatment, but the majority of radio-active daughter products in raw ore remain in the mill waste (609). A study of ^{226}Ra balances at mills employing different processes showed that most of the ^{226}Ra is present as suspended solids in mill tailings, which consist of about 99 per cent of the ore fed to the mill and are discharged on to tailings piles (609).

329. Liquids from these piles drain into tailings ponds which allow deposition and retention of ore solids and associated radio-activity. This represents a basic minimum form of treatment. Evaporation from tailings ponds in dry climates or re-use of water may reduce substantially the quantity of radio-active daughter products which reach surface or ground waters (421). Chemical treatment of process streams may also reduce significantly the concentration of dissolved pollutants, including ^{226}Ra , ^{210}Pb and various chemical components (609).

330. Solids in tailings piles are estimated to have totalled about 83 million tonnes by 1969 in the United States alone (562). This accumulation is the result of the sudden demand for uranium during the increase in the nuclear weapons production experienced in the United States after World War II. At that time, technological efforts were concentrated on the development of ore-refining facilities and on economical refining processes, and little attention was paid to waste materials. As a consequence, effective waste treatment or containment was lacking for several years (562).

331. A comprehensive survey of about 30 uranium mills in the United States was undertaken by Merritt (421) in 1967; of these half were disused. The survey showed that operators of mills still in use were planning and conducting current operations with the objective of total containment of solids and of controlling the discharge of water-borne radio-active daughter products. A proportion of the uranium output of these mills is used by the nuclear power industry.

332. Information on environmental contamination by radio-active daughter products discharged from uranium mills relates only to the legacy of past practices for disposal of ore solids and contaminated liquids and is not relevant to future production of uranium for use by the nuclear power industry. The use of tailings as fill material in habitable structures in Grand Junction, United States, is discussed in annex D.

E. EXPOSURES FROM FUEL FABRICATION AND ENRICHMENT

333. The process of fuel fabrication usually starts with the uranium-ore concentrates produced at the mills. These concentrates are further purified by chemical processing involving the use of nitric acid and

fluorine and, if fuel enriched with the ^{235}U isotope is required, the volatile uranium hexafluoride is produced. Subsequent to enrichment, usually in a multi-stage diffusion plant, this product is converted by various processes (involving ammonia as a gas or a dilute solution, steam and hydrogen) to uranium as dioxide or metal, as required (199, 534). The final stage in fuel fabrication involves the addition of cladding material.

334. Fuel fabrication and enrichment give rise to various types of wastes. Most uranium compounds are solid and conventional air-cleaning equipment is used to remove particulates from airborne wastes. The quantity of uranium and other chemicals in liquid wastes is reduced by suitable treatment before discharge to the environment; uranium wastes and contaminated plant and other equipment are buried under controlled conditions. No data on wastes discharged from fuel fabrication plants are available to the Committee; however, these wastes are of little significance from the radiation protection point of view as they consist at present largely of uranium.

335. Thermal reactors currently employed in power production use uranium fuel, but some advanced reactor types now under development are based on fuel consisting of mixed uranium and plutonium oxides or carbides. The addition of plutonium to the fuel does not radically alter the processes required in its fabrication, but it does have an influence upon the potential environmental effects of material discharged because of the high radio-toxicity of plutonium, particularly when inhaled. The plants required for producing plutonium fuel are designed to provide more thorough containment at all stages including storage of wastes.

F. EXPOSURES FROM NUCLEAR POWER REACTORS

1. Origin and amount of radio-nuclides produced

336. The production of power in nuclear reactors is accompanied by the formation of fission products and activation products. Studies of slow-neutron fission of ^{235}U and ^{239}Pu show that the masses of over 80 fission products generated during fission fall largely into two groups, a "light" group with mass numbers 80 to 110 and a "heavy" group with mass numbers from 125 to 155. Fission yields for the various mass numbers range up to over 6 per cent and vary with the fissile nuclide (199). Total ^{235}U and ^{239}Pu fission yields for nuclides of particular interest for this section are given in table 54, together with their radio-active half-lives.

337. Production rates of fission ^3H and ^{85}Kr are of interest because virtually all the activity produced is at present discharged to the environment during reprocessing. Data on production rates of ^{129}I are included with those for ^3H and ^{85}Kr in table 55 because some of the ^{129}I produced may be discharged to the environment and its radio-active half-life is very long ($1.7 \cdot 10^7$ y). Production rates per MW(e) y are given for thermal and fast fission; in practice there will be a gradual transition from ^{235}U to ^{239}Pu , because many thermal reactors will burn a significant amount of ^{239}Pu produced from ^{238}U in fuel.

338. Annual production rates (table 55) of ^3H , ^{85}Kr and ^{129}I are calculated on the basis of (a) the power produced in 1970 (9.7 GW(e)) and (b) the estimated world capacity of 4,300 GW(e) in the year 2000 (table 53) consisting of 70 per cent fast-breeder reactors, as projected for the United States (465).

Values are also given in table 55 for the integrated amounts produced and the cumulative amounts of these nuclides remaining when decay is taken into account. In all cases a load factor of 0.5 and a thermal efficiency of 0.3 are assumed. The values given for the year 2000 are very approximate as estimates of world nuclear generating capacity vary by a factor of about four (table 53) and the production rate of each of ^3H , ^{85}Kr and ^{129}I differs by a factor of about two according to the fissile material (table 55). The values for ^3H include only that produced by ternary fission in fuel.

339. Tritium is also produced by neutron activation of ^3H . In light-water reactors the rate is estimated to be about 0.004 Ci (MW(e) y) $^{-1}$, but in heavy-water reactors it could be as high as 30 Ci (MW(e) y) $^{-1}$ (505). Tritium in quantities intermediate between these values is also produced by activation of other reactor components such as boron and lithium used for neutron-density control (505) (table 56). These sources could add appreciable amounts to the ^3H produced by ternary fission, but the amounts vary too much depending on reactor design to be included in the estimates in table 55.

340. Besides ^3H , a large variety of activation products is formed in a nuclear reactor (table 56). Some of them, such as ^{134}Cs and some actinide radio-nuclides, are formed in the fuel and their activities can be calculated from data on burn-up and the neutron energy spectrum. The most important actinide radio-nuclide is ^{239}Pu which, being a fissile element, is also burnt up as fuel. Reported activities of ^{239}Pu in spent fuel are 160 Ci t $^{-1}$ for fuel in advanced gas-cooled reactors (AGRs) (54) and 330 Ci t $^{-1}$ for fuel in light-water reactors (LWRs) (465). ^{134}Cs is produced by neutron activation of ^{133}Cs , which is one of the most abundant stable nuclides formed by fission. ^{134}Cs activity in AGR fuel, after a burn-up of 18,000 MW(th) d t $^{-1}$ at a specific power of 10 MW (th) t $^{-1}$, has been calculated to be about 20 per cent of that of ^{137}Cs (112).

341. The other radio-nuclides listed in table 56 are produced by activation of reactor components other than fuel. The cross-sections for production of those nuclides are given in table 56 but their activities cannot be calculated without a knowledge of the isotopic composition of the materials used in the reactor components and of the spatial distribution of the neutron flux and energy spectrum. Neutron irradiation of graphite or of carbon dioxide leads to the production of ^{14}C and irradiation of ^{16}O contained in air or water results in the formation of ^{13}N and ^{16}N . ^{41}Ar is produced by activation of air which contains ^{40}Ar in the proportion of about 1 per cent. The presence of chromium, cobalt, or zinc in metals gives rise to the formation of ^{58}Co , ^{60}Co , ^{51}Cr and ^{65}Zn .

2. Discharges to the environment

342. The emphasis in this report is on data which specify individual radio-nuclides discharged and which are, therefore, relevant to the estimation of radiation doses to man. Data on discharges are not available for some of the operating reactors and are limited in scope for others, being mainly in the form of gross activity measurements. Comprehensive studies giving information on individual nuclides discharged have been carried out in the United States on a boiling-water reactor (BWR) (304) and a pressurized-water reactor (PWR) (303). These are both light-water reactors

(LWRs). In addition, a detailed study has been made of the Hudson River (USA) to which radio-nuclides from a PWR are discharged (357). There is a small amount of information for similar reactors in other countries.

343. Limited information on individual nuclides discharged is available for gas-cooled reactors (GCRs) (88, 146, 499) and pressurized heavy-water reactors (PHWRs) (400). Discharges of noble gases from all of the above types of reactors are relatively well documented. Other reactor types, such as fast breeder reactors (FBRs) and organic moderated and cooled reactors (OMRs), are still at the development or design stage, and no information on discharges is available.

(a) Liquid discharges

344. Tritium is present in the coolant of water-cooled reactors (paragraph 339) and some of this is discharged with miscellaneous liquid wastes arising in connexion with reactor operation. Quantities discharged in each of the years 1968-1970 are given in table 57, which also shows the quantities of ^3H discharged per unit of power generated. It is clear that PWRs and the PHWR have discharged much more ^3H than BWRs. Various causes contribute to the difference. The use of dissolved boron in PWRs and of heavy water in the PHWR gives rise to considerable quantities of activation product ^3H in the coolant. Stainless-steel cladding used on fuel elements in the first four PWRs listed in table 57 allows greater diffusion of fission product ^3H into the coolant than the zircaloy cladding on fuel elements used in Dresden-I (BWR) and Ginna (PWR) in the United States.

345. Discharges of ^3H in liquid wastes from gas-cooled reactors in 1969 and 1970 are given in table 58. These vary considerably from station to station, but are on average somewhat more than those from BWRs and less than from PWRs in total quantities discharged and quantities per MW(e) of power generated. The ^3H is partly fission-product ^3H from cooling ponds and the gas-coolant drying plant, and partly activation-product ^3H (146).

346. Individually-measured radio-nuclides discharged in liquid wastes are listed in tables 59 and 60 for water- and gas-cooled reactors, respectively. They are discharged as mixtures of fission and activation products. The nuclides are often very difficult or costly to measure individually, and the usual practice is to estimate gross beta and gamma activity only, unless this is abnormally high.

(b) Discharges of noble gases

347. Discharges of noble gases constitute the main source of external radiation around reactors. A very small proportion of the ^{85}Kr in fuel is discharged at reactor sites and all the remainder is released from fuel during reprocessing. Discharges of ^{85}Kr to the environment are discussed in paragraphs 377-378. In general, the total noble-gas activity discharged, which consists mainly of kryptons and xenons, is highest in BWRs and lowest in PWRs (table 61).

348. Activation gases are discharged from some reactors, particularly some GCRs and PHWRs (table 61). Activation of subsidiary-cooling air leads to discharge of ^{41}Ar at a rate which depends on the char-

acteristics of the reactor; discharge of gases activated in the primary coolant occurs as a result of leakage and of operational need (262).

349. In LWRs, discharges consist mainly of fission gases which enter the coolant from fuel. The composition of noble fission gases is presented in table 62 for various decay times. In BWRs, gases are discharged after a 20-30 minute hold-up of the off-gas stream to achieve removal by decay of most of the original activity (324). Table 63 shows that the measured composition of gases discharged from the Dresden-I BWR agrees reasonably well with results computed for a 21 minute decay.

350. In PWRs, gases are discharged when the coolant is depressurized after a hold-up time of up to 120 days. Values for the discharge of radio-active gases from PWRs, which consist mainly of ^{133}Xe , are shown in table 61.

(c) Other gaseous and particulate discharges

351. Discharges of other gaseous and particulate radio-nuclides to atmosphere are usually reported in general terms, such as halogens and particulates. Information available for ^3H and gaseous ^{131}I is summarized in table 64. The tritiated water discharges from the PHWR at Douglas Point in Canada resulted largely from the high production rate of ^3H in the heavy-water coolant and moderator (400). The discharges of ^{131}I from Dresden-I, Yankee Rowe and Douglas Point reactors were less than one curie per year, although the total ^{131}I content of these reactors when at their full power of about 200 MW(e) is of the order of 10^7 curies. Discharges of particulates from Dresden-I and Yankee Rowe were also well under one curie per year (303, 304), while airborne particulates from the PHWR are removed by filtration and are not normally present in detectable quantities (400). As well as ^{41}Ar , ^{14}C and the short-lived ^{16}N , the radio-nuclide ^{35}S has been reported as a constituent of GCR stack gases in the United Kingdom (499).

3. Doses resulting from environmental contamination

(a) Doses from radio-nuclides discharged to the aquatic environment

352. Radio-nuclides are discharged to rivers, sometimes in tidal reaches, or to large lakes from all the water-cooled reactors listed in table 57 except Oyster Creek and San Onofre, from which they are discharged directly to the Atlantic and Pacific Oceans, respectively. Radio-nuclides are discharged to the coastal waters of the British Isles from all the United Kingdom gas-cooled reactors listed in table 58, except those at Trawsfynydd from which they are discharged to a fresh-water lake. In the case of the reactor at Latina in Italy, they are discharged to the Mediterranean.

353. The highest measured values of tritium concentrations in environmental samples near three PWR sites quoted by Krieger *et al.* (345) relate to discharges and not to water available for intake by members of the public. The only published estimates of the very low doses to local populations due to tritium discharged are based on conservative assumptions of dilution and intake (59, 345, 400).

354. Detailed environmental studies have been conducted near two of the water-cooled reactors in the

United States for which data on specific radio-nuclides in liquid discharges are given in table 59. The study in the Illinois River near the Dresden-I reactor took place during a nine-month period in 1968 (304) and a comprehensive research programme on the Hudson River estuary, into which radio-nuclides from the Indian Point-I reactor are discharged, was carried out from 1964 to 1970 (357). A comprehensive monitoring programme is also in operation on the coastal waters of the British Isles into which four of the reactor sites listed in table 60 discharge their wastes, and on Lake Trawsfynydd to which the fifth site discharges (426, 427).

355. Monitoring results require considerable interpretation before an estimate of doses to members of the public can be made. For example, as ^{137}Cs is often the nuclide which contributes most of the dose when contaminated fish or other aquatic food-stuffs are eaten by humans, it is desirable to distinguish ^{137}Cs from reactor operations from that in fall-out. The presence of the shorter-lived isotope ^{134}Cs in the former is of assistance here and its use is suggested in the studies of the $^{134}\text{Cs}/^{137}\text{Cs}$ ratio in biota in the brackish water of the Hudson River. These studies indicated that intake of caesium by the biota was mainly from freshly introduced caesium isotopes from the reactor rather than ^{137}Cs from fall-out retained on bottom sediments (357).

356. Mean caesium concentrations measured in fish at Dresden-I, Indian Point-I and Trawsfynydd are shown in table 65. The mean ^{137}Cs concentration of 0.015 pCi g^{-1} wet in various species in the Illinois River near Dresden-I is the average of upstream and downstream values because there was no significant difference between them. The discharges of radio-caesium into the Hudson River from Indian Point-I produced a measurable difference between upstream and downstream samples for both ^{134}Cs and ^{137}Cs and, in this case, it is possible to calculate doses resulting from material discharged. The dose from both isotopes was estimated to be $10^{-6} \text{ rad y}^{-1} \text{ per g d}^{-1}$ of fish consumed (table 65). Commercial and recreational fishing take place in the affected reaches of the Hudson but neither the fish consumption rates nor the size of the population involved are known. Other nuclides (^{58}Co , ^{60}Co and ^{54}Mn) were also measured in fish, but they did not add appreciably to the dose due to the radio-caesium discharged.

357. Mean caesium concentrations measured in trout and perch from the lake at Trawsfynydd (426), where about 100 persons consume fish caught recreationally (323), are shown in table 65. Although some of the ^{137}Cs in fish from Lake Trawsfynydd may be from fall-out, the ratio of $^{137}\text{Cs}/^{134}\text{Cs}$ in the fish in 1969 was similar to that in the discharge in that year. The total annual whole-body dose due to radio-caesium is estimated to be $2 \cdot 10^{-4} \text{ rad y}^{-1} \text{ per g d}^{-1}$ of fish consumed (table 65). Values for 1970 were somewhat lower than those for 1969 (427).

358. Population dose commitments from discharges from three United Kingdom reactor sites are shown in table 66 (323). The dose commitments have been taken to be equal to the annual doses (thus implying that the various components of the food chain are in equilibrium). In the table, individual and population dose commitments are based on the consumption and

exposure rates quoted for the exposed population groups.

(b) *Doses from noble gases discharged to atmosphere*

359. Noble gases in airborne wastes cause external radiation exposure which decreases rapidly with distance from the reactor as a result of the short half-life of most of the gases discharged and of dispersion of the plume in the atmosphere. Annual doses to populations living in the vicinity of nuclear power plants are a function of the population distribution, meteorological characteristics and distance from the site boundary. Average annual doses in 1969 (table 67), both at the site boundary and for the population included within 6.4 and 80 kilometres of these plants, have been calculated (188) using realistic population distributions and wind frequencies for 11 power reactor sites in the United States and average meteorological conditions. Because no allowance has been made for the time spent in buildings and the shielding afforded by them, these doses are overestimated. As expected, the doses vary widely from one power plant to another and in the case of BWRs are much less for new reactors than for old ones because of technical improvements. The population dose beyond 80 kilometres will depend upon the amount of comparatively long-lived nuclides, particularly ^{133}Xe , present in the discharge. The ratio between the long-distance and the short-distance contributions to the population dose will increase if the radio-active gases are stored for a period sufficient to allow the short-lived components to decay, thus increasing the proportion of longer-lived components in the mixture. The contribution from ^{85}Kr is insignificant because most of the ^{85}Kr is released from the reprocessing plants (paragraph 369).

360. Estimates of doses at the site boundary of some of the reactors listed in table 61 are shown in table 68. Where annual doses at or near the boundary have not been reported, they have been estimated using the assumptions indicated in the table.

(c) *Doses from radio-nuclides following other pathways*

361. A survey in the vicinity of the Dresden-I reactor, where discharges in 1968 of a number of radio-nuclides to atmosphere and the aquatic environment were up to one curie (tables 59 and 64), showed that few of the environmental samples contained any activity attributable to the discharges (304). ^{131}I was measured in thyroids of heifers allowed to graze on pasture for several weeks before slaughter, specifically as indicators of contamination, but was not detected in milk from a herd at the nearest dairy. This and other negative results in a range of other environmental materials, including cabbage, deer and rabbit, led to the conclusion that exposure to the surrounding population through consumption of food and water from radio-nuclides discharged from Dresden-I was not measurable.

362. Doses may be incurred by the population at large living near reactors from which tritiated water is discharged to atmosphere. If ^3H intake is limited to inhalation and passage through the skin, drinking water and food being uncontaminated, the dose at the boundary fence is calculated to be $7 \cdot 10^{-7} \text{ rad (MW(e) y)}^{-1}$ for the Douglas Point PHWR (400). Considerably smaller amounts of ^3H are discharged from reactors of other types (table 64) and the doses are correspondingly lower. The contribution of ^3H discharges to global doses is discussed in paragraph 397.

G. EXPOSURES FROM FUEL REPROCESSING AND WASTE DISPOSAL

1. Fate of the radio-nuclides in fuel fed to a reprocessing plant

363. At the end of its useful life in the reactor, fuel is removed and immersed in a cooling pond at the reactor site to allow substantial decay of many short-lived nuclides. This decreases potential radiation and other hazards during subsequent handling, transport and reprocessing of fuel, and simplifies the recovery of valuable fissile materials, e.g. ^{235}Pu and uranium.

364. The principle widely employed in reprocessing plants is to separate plutonium and uranium from fission products by a multiple-stage extraction process that leaves the fission and corrosion products in aqueous solution. The aqueous solution from the first extraction usually contains more than 99.9 per cent of the fission products from the dissolved fuel (611); this highly radio-active solution is often concentrated by evaporation before storage in specially constructed and protected steel tanks, sometimes located underground. In some cases the solution is allowed to boil, in others it is cooled, but there is always a gaseous stream which may carry entrained fission products from the solution. This process stream is filtered before being discharged to the environment.

365. Although the storage of highly radio-active solutions has been satisfactory hitherto, potential problems associated with long-term maintenance and supervision of containment have led to investigation of methods of permanent disposal (547). The principle common to most of the methods is to convert the solution to suitable solid material that will withstand effects of high radiation levels, and to store or bury it in selected man-made or natural locations. There would be little airborne or water-borne radio-activity released from stored solidified wastes, but clean-up problems of gaseous process streams might be severe during solidification processes. The decision to apply the principle of solidification has already been made in the United States, where liquid storage is to be permitted only during the first five years after reprocessing (43).

366. Various aqueous solutions of fission products of relatively low activity concentration are produced as a result of the washing of organic solutions of plutonium and uranium separated from the bulk of the fission products during the multiple stage process. In some cases, chemical or other treatment may be employed to reduce the quantity of many of the radio-nuclides in these solutions, before they are mixed with other lower-activity solutions. The latter may arise from the decontamination of process equipment, protective clothing and personnel, as well as from scrubbers or similar devices used to remove radio-activity from gaseous streams. At present these waste solutions, which may be of very large volume, are discharged to the environment by way of dry wells or open pits in the ground (618) or directly into the sea (253).

637. The aqueous waste currently discharged to the environment contains, as tritiated water, virtually all of the fission-product ^3H present in fuel at dissolution (table 55), although advanced technology may reduce the rate of discharge from future reprocessing plants by factors of 10 to 100 (465). For the same reason that ^3H is practically unrecoverable after tritiated water

has been diluted with ordinary water, ^3H will not be expected to concentrate in biological material.

368. Other radio-nuclides present in fuel whose characteristics make them of interest in the present context are the noble gases ^{85}Kr and ^{133}Xe , and two isotopes of iodine, ^{129}I and ^{131}I .

369. Almost all of the ^{85}Kr produced in thermal reactors (table 55) remains in the fuel until dissolution, unless the cladding becomes defective in the reactor. The normal cooling time of about six months does not materially affect the amount of ^{85}Kr available for discharge because its half-life is relatively long (10.7 y) but methods have been developed to absorb and store the gas for a period of several half-lives (149, 420, 566).

370. The fission product ^{133}Xe has a short half-life (5.3 d) and its equilibrium level is about 1 MCi t^{-1} at a power level of 20 MW(th) t^{-1} (table 54). The activity decays to $10^{-4} \text{ Ci t}^{-1}$ when fuel is cooled for about six months. If fast-reactor fuel is cooled for only 30 days before reprocessing, the corresponding content would be about $2 \cdot 10^4 \text{ Ci t}^{-1}$. The $^{131\text{m}}\text{Xe}$ content of fuel is two orders of magnitude less than ^{133}Xe (table 54) but its longer half-life (12 d) results in a slower rate of decay than with ^{133}Xe . Several processes involving hold-up on a charcoal bed may be employed to produce an order of magnitude reduction in the radio-xenon activity discharged (465).

371. Because of its very long half-life ($1.7 \cdot 10^7 \text{ y}$), virtually all of the ^{129}I produced in small amounts in nuclear fuel (about 0.02 Ci t^{-1}) is present at the time of dissolution (87, 537). ^{131}I has a half-life of only eight days and after the usual cooling period for thermal-reactor fuel of about six months, the ^{131}I content of fuel is about 0.1 Ci t^{-1} . It is normal practice to employ general-purpose scrubbers with a decontamination factor of up to 1.000 to reduce the amounts of airborne radio-iodine discharged from the plant (90, 465).

372. The reprocessing of short-cooled fast-reactor fuels is likely to be part of a combined fast- and thermal-reactor programme because there will be a strong economic incentive to reduce to a minimum the quantity of plutonium required for the whole power programme. Investigations into control of airborne ^{131}I discharges during reprocessing of such fuel have shown that process streams will require decontamination factors well beyond those currently in use (90, 465). Because of this, discharges of ^{129}I will also be much less than the quantities in the fuel reprocessed.

2. Discharges to the environment

(a) Liquid discharges

373. The quantity of radio-nuclides discharged to the environment from reprocessing plants depends largely upon waste-management practices. These, in turn, depend upon the characteristics of the local environment and population and on the requirement of ensuring compliance with accepted radiation protection criteria. At the first commercial reprocessing plant (Nuclear Fuel Services, NFS) in the United States (393) low-activity solutions are discharged to lagoons which provide additional decontamination through settling during storage. Liquids from the lagoons are then discharged to creeks and rivers in the environment.

374. Data for individual nuclides discharged from NFS during a six-month period of special study in 1969 are given in table 69. Investigation of the distribution of the various radio-nuclides between dissolved and suspended solids showed that most of the ^{60}Co , ^{90}Sr , ^{106}Ru and ^{125}Sb were discharged in a soluble form and almost all of the ^{54}Mn , ^{95}Zr , ^{144}Ce and ^{147}Pm were discharged in an insoluble form, whereas ^{134}Cs and ^{137}Cs were discharged in both soluble (70 per cent) and insoluble forms (393). The only nuclide discharged from NFS for which data are available over a longer period is ^3H (373). These are given in table 70 and show that quantities varying from 3 to about 100 curies of ^3H were discharged per tonne of fuel processed.

375. Discharges of low-activity solutions from the reprocessing plant at Windscale in the United Kingdom are made to the Irish Sea through a pipeline terminating about 2.5 kilometres offshore. Measurements for three of the nuclides discharged are shown in table 69; these are required by the terms of the authorization for discharge (323). The composition of the effluent has changed over the operational period of 18 years, and is still changing slowly (323).

376. The low-activity solutions from the Eurochemic reprocessing plant at Mol, Belgium, are sent to the waste-treatment plant of the Belgian Nuclear Centre. Discharges from this plant are made to a tributary of the main Neet River and data for ^{90}Sr , the only individual nuclide quoted, are given in table 69 (625).

(b) Discharges of noble gases

377. The special study carried out at the NFS reprocessing plant showed that, although essentially all the available ^{85}Kr was discharged during dissolution of the fuel, up to 1 per cent was discharged during the chopping operation prior to dissolution (113).

378. No noble gas discharge measurements are available for the Windscale reprocessing plant in the United Kingdom or the Eurochemic plant at Mol in Belgium. However, ^{85}Kr discharges from the Eurochemic plant have been estimated (13), and estimates of discharges resulting from a predicted British nuclear power programme have been published (149). The Committee has estimated ^{85}Kr discharges from future power production (table 55) on the basis of 510 Ci (MW(e) y) $^{-1}$ for thermal reactors and 270 Ci (MW(e) y) $^{-1}$ for fast reactors (assuming a thermal efficiency of 0.3). The activity discharged to the environment may be less than that present at dissolution if steps are taken to absorb and store the gases (paragraphs 369 and 370).

(c) Other gaseous and particulate discharges

379. Tritium discharged through the stack to atmosphere was measured during dissolution of the two batches of fuel in the NFS and the amount (table 71) was estimated to be about 1.5 per cent of the total available (113). Preliminary data indicated that elemental ^3H was less than 10 per cent of the total ^3H discharged to atmosphere.

380. Discharges of ^{129}I from the NFS plant (table 71) were approximately 5-10 per cent of the total available; the fuel had been cooled for unusually long periods and the scrubbers were not in operation during

these dissolution cycles. The use of scrubbers is estimated to reduce discharges to about 0.5 per cent of the available radio-iodine activities (113). Data on the average particulate activity discharged during dissolution of five one-tonne batches of fuel at the NFS plant are given in table 71 (calculated from data in reference 113). These results show that no particulate discharges to atmosphere exceeded about 10^{-7} Ci (MW(e) y) $^{-1}$.

381. A study of ^{131}I balances at the Windscale plant, which normally reprocesses fuel cooled for about six months, indicates that on average about 5×10^{-4} Ci d $^{-1}$ is discharged to the atmosphere compared with 0.4 Ci d $^{-1}$ to the sea in liquid wastes out of about 0.5 Ci d $^{-1}$ fed to the plant (90). Similarly, about 0.1 per cent of ^{129}I in fuel would be expected to be in current discharges to the atmosphere.

382. The expected discharges of particulate ^{90}Sr , ^{137}Cs and ^{144}Ce from the Eurochemic plant, calculated on the basis of design figures (13), are two orders of magnitude greater than measured discharges from the NFS plant, normalized to the same rate of ^{85}Kr discharge. Predicted discharges of ^{239}Pu from Eurochemic are three orders of magnitude greater than measured discharges from NFS when normalized.

383. The development of nuclear power programmes and the increased use of fast-breeder reactors will result in a large increase in the ^{239}Pu treated in reprocessing plants. In the United States, the annual production is predicted to be 20 tonnes during the decade 1970-1980, and 80 tonnes by the year 2000, when plutonium-fuelled reactors may account for 50 per cent of the country's total energy consumption. Whether plutonium attains its predicted role in the future power economy may depend entirely on attainment of economic methods of preventing its discharge to the environment (354).

3. Doses resulting from environmental contamination

384. Data on environmental contamination and consequent doses to members of the population are presented for two reprocessing plants, the Nuclear Fuel Services plant near Buffalo in the United States and the Windscale plant of British Nuclear Fuels Limited in the United Kingdom. These were selected because they are plants known to include in their throughput a high proportion of fuel derived from reactors producing electricity commercially. The Eurochemic plant at Mol in Belgium should also be included but information about the amounts of radio-nuclides discharged is limited to ^{90}Sr and no information is available to the Committee on the levels of contamination in food-stuffs consumed by the population.

(a) Doses to local populations due to discharges of radio-nuclides to the aquatic environment

385. Data on environmental contamination in 1968 in the vicinity of the NFS reprocessing plant, which discharges liquid wastes to a creek, were used to make dose calculations for that year (556). The special study on liquid discharges was made during 1969 (data in table 69), so it is not possible to correlate monitoring results and discharge data.

386. The mean concentrations of ^{137}Cs and ^{106}Ru in fish caught in the creek are given in table 72: the mean concentration of ^{90}Sr is not included in the

table because the values were measured for whole fish and most of the ^{90}Sr will be in inedible bone (556). The mean ^{137}Cs concentration of 0.63 pCi g^{-1} in fish corresponds to an annual dose of $2 \cdot 10^{-4}$ rad for a typical fish consumption rate of 15 g d^{-1} by members of the population. Similarly the mean concentration of ^{106}Ru of 0.85 pCi g^{-1} corresponds to an annual dose to the gastro-intestinal tract equal to $9 \cdot 10^{-4}$ rad. Assuming that the 1968 operations are typical, the annual throughput of fuel irradiated to about $20 \text{ MW(e) y t}^{-1}$ is 140 t y^{-1} (table 70) and these annual doses therefore correspond to about 10^{-7} and $3 \cdot 10^{-7}$ rad (MW(e) y^{-1}) for ^{137}Cs and ^{106}Ru , respectively (table 72). However, the numbers of people to which these doses are applicable is not stated but the numbers are probably small since the consumption of fish in the sampling area is the result of recreational fishing only.

387. A comprehensive marine monitoring programme is employed in connexion with the liquid discharges from Windscale (426, 427, 654). The critical pathway involves a type of edible sea-weed which is used in making laverbread in South Wales, 500 kilometres away. The sea-weed is monitored *inter alia* for $^{90}\text{Zr}/^{90}\text{Nb}$, ^{106}Ru and ^{144}Ce , and a study in 1967-1968 showed that ^{106}Ru contributed 82 per cent of the dose to the gastro-intestinal tract (425).

388. The ^{106}Ru concentrations in laverbread of 15 and 7 pCi g^{-1} wet in 1969 and 1970, respectively (table 72), are average values for the products of three manufacturers (426, 427). Intensive market surveys in South Wales have shown that the median rate of consumption of laverbread by a small critical group (about 100 persons) is 160 g d^{-1} , and that consumption by the whole group of 26,000 laverbread eaters is about 10 per cent of this (512). Average annual doses to the gastro-intestinal tract of the whole group of laverbread eaters, as result from ^{106}Ru contamination, were $1.7 \cdot 10^{-2}$ and $8.0 \cdot 10^{-3}$ rad per 16 g d^{-1} consumed in 1969 and 1970, respectively (table 72).

389. If the average annual throughput of the Windscale plant is taken to be about 1,800 tonnes of fuel irradiated to a level of 3 MW(e) y t^{-1} , the annual plant throughput corresponds to the generation of about 5,000 MW(e) y . Thus the above annual doses are equivalent to $3.4 \cdot 10^{-6}$ and $1.6 \cdot 10^{-6}$ rad (MW(e) y^{-1}) to members of the whole population of laverbread eaters in 1969 and 1970, respectively. The contribution from this pathway to the population dose commitment to the gastro-intestinal tract is therefore about 0.09 and 0.04 man-rad (MW(e) y^{-1}) in these years. The contribution to the population gonad dose is lower by a factor about 1,000 (88).

390. Dose commitments to small groups exposed through other pathways are given in table 73. The contribution to the population dose is, however, very small because of the small numbers of individuals exposed as well as the generally smaller individual dose commitments. On the other hand, plaice is fished commercially over a wide area of the Irish Sea and radio-caesium contamination of the fish is estimated to give rise to a population whole-body dose commitment of $3 \cdot 10^{-2}$ man-rad (MW(e) y^{-1}) (427). This is over three orders of magnitude greater than the population whole-body dose commitment resulting from consumption of fish by the much smaller group of 100 persons (table 73).

391. Concentrations of ^3H have been measured in various local food-stuffs around the NFS plant (556). Although ^3H discharged to the atmosphere may have contributed to amounts of this nuclide in such food-stuffs as deer meat and milk, the fraction coming from this source (1.5 per cent of the total discharged) is probably small compared to that coming from liquid discharges. Observed levels in milk were similar to those to be expected from ^3H released by the testing of nuclear weapons in the atmosphere. Levels in fish were about 10 times greater than those expected from fall-out alone while levels in deer were about 30 times greater. The latter results suggest that the deer were obtaining drinking water from the creek at points closer to the plant than the points where the fish were sampled. Members of the public eat deer meat and fish caught in the area, but Shleien (556) concluded that doses from ^3H to individuals eating typical amounts of these local food-stuffs were negligible.

(b) *Doses to local populations from discharges of noble gases to atmosphere*

392. Assuming a ^{85}Kr discharge of $510 \text{ Ci (MW(e) y)}^{-1}$ (table 55), the average rate of discharge of this nuclide from a plant processing fuel from a thermal reactor at the rate of 1 MW(e) y annually is about $1.6 \cdot 10^{-5} \text{ Ci s}^{-1}$. At a distance of a few kilometres the long-term mean concentration in ground-level air is about $10^{-7} \text{ Ci m}^{-3}$ per Ci s^{-1} discharged (85) so that the concentration near the plant would be about 1.6 pCi m^{-3} and the gonad dose commitment $2.7 \cdot 10^{-8}$ rad (MW(e) y^{-1}). The actual dose received by members of a population near a reprocessing plant would, of course, depend on the quantity and irradiation of fuel processed. Similarly, the dose to the population would depend on the population distribution around a specific plant. Taking the estimates of average concentrations per unit rate of discharge as a function of distance given by Bryant (85), and a uniform density of 100 persons per square kilometre, the population gonad dose commitment is $5.4 \cdot 10^{-3}$ man-rad (MW(e) y^{-1}) to the population (about 20 million) living within 250 kilometres of the site (table 74).

(c) *Dose to local populations due to other airborne radio-nuclides*

393. The concentrations of ^{90}Sr in milk from farms about five kilometres from the Windscale plant are not significantly different from those expected (typically $15 \text{ pCi (gCa)}^{-1}$) from the fall-out from weapons tests (654). Somewhat higher levels (about $40 \text{ pCi (gCa)}^{-1}$) have been found at farms nearer the site but these are believed to be due to the ^{90}Sr deposited as a result of discharges from the experimental reactors at Windscale during their early years of operation (414).

394. Levels of ^{90}Sr and ^{137}Cs in the diet, excluding fish and deer caught locally, of persons living near the NFS plant in New York State cannot be distinguished from those observed elsewhere in the state which arise from the fall-out from nuclear weapons tests.

395. Doses to individuals living near the reprocessing plants, resulting from discharges of ^3H to the atmosphere, can be calculated using methods similar to those used to estimate corresponding doses

from ^{85}Kr . Thus, taking the ^3H production rate of a thermal reactor to be $21 \text{ Ci (MW(e) y)}^{-1}$ (table 55), the average from a plant handling fuel at the annual rate equivalent to 1 MW(e) y is $6.3 \cdot 10^{-9} \text{ Ci s}^{-1}$ assuming that 1 per cent of the total ^3H is discharged to the atmosphere (paragraph 379). At a long-term concentration of $10^{-7} \text{ Ci m}^{-3}$ per Ci s^{-1} discharged (paragraph 392), the concentration in ground-level air within a few kilometres of the plant would be $6.3 \cdot 10^{-4} \text{ pCi m}^{-3}$ and the annual dose to the persons exposed $6.3 \cdot 10^{-10} \text{ rad (MW(e) y)}^{-1}$. For the population within 250 kilometres of the site as previously described the corresponding population dose commitment is about $10^{-4} \text{ man-rad (MW(e) y)}^{-1}$ (table 74).

(d) *Doses to the world population resulting from ^{85}Kr and ^3H discharged by the nuclear power industry*

396. Since the beginning of the nuclear era the concentration of ^{85}Kr in the atmosphere has steadily increased (figure XXXII) from 0 to about 15 pCi m^{-3} in 1970 in the middle latitudes of the northern hemisphere (45, 130, 142, 153, 154, 327, 476, 477, 545, 560, 561). From experimental results of the distribution of ^{85}Kr throughout the troposphere (figure XXXIII) the Committee has calculated that a world-

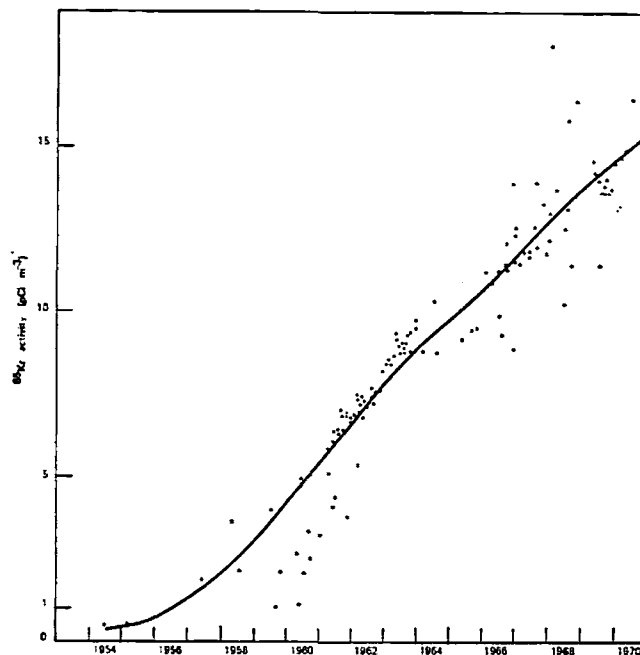


Figure XXXII. Activity of ^{85}Kr in northern hemisphere air samples (45, 130, 142, 153, 154, 327, 476, 477, 545, 560, 561)

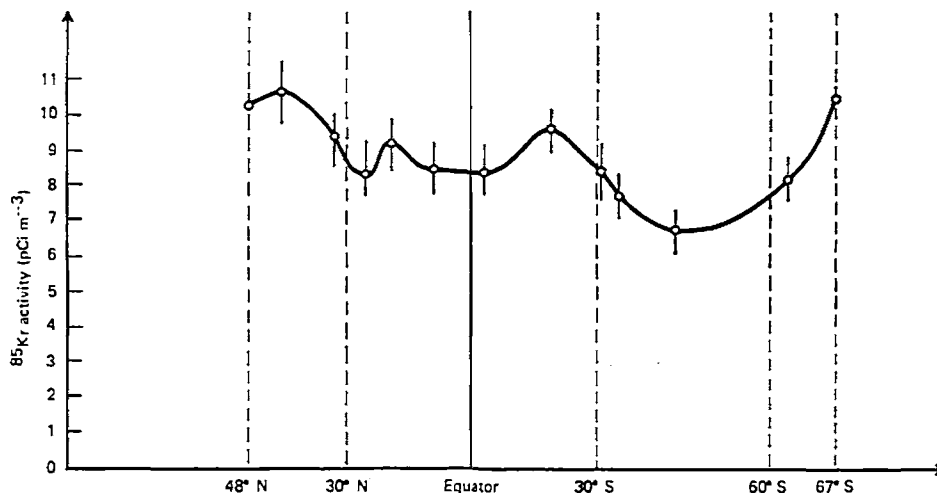


Figure XXXIII. Activity of ^{85}Kr in ground-level air as a function of latitude at the end of 1964 (476)

wide average concentration at sea level of 4.6 pCi m^{-3} corresponds to the cumulative amount of ^{85}Kr in the world in 1970 due to nuclear power production (19 MCi , table 55). The average concentration due to the discharge of $510 \text{ Ci (MW(e) y)}^{-1}$, would, therefore, be about $1.2 \cdot 10^{-4} \text{ pCi m}^{-3}$. But a ^{85}Kr concentration of 1 pCi m^{-3} delivers $1.7 \cdot 10^{-8} \text{ rad y}^{-1}$ to the gonads (table 22), so that the gonad dose commitment resulting from generation of one megawatt-year of electricity by a thermal reactor is $3.1 \cdot 10^{-11} \text{ rad (MW(e) y)}^{-1}$ (table 74). The gonad dose commitment per year of generation of electricity at the 1970 rate is thus about $3 \cdot 10^{-7} \text{ rad}$. In the year 2000, because of the large proportion of fast reactors, the dose commitment per unit of power generated given above does not apply. The gonad dose commitment per year of generation of electricity at the rate estimated for the year 2000 has been calculated from the ratio of the annual production of ^{85}Kr in the years 2000 and 1970 given in table 55 and has been found to be $4.5 \cdot 10^{-5} \text{ rad}$.

397. From the relationship that $1,900 \text{ MCi } ^3\text{H}$ produced in weapons tests up to 1963 gives rise to a dose commitment of $4 \cdot 10^{-8} \text{ rad}$ (paragraph 166) and the value of $21 \text{ Ci } ^3\text{H}$ per MW(e) y discharged (table 55), gonad dose commitments can be calculated in the same way as for ^{85}Kr . The results are given in table 74.

H. SUMMARY OF DOSES FROM THE NUCLEAR POWER INDUSTRY

398. The preceding paragraphs and table 75 contain the results of the Committee's first attempt to assess the dose commitments associated with the nuclear power industry, which, in several countries, is now a firmly based and expanding commercial undertaking. The information available relates for the most part to special groups within populations, which, by virtue of place of residence or living habits, are expected to receive the greatest doses.

399. The population dose to defined groups has been given in those cases where the numbers of persons receiving the estimated dose commitments are known. In many instances, however, it has not been possible to calculate the additional component of the dose commitment relevant to the world population although this has been done for the important cases of the discharge to atmosphere of ^{85}Kr and ^3H from reprocessing plants.

400. In some cases, the dose commitments and associated population dose commitments to defined groups are overestimates because they include the dose contribution from fall-out from nuclear weapons testing. Since the fraction due to this cause is usually unknown it cannot be subtracted from the estimate of the gross dose commitment.

401. The amounts of radio-nuclides discharged to the environment and also the dose commitments per unit of electricity generated have, on average, decreased during the past several years due to improvements in technology and operating practices in existing and new reactors. Since there is reason to suppose that these improvements will continue to be made, extrapolating the dose commitments given in this report to future power production is not necessarily valid.

402. The discharge of long-lived radio-nuclides to the environment carries a dose commitment to the worldwide population. In the important cases of ^3H and ^{85}Kr the Committee has estimated the magnitude of the global dose commitment. The global doses from ^{85}Kr and ^3H per unit of power generated are at present about 10^{-1} man-rad $(\text{MW(e)} \text{ y})^{-1}$ and by the year 2000, on the basis of an installed power of 4,300 GW(e) at a load factor of 0.5, the dose commitment incurred per year of power generation would then represent only about 0.2 per cent of that due to natural background, even if the methods at present available for restriction of these releases are not by that date widely applied.

403. In the case of other long-lived radio-nuclides such as ^{137}Cs and ^{90}Sr the data available relate specifically to the immediate environs of the plants. Table 75 gives the dose commitments to persons living there from ^{137}Cs and other nuclides per megawatt-year of power generated. For the power-generating plants even of substantial sizes, the dose commitments from these nuclides and also from the shorter-lived noble gases correspond to individual

dose rates of only a few millirads per year which may be compared with the natural background dose rate of about 100 millirads per year. Increase in power production would tend to increase the numbers of persons involved as more plants come into operation so that while the individual doses may not change much, the population dose commitment would rise with increasing installed power. However, even by the year 2000, this would still be extremely small.

404. In the case of the fuel-processing plants for which data are available, the individual dose rates at present are also similarly very small. It is difficult to predict the trend of events as the amount of fuel processing is increased. It seems likely that the doses in the vicinity of the plants will be kept to levels similar to current levels by regulatory control and that improved technology will be introduced so that this situation is maintained despite increased throughput.

III. Recapitulation of dose commitments

405. Table 76 summarizes the estimates of worldwide average dose commitments from all the considered sources of man-made environmental radiation. For underground testing and electric power production, the population dose commitments were divided by the world population to give the average individual dose commitments. For atmospheric testing, the estimates are the dose commitments for all tests conducted before 1971. Although it is acknowledged that the estimated doses from peaceful uses of explosives and production of electrical power are at this stage approximate, it is clear that the radio-active contamination of the environment is mainly the result of atmospheric testing.

406. The annual radiation exposures from natural background are also presented in table 76. The periods of time during which natural radiation would have to be doubled to give a dose increase equal to the total doses expected by the year 2000 from the current contamination of the environment are estimated to be of the order of two years for that due to the atmospheric tests carried out before 1971 and two hours for that due to the peaceful uses of explosives before 1972. Likewise, one year of electric power production at the 1970 rate and at the assumed 2000 rate would involve doses corresponding to about five minutes and one day of natural background, respectively.

TABLE I. COMPOSITION OF PRIMARY GALACTIC COSMIC RAYS AT 51°N IN 1952 AND 1954 (197)

Atomic number	Vertical flux density (particles $\text{m}^{-2} \text{sr}^{-1} \text{s}^{-1}$)
1	1,300
2	88
3-5	1.9
6-9	5.7
10-19	1.9
20 or more	0.5

TABLE 2. PROPERTIES OF SOME COSMIC-RAY PARTICLES PRESENT IN THE EARTH'S ATMOSPHERE (159)

<i>Class</i>	<i>Name</i>	<i>Mass (MeV)</i>	<i>Mean life (s)</i>	<i>Principal mode of decay</i>
Hadrons				
Nucleons	Proton (p)	938.2	Stable	Stable
	Neutron (n)	939.5	1.01 10 ³	p + e ⁻ + ν_e
Mesons	Pion (π^+)	139.6	2.55 10 ⁻⁸	$\mu + \nu_\mu$
	(π^0)	134.9	1.78 10 ⁻¹⁶	$\gamma + \gamma$
	Kaon (K [±])	493.7	1.23 10 ⁻⁸	$\mu + \nu_\mu$
	(K ₁)	497.7	0.91 10 ⁻¹⁰	$\pi + \pi^-$
	(K ₂)	497.7	5.7 10 ⁻⁸	$\pi + e + \nu_e$
Leptons				
	Muon ($\mu^\pm$)	105.6	2.2 10 ⁻⁶	e [±] + ν_e + ν_μ
	Electron (e [±])	0.511	Stable	Stable
	Neutrino (ν_e)	0	Stable	Stable
	(ν_μ)	0	Stable	Stable
Photons	Photon (γ)	0	Stable	Stable

TABLE 3. ABSORBED DOSE RATES PER NEUTRON CM⁻² S⁻¹ FOR SEA-LEVEL COSMIC-RAY NEUTRONS INCIDENT UPON A 30-CM TISSUE-EQUIVALENT SLAB, AND ASSOCIATED QUALITY FACTORS (219)

<i>Depth (cm)</i>	<i>Monolateral</i>		<i>Bilateral</i>	
	<i>$\mu\text{rad h}^{-1}$</i>	<i>quality factor</i>	<i>$\mu\text{rad h}^{-1}$</i>	<i>quality factor</i>
<i>Normal incidence</i>				
Surface	9.1	10.0	6.5	8.2
5	8.2	7.7	6.2	6.7
0-15 ^a			6.3	7.2
<i>Isotropic incidence</i>				
Surface	8.2	8.3	5.4	7.1
5	6.1	5.5	4.6	4.7
0-15 ^a			4.9	6.0

^a For a 30-cm diameter cylinder. The mean is weighted proportionally to the radius.

TABLE 4. SUMMARY OF SEA-LEVEL COSMIC-RAY NEUTRON DATA
(Average dose rates in a 30-cm cylinder)

<i>North latitude (degrees)</i>	<i>Flux density (n cm⁻² s⁻¹)</i>	<i>Dose rate (mrad y⁻¹)^a</i>	<i>Reference</i>
41	0.01	0.43	615
54	0.0065	0.28	468
46	0.0065	0.28	64
46	0.0180 ^b	0.77	65
55	0.0180 ^c	0.77	642
46	0.0084	0.36	325
44	0.0074	0.32	659
41	0.0082	0.35	219

^a The quality factor of this radiation is 6.

^b Obtained by Watt (642) extrapolating higher altitude data to the sea level using 145 g cm⁻² relaxation length.

^c Average value from several investigators' results, as extrapolated.

TABLE 5. DOSE RATES TO PERSONS IN CONVENTIONAL JETS AND IN SST AIRCRAFT
ASSUMED TO FLY IN POLAR REGIONS^a

Altitude (km)	Dose rates ($\mu\text{rad h}^{-1}$) ^b			
	Galactic ionizing component ^c	Galactic neutron component ^c	Galactic star component ^d	Solar radiation (average) ^e
12	300	20		4
20	600	30	64	90

^a If the flight altitude is less than 20 km and the latitude is lower, the dose rates for SST flights will also be lower.

^b These radiations do not have the same quality factor. See table 3.

^c Taken from figure VI. Data corresponding to solar minimum. At solar maximum the dose rates would be reduced by a factor of about 2.

^d Taken from reference 185.

^e Taken from reference 267.

TABLE 6. COSMIC RAY PRODUCED RADIO-ACTIVE NUCLIDES (348)

Radio-nuclide	Calculated atmospheric production rate (atoms $\text{cm}^{-2} \text{s}^{-1}$)	Half-life	Maximum energy of beta radiation (keV)
³ H	0.20 ^a	12.3 y	18
⁷ Be	8.1 10^{-2}	53 d	Electron capture
¹⁰ Be	4.5 10^{-2}	2.5 10^6 y	
¹⁴ C	2.5	5,730 y	156
²² Na	8.6 10^{-5}	2.6 y	545 (β^+)
²⁴ Na	3.0 10^{-5}	15.0 h	1,389
²⁸ Mg	1.7 10^{-4}	21.2 h	460
²⁶ Al	1.4 10^{-4}	7.4 10^5 y	1,170
³¹ Si	4.4 10^{-4}	2.6 h	1,480
³² Si	1.6 10^{-4}	700 y	210
³² P	8.1 10^{-4}	14.3 d	1,710
³³ P	6.8 10^{-4}	25 d	248
³⁵ S	1.4 10^{-3}	87 d	167
³⁸ S	4.9 10^{-5}	2.9 h	1,100
^{34m} Cl	2.0 10^{-4}	32.0 min	2,480
³⁶ Cl	1.1 10^{-3}	3.1 10^5 y	714
³⁸ Cl	2.0 10^{-3}	37.3 min	4,910
³⁹ Cl	1.4 10^{-3}	55.5 min	1,910
³⁹ Ar	5.6 10^{-3}	270 y	565
⁸¹ Kr	1.5 10^{-7}	2.1 10^5 y	Electron capture

^a Taken from reference 604.

TABLE 7. SOME NON-SERIES PRIMORDIAL RADIO-ISOTOPES (516, 615)

Radio-nuclide	Abundance in the lithosphere (ppm)	Half-life (years)	Alpha or maximum beta ray energy (keV) ^a	Gamma ray energies (keV) ^a
⁴⁰ K	3	1.3 10^9	β 1,314 (89)	1,460 (11)
⁵⁰ V	0.2	6 10^{15}	β ? (30)	783 (30), 1,550 (70)
⁸⁷ Rb	75	4.8 10^{10}	β 274 (100)	
¹¹⁵ In	0.1	6 10^{14}	β 480 (100)	
¹³⁸ La	0.01	1.1 10^{11}	β 210 (30)	810 (30), 1,426 (70)
¹⁴⁷ Sm	1	1.1 10^{11}	α 2,230 (100)	
¹⁷⁶ Lu	0.01	2.2 10^{10}	β 430 (100)	88 (15), 202 (85), 306 (95)

^a Figures in parentheses indicate percentage yield per disintegration.

TABLE 8. ANNUAL INTERNAL BETA AND GAMMA DOSES FROM NATURALLY OCCURRING RADIO-NUCLIDES (mrad)

Radio-nuclide	Gonads	Cortical bone		Trabecular bone	
		Osteocytes	Haversian canals	Surfaces ^a	Marrow
³ H	~0.001	~0.001	~0.001	~0.001	~0.001
¹⁴ C	0.7	0.8	0.8	0.8	0.7
⁴⁰ K	19	6	6	15	15
⁸⁷ Rb	0.3	0.4	0.4	0.6	0.6
TOTAL	20.0	7.2	7.2	16.4	16.3

^a Cells close to surfaces of bone trabeculae.

TABLE 9. ANNUAL ALPHA DOSES (mrad) FROM NATURALLY OCCURRING RADIO-NUCLIDES CALCULATED BY THE METHOD OF SPIERS (577)

Radio-nuclide	Location	Activity in bone ^a (pCi kg ⁻¹)	Doses				
			Gonads	Cortical bone		Trabecular bone	
				Osteocytes	Haversian canals ^b	Surfaces ^c	Marrow
²³⁸ U	Normal areas (U.S.A., U.K.)	4.5	0.03	0.8	0.5	0.3	0.06
²²⁶ Ra	Normal areas (average)	7.6	0.02	1.6	1.0	0.6	0.1
	India (Kerala State)	77	0.2	16.0	9.8	6.6	1.2
	Brazil (Araxa-Tapira region)	46	0.1	9.5	5.8	3.9	0.7
²²⁶ Ra	Normal areas (average)	3.8	0.03	1.9	1.1	0.8	0.1
²²² Rn ^d	Normal areas (continents)		0.07	0.04	0.04	0.08	0.08
²²⁰ Rn ^d	Normal areas (continents)		0.003	0.02	0.02	0.05	0.05
²¹⁰ Po	Normal areas (northern temperate latitudes)	40	0.6	4.0	2.4	1.6	0.3
	Arctic regions ^e	100	7.2	10.0	6.0	4.0	0.7
TOTAL FOR NORMAL AREAS		55.9	0.7	8.4	5.1	3.4	0.7

^a The total mass of bone (defined as calcified matrix) in man has been taken to be 5,000 grammes yielding 1,000 grammes of calcium and 2,700 grammes of ash (see reference 401 and paragraphs 80 and 205). The alpha-emitting radio-nuclides were assumed to be uniformly distributed in mineral bone, although that may not be the case (269).

^b Cells lining surfaces of Haversian canals.

^c Cells close to surfaces of bone trabeculae (averaged dose over the first 10 μ m).

^d Doses extrapolated from experiments in guinea-pigs. Other assumptions are given in table 16.

^e Calculated from an arctic/non-arctic ²¹⁰Po concentration ratio of 2.5 in bone and 12 in soft tissue.

TABLE 10. ESTIMATES OF TOTAL INTAKE OF ^{226}Ra AND OF ^{228}Ra
CONTRIBUTIONS FROM DIFFERENT FOOD-STUFF CATEGORIES

	Areas of normal external radiation background										Area of high external radiation background		
	²²⁶ Ra									²²⁸ Ra		²²⁶ Ra	²²⁸ Ra
	France		India		Union of Soviet Socialist Republics	United Kingdom	United States			United States			
	Argentina (48)	Paris (550)	Bombay (110)	Tarapur (309)	Large town in central Asia (676)	Country-wide study (570)	New York (173)	San Francisco (173)	San Juan (220)	New York (508)	San Francisco (508)		
Cereals and grain products	0.20		0.42	0.39	3.60 ^a	0.17	0.56	0.39		0.42	0.37	1.48	3.23
Meat, fish, eggs	0.14		0.05	0.08	0.66	0.38	0.46	0.07		0.14	0.08	0.50	62.70
Milk and dairy products	0.05		0.04	0.01	0.98	0.14	0.14	0.05		0.05	0.10	0.19	15.30
Green vegetables, fruits and pulses . .	0.23		0.17 ^b	0.05	2.70 ^c	0.32	0.54	0.24		0.44	0.38	0.81	9.17
Root vegetables	0.14					0.10	0.06	0.04		0.12	0.08		29.58
Water			0.06	0.02	8.8	0.07	0.02	0.03				0.29	0.01
Miscellaneous	0.01		0.02									0.07	42.50
Total (pCi d ⁻¹)	0.8	1.1	0.8	0.5	17	1.2	1.8	0.8	0.7	1.2	1.0	3.3	160
Total (pCi (gCa) ⁻¹)	1.1	1.1	1.6	1.0	17	1.1	1.8	0.8	1.3	1.2	1.0	6.6	320

^a Bread only.

^b Vegetables, fruits and pulses.

^c Vegetables and fruits.

TABLE 11. ^{226}Ra IN HUMAN BONE

<i>Location</i>	<i>Number of samples</i>	<i>Mean concentration in bone ash (fCi g⁻¹)</i>	<i>Reference</i>
<i>Normal areas</i>			
Argentina: 1	18	11	641
2	360	12	48
Australia	22	10	641
Canada	12	6	641
Chile	24	4	641
Congo	14	22	641
Federal Republic of Germany	22	13	582
Guatemala	29	5	641
India (Bombay): 1	12	8	641
2	1	8	110
Israel	13	36	641
Japan	36	4	641
South Africa	13	11	641
United Kingdom	21	15	641
United States:			
Boston	77	14	641
Houston	23	23	641
Illinois	128	37	249
New England: 1	18	16	57
2	218	16	256
New York: 1	143	10	641
2		13	173
Puerto Rico: 1	42	5	641
2		6	220
San Francisco		11	173
Wisconsin	75	12	403
Union of Soviet Socialist Republics (Ukraine)		39	440
<i>High-level areas</i>			
India (Kerala)	1	143	110
Union of Soviet Socialist Republics (large town in central Asia)	282	1,340	676

TABLE 12. MEAN ^{222}Rn CONCENTRATIONS IN EQUILIBRIUM WITH SHORT-LIVED DECAY PRODUCTS
IN GROUND-LEVEL AIR

Site	^{222}Rn activity (pCi l ⁻¹)	Reference
<i>Continental</i>		
Czechoslovakia		
Bratislava	0.14	662
Hungary		
Budapest	0.07	564
USA		
Chicago	0.03	60
Cincinnati	0.26	203
USSR		
Moscow	0.07	397
<i>Coastal areas and islands</i>		
American Samoa	0.001	60
Bolivia		
Chacaltaya	0.04	370
Brazil		
Rio de Janeiro	0.05	370
Japan	0.09	442
Morocco		
Kenitra	0.008	60
Peru		
Lima	0.04	370
Philippines		
Luzon	0.004	60
USA		
Kodiak	0.003	60
Oahu	0.001	60
Washington, D.C.	0.12	370
<i>Areas of negligible exhalation rate</i>		
Antarctic Ocean	0.001	549
Indian Ocean	0.002	549
North Atlantic Ocean	0.006	549
South Pacific Ocean	0.002	549
South Pole	0.0005	370

TABLE 13. ^{222}Rn CONCENTRATION IN DWELLINGS

Location	Number of buildings investigated	Type of building and building material	²²² Rn concentration outdoors (pCi l ⁻¹)		²²² Rn concentration indoors (pCi l ⁻¹)		Comments	Reference
			Range	Mean	Range	Mean		
Poland	28	Apartments — Concrete	0.06–0.16	0.11	0.14–2.14	0.44	Measurements made under similar conditions of ventilation	498
	8	Aggregate	0.06–0.09	0.08	0.26–1.10	0.35		
	6	Brick			0.08–0.37	0.19		
Sweden	55	Houses — Wood			0.3–0.9	0.54	Four air changes per hour	255
	87	Brick			0.3–2.1	0.91		
	83	Concrete (including alum shale)			0.3–4.5	1.86		
Union of Soviet Socialist Republics		Silicate brick			0.12–4.3	}		680
		Red brick			0.19–1.10			
		Concrete			0.4			
		Adobe			0.3–10.0			
		Slag			4.0–8.0			
United Kingdom	1	House		0.04	0.06–0.31	0.16	Adequately ventilated Inadequately ventilated Poor ventilation Air conditioned	227
	1	House		0.13	0.2–0.7	0.4		
	6	Industrial premises	0.04–0.19	0.09	0.005–1.2	0.3		
	4	Office buildings		0.04	0.06–0.35	0.17		
United States of America:								
Boston area	7	One-family houses: first floor (wood frame)	0.01–0.15	0.05	0.005–0.23	0.07	Number of air changes per hour: one to three in the basement, two to six on the first floor	660
		basement (concrete)			0.1–0.94	0.40		
	3	Apartments — Brick			0.01–0.19	0.09	Number of air changes per hour: five to nine	660
	4	Offices and laboratories			0.02–0.10	0.05	Number of air changes per hour: five to twelve. Air conditioned buildings	660
Tennessee	15	Houses — most of them of concrete construction			0.13–4.8 ^a	1.40	The ventilation rate was probably higher in Florida than in Tennessee as the outdoors temperatures were respectively, 23° C and 0° C	377
Florida	16				0.03–3.6 ^a	1.26		377
New York				0.13		0.25		377

^a Converted from working level units by assuming that ^{222}Rn and its daughters are in the equilibrium ratio 1/0.9/0.6/0.4.

TABLE 14. AIRWAY CHARACTERISTICS OF WEIBEL'S LUNG MODEL A (REGULAR DICHOTOMY)
(238, 644)

Region	Generation	Number	Radius (cm)	Length (cm)	Mucus transit time (min)
Trachea	0	1	0.9000	12.0	8
Main bronchi	1	2	0.6100	4.76	6
Secondary bronchioles	2	4	0.4150	1.90	8
	3	8	0.2800	0.76	3
Tertiary bronchioles	4	16	0.2250	1.27	14
	5	32	0.1750	1.07	12
	6	64	0.1400	0.90	10
Quarternary bronchioles	7	128	0.1150	0.76	32
	8	256	0.0930	0.64	27
	9	512	0.0770	0.54	23
Terminal bronchioles	10	1,024	0.0650	0.46	445
	11	2,048	0.0545	0.39	378
	12	4,096	0.0475	0.33	320
	13	8,192	0.0410	0.27	261
	14	16,384	0.0370	0.23	223
	15	32,768	0.0330	0.20	194
Respiratory bronchioles	16	65,536	0.0300	0.165	160
	17	131,072	0.0270	0.141	
	18	262,144	0.0250	0.117	
Alveolar ducts	19	524,288	0.0235	0.099	
	20	1,048,576	0.0225	0.083	
	21	2,097,152	0.0215	0.070	
Alveolar sacs	22	4,194,304	0.0205	0.059	
	23	8,388,608	0.0205	0.050	
Alveoli			~0.02		

TABLE 15. CALCULATED ALPHA DOSE RATES FROM INHALATION OF SHORT-LIVED ^{222}Rn
DAUGHTER PRODUCTS TO THE BASAL CELL NUCLEI OF SEGMENTAL BRONCHI (226)

	Depth (μm)				
	15	30	45	60	70
Living accommodation: adequate ventilation ^a	550	280	100	40	1.5
Living accommodation: inadequate ventilation ^b	1,490	790	330	120	5
Industrial premises ^c	840	445	190	75	3
Air-conditioned sites ^d	280	140	50	15	0.6

^a ^{222}Rn , ^{218}Po , ^{214}Pb and ^{214}Bi concentrations: 0.164, 0.148, 0.083 and 0.057 pCi l⁻¹ respectively. Annual dose (6,000 h) in millirads.

^b ^{222}Rn , ^{218}Po , ^{214}Pb and ^{214}Bi concentrations: 0.37, 0.35, 0.26 and 0.21 pCi l⁻¹ respectively. Annual dose (6,000 h) in millirads.

^c ^{222}Rn , ^{218}Po , ^{214}Pb and ^{214}Bi concentrations: 0.32, 0.31, 0.27, 0.25 pCi l⁻¹ respectively. Annual dose (2,000 h) in millirads.

^d ^{222}Rn , ^{218}Po , ^{214}Pb and ^{214}Bi concentrations: 0.17, 0.15, 0.074, 0.060 pCi l⁻¹ respectively. Annual dose (2,000 h) in millirads.

TABLE 16. ESTIMATED ANNUAL ALPHA DOSES (mrad) IN HUMAN ORGANS RESULTING FROM INHALATION OF RADON DAUGHTERS WITH A MEAN ASPIRATION RATE OF 13.9 LITRES PER MINUTE (511)

	²²² Rn concentration 0.3 pCi l ⁻¹ (²²² Rn and daughters in the ratio 1/0.8/0.4/0.3)	²²² Pb concentration 3 pCi l ⁻¹ (²²² Pb, ²¹² Bi in equilibrium)
Lungs (alveolar tissue)	2.2	0.6
Blood	0.2	0.1
Liver	0.1	0.07
Kidneys	0.5	0.2
Adrenal glands	0.1	0.02
Muscle	0.05	0.003
Bone	0.04	0.02
Bone marrow	0.08	0.05
Gonads	0.07	0.003

TABLE 17. DIETARY INTAKE OF ²¹⁰Pb AND ²¹⁰Po IN SOME COUNTRIES

Country	Dietary intake (pCi d ⁻¹)		Reference
	²¹⁰ Pb	²¹⁰ Po	
Areas of normal dietary intake			
Argentina		1.3	45
Federal Republic of Germany	4.6	4.6	200
Union of Soviet Socialist Republics (Leningrad)	4	3.0	664
United Kingdom	1-10	1-10	247
United States of America:			
Palmer, Alaska	1.7	}	391
Los Angeles, California	1.5		
Honolulu, Hawaiian Islands	1.6		
Chicago, Illinois	1.8		
New Orleans, Louisiana	1.8		
Boston, Massachusetts	1.7		
New York City, New York	1.2		437
Areas of high dietary intake			
Finland (Lapps)	8.6	69	317
Japan	17		599

TABLE 18. MEASURED DOSE RATES IN AIR FROM TERRESTRIAL GAMMA RADIATION IN SELECTED AREAS (mrad y⁻¹)

Country	Area	Outdoors			Indoors			Reference
		No. of sites	Range	Mean	No. of sites	Range	Mean	
Egypt				52			49	483
Federal Republic of Germany		27,000 km of roads		34	2,000		70	193
Finland		11		86	11	59-142	82	281
German Democratic Republic	Country-wide	1,097	15-400	82	607	30-230	64	470
Italy	Rome	78	91-250	181	15	90-230	162	102
Japan ^a		225	0-83	42				8, 9, 10
New Zealand	Dunedin			37			37	287
Poland	Country-wide	16	20-113	51		49-76	60	497
Sweden	Lapp communities	5	43-69	53	9	50-60	53	217
Union of Soviet Socialist Republics					33	25-168	66	680
United Kingdom	Aberdeenshire	217	34-103	70	172	51-118	82	579
United States	Country-wide	>200	25-100	55			38	37

^a These figures obtained by subtracting 30 mrad y⁻¹ as estimated cosmic-ray contribution

TABLE 19. DOSE CONVERSION FACTORS: GONADS/AIR (49, 297)

Radio-nuclide	Distribution in soil	Results of Bennett			Results of Jones		
		Testes	Ovaries	Mean	Testes	Ovaries	Mean
²³⁸ U series	Uniform	0.85	0.75	0.80	0.87	0.74	0.80
²³² Th series	Uniform	0.86	0.76	0.81	0.87	0.75	0.81
⁴⁰ K	Uniform	0.87	0.79	0.83	0.85	0.73	0.79
¹³⁷ Cs	Plane	0.88	0.80	0.84	0.83	0.69	0.76
¹³⁷ Cs	Exponential	0.87	0.77	0.82	0.84	0.71	0.77

TABLE 20. DOSE RATES DUE TO INTERNAL AND EXTERNAL IRRADIATION FROM NATURAL SOURCES IN "NORMAL" AREAS. ESTIMATES OF THE 1966 REPORT ARE GIVEN IN PARENTHESES.

Source of irradiation	Dose rates (mrad y ⁻¹)					Paragraph
	Gonads		Bone-lining cells	Bone marrow		
<i>External irradiation</i>						
Cosmic rays: ionizing component	28	(28)	28	28	(28)	41
neutron component	0.35	(0.7)	0.35	0.35	(0.7)	46
Terrestrial radiation (including) air	44	(50)	44	44	(50)	145
<i>Internal irradiation</i>						
³ H	0.001	(—)	0.001	0.001	(—)	62
¹⁴ C	0.7	(0.7)	0.8	0.7	(1.6)	67
⁴⁰ K	19	(20)	15	15	(15)	72
⁸⁷ Rb	0.3	(0.3)	0.6	0.6	(<0.3)	73
²¹⁰ Po	0.6	(0.3)	1.6	0.3	(0.3)	131
²²⁰ Rn	0.003	(—)	0.05	0.05	(—)	119
²²² Rn	0.07	(0.3)	0.08	0.08	(0.3)	118
²²⁶ Ra	0.02	(—)	0.6	0.1	(0.03)	92
²²⁸ Ra	0.03	(—)	0.8	0.1	(0.03)	92
²³⁸ U	0.03	(—)	0.3	0.06	(—)	80
ROUNDED TOTAL	93	(100)	92	89	(96)	
Percentage from alpha particles plus neutrons.	1.2	(1.3)	4.1	1.2	(1.4)	

TABLE 21. INITIAL VERTICAL DISTRIBUTION OF RADIO-ACTIVITY ASSUMED WITHIN "MUSHROOM CAP" OF THE CLOUD FROM A NUCLEAR EXPLOSION (506)

Layer, fraction of "mushroom cap" (from base to top)	Percentage of activity within layer
0 — $\frac{1}{7}$	1
$\frac{1}{7}$ — $\frac{2}{7}$	14
$\frac{2}{7}$ — $\frac{3}{7}$	25
$\frac{3}{7}$ — $\frac{4}{7}$	25
$\frac{4}{7}$ — $\frac{5}{7}$	15
$\frac{5}{7}$ — $\frac{6}{7}$	15
$\frac{6}{7}$ — $\frac{7}{7}$	5

TABLE 22. ANNUAL DOSES RECEIVED BY AN INDIVIDUAL EXPOSED TO AN ACTIVITY CONCENTRATION OF 1 PCI M⁻³ OF ⁸⁵Kr

Organs and tissues	Annual dose (mrad)	Reference
Lung	32	648
Tracheal mucosa	52	648
Fatty tissue	2	610
Blood	0.2	610
Muscle	0.2	610
Skin	2,100	149
Subcutaneous tissue	51	610
Gonads	17	149
Entire body	14	149

TABLE 23. ⁹⁰Sr INVENTORY IN MEGACURIES (340, 343, 344, 385, 616, 632, 635)

	1967				1968				1969			1970				1971
	Jan.	Apr.	July	Oct.	Jan.	Apr.	June	Oct.	Feb.	Apr.	July	Jan.	May	Aug.	Nov.	Feb.
Stratosphere	0.3	0.3	0.3	0.4	0.3	0.2	0.2	0.4	0.4	0.3	0.2	0.4	0.3	0.3	0.4	0.5
Troposphere	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Local fall-out	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.0	2.0	2.0	2.0	1.9	1.9	1.9	1.8	1.8
Global fall-out	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.1	12.2	12.1	12.1	12.2	12.2	12.2
TOTAL	14.6	14.6	14.6	14.7	14.6	14.5	14.5	14.6	14.6	14.4	14.4	14.4	14.3	14.4	14.4	14.5

TABLE 24. ANNUAL AND CUMULATIVE WORLD-WIDE ⁹⁰Sr DEPOSITION (MCi) (634)

	Annual deposition			Cumulative deposit		
	Northern hemisphere	Southern hemisphere	Global	Northern hemisphere	Southern hemisphere	Global
Pre-1958	1.80 ^a	0.65 ^a	2.45 ^a	1.7	0.6	2.3
1958	0.63	0.25	0.88	2.28	6.84	3.12
1959	1.05	0.18	1.23	3.26	1.00	4.26
1960	0.26	0.17	0.43	3.44	1.14	4.58
1961	0.35	0.17	0.52	3.70	1.29	4.99
1962	1.44	0.26	1.70	5.84	1.51	7.35
1963	2.62	0.31	2.93	7.51	1.78	9.29
1964	1.65	0.42	2.07	8.96	2.16	11.12
1965	0.77	0.36	1.13	9.50	2.46	11.96
1966	0.32	0.21	0.53	9.59	2.68	12.27
1967	0.17	0.11	0.28	9.52	2.65	12.17
1968	0.19	0.10	0.29	9.48	2.69	12.17
1969	0.15	0.14	0.29	9.40	2.76	12.16
1970	0.21	0.13	0.34	9.37	2.82	12.19
TOTAL	11.61	3.46	15.07			
Stratospheric inventory	0.29	0.16	0.45			
All injections to 1970	11.90	3.62	15.52			

^a Estimated from the cumulative deposition, assuming there had been a two-year decay.

TABLE 25. ACTIVITY OF ^{90}Sr IN RAIN (pCi l^{-1}) AND WET DEPOSITION (mCi km^{-2}) (101, 230, 231)

		1965		1966		1967		1968		1969		1970	
		pCi l^{-1}	mCi km^{-2}	pCi l^{-1}	mCi km^{-2}	pCi l^{-1}	mCi km^{-2}	pCi l^{-1}	mCi km^{-2}	pCi l^{-1}	mCi km^{-2}	pCi l^{-1}	mCi km^{-2}
1. Continents													
51° N Milford Haven		5.06	4.82	2.63	3.08	1.17	1.22	1.25	1.24	0.82	0.85	1.18	1.19
51° N Abingdon		5.49	3.09	2.40	1.78	1.30	0.78	1.20	0.91	1.34	0.81	0.96	0.57
40° N New York		8.35	5.53	2.40	2.43	1.31	1.64	1.14	1.32	1.16	1.43	1.65	1.48
25° N Miami		2.41	3.58	1.07	2.25	0.37	0.62	0.42	0.88	0.50	0.91	0.77	0.88
40° N Misawa		2.91	3.17	1.05	1.41	0.67	0.77	0.65	0.99	0.71	0.99	1.07	0.73
Mean		4.84	4.04	1.91	2.19	0.96	1.01	0.93	1.07	0.90	1.00	1.13	0.97
2. Islands													
21° N Honolulu		1.84	2.77	1.75	1.68	1.22	1.91	2.51	3.42	1.06	1.15	1.14	1.13
38° N Azores		2.08	2.84	1.35	2.14	0.43	0.54	0.27	0.33	0.50	0.53	0.96	1.30
32° N Bermuda		2.59	3.02	1.23	1.84	0.62	0.83	0.99	1.04	0.60	0.73	0.76	1.04
22° N Taiwan		0.99	1.18	1.68	0.29	0.10	0.17	0.07	0.20	0.08	0.15	0.09	0.18
Mean		1.87	2.45	1.50	1.49	0.59	0.86	0.96	1.25	0.56	0.64	0.74	1.22
3. Ships													
56° N Bravo		2.58	1.33	2.00	0.74	0.89	0.34	1.19	0.53	1.19	0.48	1.46	0.51
52° N Charlie		5.44	3.18	3.08	1.42	0.91	0.49	1.09	0.60	1.16	0.55	1.73	0.69
44° N Delta		2.80	2.25	2.42	1.59	0.80	0.66	1.01	0.81	0.83	0.63	0.87	0.71
35° N Echo		3.24	2.45	3.59	1.50	0.61	0.57	1.14	0.62	0.88	0.56	0.74	0.43
Mean		3.51	2.30	2.77	1.31	0.80	0.52	1.11	0.64	1.01	0.55	1.20	0.58

TABLE 26. LATITUDE POPULATION AND FALL-OUT DISTRIBUTION

Latitude	Area (10 ⁶ km ²)	Population (per cent)	Integrated deposit of ⁹⁰ Sr (mCi km ⁻²) ^a		Integrated deposit of ⁹⁰ Sr (mCi km ⁻²) 1961-1969 (228)
			1958-1970 (635)	From all tests to 1970 ^b	
70°-80° N	11.6		14.4	17.5	35
60°-70° N	18.9	0.4	37.2	45.2	217
50°-60° N	25.6	11.9	62.0	75.3	261
40°-50° N	31.5	17.7	68.9	83.7	346
30°-40° N	36.4	23.4	49.4	60.0	302
20°-30° N	40.2	25.2	38.3	46.5	229
10°-20° N	42.8	8.4	25.9	31.4	128
0°-10° N	44.1	4.0	16.9	20.5	117
0°-10° S	44.1	4.2	9.6	12.3	96
10°-20° S	42.8	1.7	8.2	10.5	36
20°-30° S	40.2	1.5	13.5	17.4	71
30°-40° S	36.4	1.4	14.5	18.6	43
40°-50° S	31.5	0.1	17.2	22.1	35
50°-60° S	25.6		9.6	12.3	

^a The integrated deposit is sum of the activities deposited each month. There is no correction for radio-activity decay.

^b The distribution of ⁹⁰Sr in the northern hemisphere for all injections up to 1970 is obtained by multiplying results in the previous column by 11.9/9.8, the ratio of the total deposition in the northern hemisphere for all injections to 1970 to that for the period 1958-1970 (see table 24). The data for the southern hemisphere are computed in like manner.

TABLE 27. POPULATION-WEIGHTED DEPOSITION OF STRONTIUM (mCi km⁻²)^a

	⁹⁰ Sr (1961-1969)	⁹⁰ Sr (1958-1970)	⁹⁰ Sr (All injections to 1970)
Northern hemisphere	260	48.1	58.4
Southern hemisphere	71	10.8	13.9
Global	243	44.8	54.4

^a Estimated from data of table 26.

TABLE 28. ANNUAL DEPOSITION OF ⁹⁰Sr (MCi)^a

	1961	1962	1963	1964	1965 ^b	1966	1967	1968	1969
Northern hemisphere	8.1	27	15	0.35	—	0.67	0.57	0.74	0.56
Southern hemisphere	0.48	4.5	0.91	0	—	2.6	0.49	2.3	0.18

^a Based upon measurements made at the United States fall-out sampling network (228).

^b No results reported for 1965.

TABLE 29. ^{90}Sr AND ^{137}Cs IN MILK

Region or country	^{90}Sr to calcium ratio ($\mu\text{Ci g}^{-1}$)						^{137}Cs concentration ($\mu\text{Ci l}^{-1}$)						Reference
	1966	1967	1968	1969	1970	1971	1966	1967	1968	1969	1970	1971	
Northern hemisphere													
Austria	23	14	13	12			70	33	28	27			93, 94, 95, 653
Belgium	13	9	8	9	6		36	17	20	15	10		120, 551
Canada	13	10	8	9	9		51	33	25	20	21		136, 412, 515
Colombia	2	1	1		1								528
Czechoslovakia	12												441
Denmark	12	9	9	7	8	7	22	14	14	14	10	14	4, 5
Egypt	13		6										394, 395
Faroe Islands	73	51	45	35	37	34	800	586	507	463	357	352	4, 6
Federal Republic of Germany	16	11	9	9	7		61	35	27	25	31		91, 92
Finland	13	10	9	8			134	92	70	54	49		105
France: 1	19	14	12	9	8	9		21	20	19	21	22	186, 490, 550
2	18	15	12	12	12	11	62	34	24	24	26	28	123
Guiana	11	14			7								528
India (Bombay)							11	6	5				422, 423
Israel	2	2					14	11					170
Italy	13	10	8										119
Jamaica	9	7	4	4			200	184	109	95	81		621
Japan	11	8	7	5	5		52	30	28	18	16		19
Korea	22	11	15										335
Netherlands	15	9	8	7			43	37	28	23			120, 405, 460
Norway	28	16	11	10			244	181	146	128			260
Panama	4						21	22	11	11			621
Puerto Rico	6	4	4	4			21	14					621
Senegal	10	8	5		2								528
Sweden	15	10	8	7	7		63	38	30	20	23		218, 591
Switzerland	18	13	11	10	10		26	17	7	13	12		254
Union of Soviet Socialist Republics	12	8	8	7	7		56	38	30	20	20		671, 672, 681, 682
United Kingdom	12	9	8	7	6	6	46	20	16	14	17	18	11, 12
United States	12	9					29	16					621
Alaska	12	6	6	5			34	20	13				621
Chicago	9	8	8	6					14	16	14	14	74, 621
Hawaii	4	3	4	2			25	9					621
New York City	12	10	9	9	8	8							232
Tampa	11	11	7	5			139	102	66	55	51		521, 632
Venezuela	4						14	9					621
Southern hemisphere													
Argentina	5	5	4	4	3		24	21	19	20	20		118
Australia	7	5	4	5	6		28	20	15	18	19		23, 69, 177, 178, 194, 585
Chile	2	1	1										528
Ecuador	4	1	1		1								528
Malagasy Republic	2	2	1		2								528
New Caledonia	3	2	2		2								528
New Zealand	8	6	5	7	7		55	43	32	40	35		450
Peru	2	1	1										528
Réunion (La)		4	3	3	5			17	15	18	16		550
Society Islands	5	3	1		3								528

TABLE 30. ANNUAL AVERAGE $^{90}\text{Sr}/\text{Ca}$ RATIOS IN MILK BY COUNTRY OR AREA IN THE NORTH TEMPERATE ZONE
(pCi (gCa)^{-1})

Year	Country or area										United States of America				Mean
	Canada (136, 412, 515, 616)	Czecho- slovakia (616)	Den- mark (2, 4, 5)	Federal Republic of Germany (92)	Finland (105, 616)	France (490)	Nether- lands (405, 460, 616)	Ukrainian SSR (678)	USSR Moscow (666, 672, 682)	United Kingdom (11, 12, 616)	Whole country	Chicago (232, 616, 621)	New York City	Salt Lake City	
1955 ..				3						4					3.5
1956 ..				4						6					5.0
1957 ..				6						6			5	4	5.3
1958 ..				5						7		7	8	4	6.2
1959 ..			9	9					8	10		7	11	6	8.6
1960 ..			5	7	7				6	6		8	8	6	6.6
1961 ..			4	6	6				4	6	7	6	7	4	5.6
1962 ..			10	11	13		9		13	12	11	9	12	8	10.8
1963 ..	26	21	24	26	22		25	27	23	26	19	17	26	19	23.2
1964 ..	28	20	25	27	23		22	20	18	28	19	16	23	23	22.5
1965 ..	19	18	17	24	18	24	17	11	14	19	14	12	19	17	17.4
1966 ..	13	12	12	16	13	19	15	9	15	12	11	9	12	10	12.7
1967 ..	10		9	11	10	14	9		8	9	9	8	10	5	9.3
1968 ..	8		9	9	9	12	8			8		8	9		8.9
1969 ..	9		7	9	8	9	7			7		6	9		7.9
1970 ..	9		8	7		8			6	6			8		7.4
1971 ..			7			9				6			8		7.5

TABLE 31. ^{90}Sr AND ^{137}Cs IN TOTAL DIET

Region or country	⁹⁰ Sr to calcium ratio (pCi g ⁻¹)						¹³⁷ Cs intake (pCi d ⁻¹)						Reference
	1966	1967	1968	1969	1970	1971	1966	1967	1968	1969	1970	1971	
Northern hemisphere													
Austria	25	15	15	14			135	53	60	51			95
Denmark	14	10	8	8	7	7	79	44	39	38	32	34	4, 5
Egypt	45		13										394, 395
Faroe Islands	33	22	23	17	20		496	480	502	403	384		6
Federal Republic of Ger- many	17	13	11	10	9		123	77	43	37	30		92
Finland	21						260						259
France: 1	22	19	17	15	15	14							123
2			21	20	18	18			38	34	37	37	186, 490, 550
Greenland	15	9	7	8	6		89	297	346	61	137		7
Japan (urban)	24	18	19	21	15		20	14	13	14	9		20
Netherlands	20	14	12	11			90	50	32	28			460
Norway	38						420						259
Sweden	22						132	88	71	65	58		259, 390, 594
Union of Soviet Socialist Republics	40	28	25	19	20		145	93	56	38	38		671, 672, 681, 682
United States average ...	16	12					55	30	34	28	25	24	74, 214, 621
Alaska	29	16											621
Hawaii	10	6					65	35					621
New York City	17	16	14	12	12	13							51
San Francisco	6	6	4	4	4	4							51
Southern hemisphere													
Argentina	7	7	5	6	4			24	19	18	17		118
Australia	7	6	5	5	6								23, 177, 178, 194, 585

TABLE 32. RATIO OF $^{90}\text{Sr}/\text{Ca}$ IN WHOLE DIET TO THAT IN MILK^a

Country	1963	1964	1965	1966	1967	1968	1969	1970	Mean for 1963-1970
Argentina	1.8	1.5	1.3	1.4	1.4	1.3	1.5	1.3	1.4
Australia	1.1	1.0	0.9	1.0	1.2	1.3	1.0	1.0	1.1
Denmark	1.3	1.7	1.3	1.2	1.1	0.9	1.1	0.9	1.2
Federal Republic of Germany	1.3	1.6	1.7	1.1	1.2	1.2	1.1	1.3	1.3
Finland			1.8	1.6					1.7
France				1.2	1.3	1.4	1.3	1.3	1.3
India				3.6					(3.6)
Japan	2.1	2.2	2.3	2.2	2.3	2.7	4.2	3.0	2.6
Norway			1.3	1.4					1.3
Sweden			1.4	1.5					1.4
United Kingdom	0.9	0.9	1.0						0.9
Union of Soviet Socialist Republics ..	2.3	3.1	3.7	3.3	3.5	3.1	2.7	2.9	3.1
United States, New York City	1.1	1.3	1.2	1.4	1.6	1.6	1.3	1.5	1.4
Hawaii	1.6	2.2	3.5	2.5	2.0				2.4

^a Data taken from tables 29, 31 and from the 1969 report.TABLE 33. PARAMETERS OBTAINED BY FITTING THE $^{90}\text{Sr}/\text{Ca}$ RATIO IN MILK TO THE ^{90}Sr DEPOSITION

	New York (eq. 15)	Denmark (eq. 15)	United Kingdom (eq. 14)	United Kingdom (eq. 15)	Northern hemisphere ^a (eq. 15)
p_1 (pCi (gCa) ⁻¹ per mCi km ⁻² y ⁻¹)	0.69	0.99	0.70	0.86	0.86
p_2 (pCi (gCa) ⁻¹ per mCi km ⁻² y ⁻¹)	0.21	0.47	1.41	0.47	0.48
p_3 (pCi (gCa) ⁻¹ per mCi km ⁻² y ⁻¹)	0.20	0.25	0.21	0.11	0.20
μ (y ⁻¹)	0.14	0.15	0.18	0.08	0.10
P_{23} (pCi y (gCa) ⁻¹ per mCi km ⁻²)	2.23	3.01	2.33	2.65	3.24

^a Calculated using data from table 30.

TABLE 34. $^{90}\text{Sr}/\text{Ca}$ RATIOS IN HUMAN BONE (pCi (gCa) $^{-1}$)

(Number of samples in parentheses)

Region or country	Year	New-born or stillborn	0-1 year	1 year	2 years	3 years	4 years	5-19 years	>19 years	Adult bone type ^a	Reference
<i>Northern hemisphere</i>											
Canada	1968	3.2 (8)	4.1 (86)	4.8 (17)	4.3 (16)	4.4 (12)	5.8 (4)	3.8 (59)	2.7 (38)	V	603
	1969	2.5 (6)	4.0 (47)	5.0 (5)	5.1 (5)	4.4 (4)	4.2 (8)	3.3 (48)	2.2 (37)	V	603
Czechoslovakia	1966	2.2 (30)	3.3 (63)	3.5 (9)	3.3 (8)	3.8 (11)	3.0 (5)	2.9 (59)	1.8 (103)	V	75
	1967	1.6 (31)	2.8 (91)	4.1 (20)	3.8 (12)	2.9 (12)	2.9 (9)	2.8 (63)	1.9 (122)	V	75
	1968								1.7 (54)	V	76
	1969			3.2 (23)	2.3 (9)	2.8 (10)	3.0 (10)	2.4 (59)	1.8 (62)	V	78
	1970								1.7 (57)	V	79
Denmark	1969	1.2 (19)	1.7 (33)	2.4 (3)		2.1 (1)	1.8 (3)	1.9 (36)	1.3 (27)	V	5
	1970	0.9 (18)	1.9 (26)	1.9 (4)	1.9 (4)	1.7 (4)	0.8 (1)	1.5 (31)	1.3 (49)	V	5
	1971	1.2 (8)	1.7 (15)				1.4 (3)	2.0 (26)	1.8 (31)	V	4
Egypt	1968								0.4 (7)	V	396
	1969							0.1 (8)	0.2 (14)	V	396
Federal Republic of Germany	1968	1.2 (159)	2.4 (25)	2.8 (17)				2.5 (34)	1.8 (64)	V	92
	1969	1.1 (98)	1.9 (14)	2.3 (10)				2.0 (21)	1.7 (40)	V	92
France 1	1967	1.9 (5)	3.7 (53)	5.3 (10)	5.0 (5)		4.0 (1)	3.5 (41)	2.2 (55)	V	292
	1968	1.6 (60)	3.2 (102)	4.4 (13)	3.7 (9)	3.9 (4)	3.8 (6)	2.8 (38)	2.3 (88)	V	292
	1969	1.6 (25)	3.2 (87)	3.7 (15)	3.1 (12)	3.6 (5)	3.0 (6)	2.8 (54)	2.0 (105)	V	292
	1970	1.6 (37)	2.7 (73)	2.9 (15)	2.6 (11)	3.2 (6)	2.3 (15)	2.1 (42)	1.9 (132)	V	292
France 2	1967								1.7 (55)	Rib	490
	1968								1.0 (45)	Rib	490
	1969								1.3 (61)	Rib	490
	1970								1.2 (18)	Rib	490
Indonesia	1970								1.0 (6)	V	234
Jamaica	1970								0.9 (21)	V	234
Japan	1967		3.9 (2)	3.8 (2)	3.3 (2)	2.5 (1)	2.1 (1)	2.5 (21)	0.4 (1)	Composite	601
	1968	1.1 (12)	2.0 (31)	3.2 (10)	2.3 (4)	2.3 (3)	1.8 (3)	2.1 (47)	0.6 (13)	Composite	601
	1969	0.7 (30)	1.5 (15)	2.1 (5)	2.6 (7)	1.5 (7)	0.6 (1)	1.4 (26)	0.7 (12)	Composite	601
	1970	0.7 (23)			2.5 (1)		2.0 (3)	1.7 (14)	1.2 (6)	Composite	602

TABLE 34. $^{90}\text{Sr}/\text{Ca}$ RATIOS IN HUMAN BONE (pCi (gCa)^{-1}) (continued)

(Number of samples in parentheses)

Region or country	Year	New-born or stillborn	0-1 year	1 year	2 years	3 years	4 years	5-19 years	>19 years	Adult bone type ^a	Reference
<i>Northern hemisphere (continued)</i>											
Senegal	1969								1.0 (12)	V	234
	1970								1.3 (24)	V	234
Switzerland	1970								2.5 (47)	V	254
Thailand	1970								0.7 (7)	V	234
	1971								0.6 (6)	V	234
Uganda	1970								1.1 (23)	V	234
Union of Soviet So- cialist Republics	1968	1.7 (81)	2.4 (19)	3.0 (13)			2.2 (224)	1.2 (694)		Normalized to whole skeleton	674
	1969	1.5 (103)	2.1 (30)	3.1 (12)			2.0 (288)	1.2 (1,142)		Normalized to whole skeleton	675
	1970 ^b	1.4 (81)	2.4 (32)	2.9 (35)			3.1 (329)	1.4 (1,249)		Normalized to whole skeleton	675
	1971 ^b	1.0 (55)	2.3 (7)	2.5 (8)			2.7 (162)	1.3 (867)		Normalized to whole skeleton	675
United Kingdom	1968	1.3 (101)	2.9 (27)	3.2 (9)	2.7 (7)	3.4 (4)	2.7 (5)	1.9 (73)	1.6 (34)	Mainly vertebrae	415
United States: New York, N. Y.	1969		2.6 (23)	2.7 (1)	3.2 (2)	3.6 (1)	2.8 (2)	2.5 (29)	1.7 (25)	V	229
	1970		2.5 (12)	2.8 (1)		2.4 (1)		2.1 (20)	1.6 (52)	V	50
San Francisco, California	1969		1.4 (80)	1.6 (5)	1.2 (5)	1.5 (4)	1.0 (2)	1.3 (21)	0.9 (80)	V	229
	1970		0.9 (74)	1.7 (5)	0.9 (1)	1.1 (3)	0.9 (1)	1.1 (14)	0.9 (46)	V	50
Venezuela	1969								0.8 (22)	V	234
	1970								0.8 (23)	V	234
<i>Southern hemisphere</i>											
Argentina	1969	1.3 (19)	1.4 (29)	1.2 (9)	1.3 (6)	1.3 (9)		1.3 (75)		V	45, 118
	1970	1.4 (9)	1.4 (21)	1.3 (12)	1.5 (10)	1.4 (11)		1.3 (69)		V	45, 118
Australia	1968	0.8 (79)	1.5 (98)	2.0 (26)	2.0 (14)	1.9 (8)	2.2 (14)	1.4 (75)	0.9 (75)	V	194
	1969	0.9 (108)	1.4 (98)	1.6 (27)	1.5 (11)	1.6 (7)	1.4 (13)	1.2 (136)	0.9 (112)	V	70
	1970	0.7 (208)	1.3 (86)	1.6 (23)	1.6 (12)	1.2 (9)	1.3 (7)	1.1 (90)	0.9 (130)	V	585
Brazil	1969								1.3 (45)	V	234, 417
Chile	1969								1.7 (20)	V	234
South Africa	1966-1969		1.1	1.3			2.0	0.5		Rib	623

^a V represents vertebrae.^b The data up to 4 years refer to Moscow City only.

TABLE 35. ^{90}Sr IN ADULT VERTEBRÆ OF THE NORTHERN HEMISPHERE (pCi (gCa)^{-1})

Year	Canada	Czechoslovakia	Denmark	France	Poland	USSR (Moscow)	United Kingdom	United States (New York)	Average
1962	1.2		0.8		1.4			1.0	1.10
1963	1.7		1.2		1.6	1.7		1.6	1.56
1964	3.1	1.8	2.4		2.5	2.4		2.0	2.37
1965	3.1	2.2	2.7	2.2	2.5	3.1	1.9	2.1	2.47
1966	2.6	1.8	2.6	2.1	2.9	2.7	2.2	2.1	2.37
1967	2.5	1.9	2.1	2.2		2.3	1.6	1.9	2.07
1968	2.7	1.7	1.9	2.3		1.7	1.6	1.9	1.97
1969	2.2	1.8	1.3	2.0		1.7		1.7	1.78
1970		1.7	1.3	1.9		1.4		1.6	1.58
1971			1.8			1.2			

TABLE 36. PARAMETERS OBTAINED BY FITTING THE ^{90}Sr BONE DATA (ADULT VERTEBRÆ) TO THAT IN DIET^a

	New York, 1954-1970	San Francisco, 1961-1970	Denmark, 1960-1970	Northern hemisphere, 1954-1970	United Kingdom, 1961-1969
<i>c</i>	0.027	0.011	0.001	0.023	
<i>g</i>	0.014	0.027	0.043	0.031	0.035
μ (y^{-1})	0.17	0.20	0.48	0.25	0.275
P_{34}	0.116	0.16	0.114	0.117	0.124

^a The New York, San Francisco and Danish data were fitted using as the transfer function equation 30.

^b In the fit to the United Kingdom data (478) the parameters were determined by simultaneously fitting an exponential transfer function (equation 28) to the ^{90}Sr in vertebræ and a double exponential transfer function (equation 29) to the ^{90}Sr in femur.

TABLE 37. DOSE COMMITMENTS FROM ^{90}Sr FROM ALL TESTS UP TO 1970 (mrad)

	Northern hemisphere		Southern hemisphere	
	Temperate latitudes	Average	Temperate latitudes	Average
Bone marrow	62	45	17	11
Endosteal cells	85	61	23	15

TABLE 38. RANGE AND ADOPTED VALUES OF THE PARAMETERS USED TO CALCULATE THE DOSE TO THE THYROID OF INFANTS FROM INGESTION OF MILK CONTAMINATED BY ^{131}I FALL-OUT

	Adopted value	Range
Deposition velocity (m s^{-1})	$5 \cdot 10^{-3}$	(1-20) 10^{-3}
Transfer coefficient from deposition to milk (pCi d l^{-1} per pCi m^{-2})	0.8	0.23-1.5
Daily intake of fresh animal milk (litre)	0.7	0-1
Dose factor ($\mu\text{rad per pCi}$)	16.5	15.5-18.5

TABLE 39. ^{131}I IN MILK AND THYROID DOSES RESULTING FROM 1970 AND 1971
ATMOSPHERIC TESTS

<i>Region, area or country</i>	<i>Year</i>	<i>Integrated milk concentration ($\mu\text{Ci d l}^{-1}$)</i>	<i>Integrated thyroid doses to infants (mrad)</i>	<i>Reference</i>
Argentina				
Buenos Aires	1970	4,600	53	47
Australia				
Malanda	1970	5,800	67	67
	1971	5,300	61	68
Hobart-Launceston	1970	900	10	67
	1971	350	4	68
Country average	1970	1,500	17	67
	1971	1,100	13	68
Bolivia				
La Paz	1970	11,000	130	527
	1971	2,400	28	528
Brazil				
Guanabara	1970	3,600	42	622
Chile				
Santiago	1970	3,000	35	527
	1971	5,200	60	528
Colombia				
Bogotá	1970	900	10	527
Fiji				
Suva	1970	3,200	37	448, 449
	1971	2,400	28	451, 452
Malagasy Republic				
Diego Suarez	1971	6,400	74	528
New Caledonia				
Noumea	1970	3,000	35	527
	1971	2,600	30	528
New Zealand	1970	700	8	448, 449
	1971	300	3	451, 452
Peru				
Arequipa	1970	7,500	87	527
	1971	2,900	33	528
Society Islands				
Tahiti	1970	11,000	130	527
	1971	18,000	210	528
South Africa				
Cape Town	1970	1,500	17}	624
Pretoria	1970	8,000	92}	
Western Samoa				
Apia	1970	6,400	74	448, 449
	1971	7,100	82	451, 452

TABLE 40. ^{137}Cs BODY BURDENS (pCi (gK) $^{-1}$)

Region or country	Latitude	Sex	1964	1965	1966	1967	1968	1969	1970	1971	Reference
<i>Northern hemisphere</i>											
Belgium	~ 50°	MF	158	135	87	50	29				616
Canada (Ottawa)	~ 45°	MF		170							431
Denmark	55°-60°	MF	185	168	106	65	46	40	23	14	4, 5, 616
Egypt	~ 30°	MF				23	14		12		157, 438
Federal Republic of Germany	47°-55°										
Berlin		MF				68	48	47	36		92
Karlsruhe		MF	151	111	81	49	27	16	15		
Düsseldorf		M	243	186	128	76	41	32	31		
Finland	~ 60°	MF		182	150	107	72	53	44		590, 592
France	~ 50°	MF	227	194	93	64	36	32	26	28	490
Israel	~ 35°	M					48				170
Japan	30°-45°	M	93	77	54	33	20	14	13		444
Norway	~ 60°	MF		430	290						259
Poland	50°-55°	MF	164	185		71					311, 366
Sweden (Stockholm)	~ 60°	MF	205	187	139	107	74	54	47		388, 595
Switzerland (Geneva)	~ 45°	M	206	179	103	54	30	24	21		254
		F	139	121	66	41	26	19	18		
Union of Soviet Socialist Republics											
Moscow	~ 55°	M	258			50	34	29	38		665, 672, 685
		F				42	27	22	36		
Leningrad	~ 60°	MF	174	142	92	68	70				663, 684
United Kingdom	50°-60°	M		148	89	45					201
London area		F	149	109	60	33					
West Cumberland		M	257	190	110	52	30				242
United States average	25°-50°	MF	141	109	60	35	17				214
Florida	25°-30°	MF		149	132	120					533
<i>Subarctic region</i>											
Canada	60°-70°										
Eastern Arctic Eskimos		M			5,800						56
Central Arctic Eskimos		M				11,000					
Finland: Inari reindeer herders	65°-70°	M	7,800	9,000	7,800	5,500	5,200	3,400	3,100		519, 520, 521
		F	8,800	11,200	7,900	3,800	4,200	3,600	2,800		
Union of Soviet Socialist Republics											
Murmansk	65°-70°	M	14,000	18,000	21,500		16,500				679
United States, Alaska	65°-70°	M	9,100	6,600	4,900	4,300	2,400				108, 151, 524
<i>Southern hemisphere</i>											
Argentina	35°-40°				31	20	16	13	15		118
Australia	30°-40°			65	42	37	18		16		585, 616

TABLE 41. MEAN ANNUAL DOSES TO VARIOUS TISSUES (rad) RESULTING FROM THE INHALATION OF 1 μCi OF PuO_2 (628)

Time post-exposure (years)	Pulmonary region	Lymph nodes	Liver	Bone
a — 0.05 μm AMAD (pulmonary deposition fraction: 0.59)				
0-1	46	184	0.2	0.04
1-5	15	510	0.8	0.14
5-50	0.2	530	1.0	0.20
b — 0.10 μm AMAD (pulmonary deposition fraction: 0.50)				
0-1	39	156	0.2	0.04
1-5	13	430	0.7	0.12
5-50	0.2	450	0.9	0.17
c — 0.50 μm AMAD (pulmonary deposition fraction: 0.30)				
0-1	23	94	0.2	0.03
1-5	8	260	0.5	0.08
5-50	0.1	270	0.6	0.11

TABLE 42. ²³⁹Pu CONTENT IN VARIOUS HUMAN ORGANS AND TISSUES (pCi kg⁻¹)

Location	Year	Number of samples	Respiratory lymph nodes	Lung	Liver	Bone	Reference
United States							
New Jersey	1959		5.0	0.78			342
Union of Soviet Socialist Republics	1965	12	6.85	0.15 } 0.11 }			686
	1965	14					
	1966	12	9.6				
	1966	20					
United States							
Massachusetts	1965-1966	12		0.45	0.78	0.05 }	392
	1965-1966						
Los Alamos	1960-1971	60		0.5	0.7		439
Los Alamos ^a	1958	1	56 250	2 160	4 455	945	355
	1959-1962	1	11 430	2 835	1 215	225	
	1959-1962	1	200	27	9	0.45	
Rocky Flats ^a	1967	1	630	95	145	58	347

^a Radiation employees.

TABLE 43. CONVERSION FACTORS FOR THE AIR-DOSE AT ONE METRE ABOVE A PLANE SOURCE (38)

	⁵⁴ Mn	⁶⁰ Zr	¹⁰⁶ Ru	¹⁰⁶ Rh	¹³⁷ Sb	¹³⁷ Cs ^a	¹⁴⁰ Ba	¹⁴¹ Ce	¹⁴⁴ Ce
Dose-rate conversion factor, mrad y ⁻¹ per mCi km ⁻²	0.119	0.341 ^b	0.072	0.042	0.063	0.033	0.316 ^b	0.011	0.004
Mean life, years	1.24	0.257	0.157	1.44	3.90	43.7	0.051	0.129	1.13
Dose-commitment conversion factor, mrad per mCi km ⁻²	0.147	0.087	0.011	0.060	0.246	1.44	0.016	0.0014	0.0045

^a For ¹³⁷Cs the source is exponentially distributed with a mean depth of 3 cm.^b These factors include contributions from the daughter radio-nuclides assumed in transient equilibrium.

TABLE 44. EXTERNAL DOSE COMMITMENT FROM FALL-OUT (mrad)

	Northern hemisphere		Southern hemisphere	
	Temperate latitudes	Average	Temperate latitudes	Average
Short-lived radio-nuclides	65	47	19	13
Caesium-137	59	43	16	10

TABLE 45. DOSE COMMITMENTS FROM NUCLEAR TESTS CARRIED OUT BEFORE 1971. (THE DOSE COMMITMENTS FROM NUCLEAR TESTS CARRIED OUT BEFORE 1968, TAKEN FROM THE 1969 REPORT, ARE INDICATED BETWEEN PARENTHESES)

Source of radiation	Dose commitments (mrad) for the north temperate zone			Dose commitments (mrad) for the south temperate zone			Dose commitments (mrad) to the world population		
	Gonads	Bone-lining cells	Bone marrow	Gonads	Bone-lining cells	Bone marrow	Gonads	Bone-lining cells	Bone marrow
External									
Short-lived	65 (36)	65 (36)	65 (36)	19 (8)	19 (8)	19 (8)	44	44	44
¹³⁷ Cs	59 (36)	59 (36)	59 (36)	16 (8)	16 (8)	16 (8)	40	40	40
⁸⁵ Kr	2 10 ⁻⁴	2 10 ⁻⁴	2 10 ⁻⁴	2 10 ⁻⁴	2 10 ⁻⁴	2 10 ⁻⁴	2 10 ⁻⁴	2 10 ⁻⁴	2 10 ⁻⁴
Internal									
³ H	4	4	4	1	1	1	4	4	4
¹⁴ Ca	12 (13)	15 (16)	12 (13)	12 (13)	15 (16)	12 (13)	12	15	12
⁵⁵ Fe	1	1	0.6	0.3	0.3	0.2	0.7	0.7	0.4
⁹⁰ Sr		85 (130)	62 (64)		23 (28)	17 (14)		57	42
¹³⁷ Cs	26 (21)	26 (21)	26 (21)	7 (4)	7 (4)	7 (4)	18	18	18
²³⁹ Pu ^b		0.2			0.05			0.1	
TOTAL ^c	170 (110)	260 (240)	230 (170)	55 (33)	81 (64)	72 (47)	120	180	160

^a Dose accumulated up to year 2000. The total dose commitment to the gonads and bone marrow is about 140 mrad; it is about 170 mrad to cells lining bone surfaces.^b The dose commitment to bone-lining cells for the north temperate zone has been taken to be equal to the integrated

dose over 50 years to bone. A reduction by a factor of four has been assumed for the south temperate zone. Because of insufficient data, the dose commitments to gonads and to bone marrow have not been estimated.

^c Totals have been rounded off to two significant figures.

TABLE 46. REACTION PRODUCTS FOR AN UNDERGROUND EXPLOSION, CONSISTING OF ONE-MEGATON FUSION AND TEN-KILOTON FISSION (583)

Source	Fission products (curies)	Induced products (curies) ^a	Fusion products (curies)
Fission (10 kt) ..	3.0 10 ^{9b}	10 ⁵	
⁹⁰ Sr	1.5 10 ³		
¹³⁷ Cs	1.6 10 ³		
⁶⁰ Co		Small	
¹⁴ C		Small	
Fusion (1 Mt) ..		10 ⁸	
³ H			6.7 10 ⁶
⁶⁰ Co		10 ⁴	
¹⁴ C		15	

^a Induced gamma-ray activities at one hour after detonation, based on average chemical composition of earth's crust.

^b Fission-product gamma-ray activities at one hour after detonation, decaying at $t^{-1.2}$.

TABLE 47. SELECTED FISSION, FUSION, AND NEUTRON ACTIVATION PRODUCTS (AT DETONATION TIME) EXPECTED TO BE RELEASED TO THE ENVIRONMENT FOLLOWING A CRATERING EXPERIMENT WITH A 170-KT EXPLOSION (127)

Nuclide	Half-life	Amount released (kCi)		
		Immediate fall-out	Remaining content	
			Main cloud	Base surge
⁹⁰ Sr	28 y	0.0011	0.0002	0.00005
¹⁰³ Ru	40 d	1.0	0.16	0.014
¹⁰⁶ Ru	370 d	0.08	0.013	0.0010
¹³¹ I	8 d	2.4	0.5	0.04
¹³³ I	20 h	40	7	0.6
¹³⁷ Cs	30 y	0.0015	0.0006	0.0002
³ H	12 y	500	1,000	500
³² P	14 d	1.2	0.24	0.02
⁴⁸ Sc	44 h	16	1.4	0.09
¹⁸¹ W	140 d	30	5	0.6
¹⁸⁵ W	75 d	60	10	1.1
¹⁸⁷ W	24 h	800	140	14
²⁰³ Hg	47 d	3	0.5	0.06
²⁰² Tl	12 d	70	12	1.2
²⁰³ Pb	52 h	4,000	600	70

TABLE 48. COMPARISON OF PRE-PRODUCTION RADIO-ACTIVITY IN GASBUGGY AND RULISON GAS (176, 568, 569)

	Gasbuggy	Rulison
Date	10 December 1967	10 September 1969
Place	San Juan Basin in New Mexico	Piceance Basin in Colorado
Yield	29 kt	48 kt
Depth	1.3 km	2.6 km
Tritium		
Total in gaseous products (Ci)	2,100	1,300
Pre-production concentration in gas (pCi cm ⁻³)	710	180
Krypton-85		
Total (Ci)	350	1,100
Pre-production concentration in gas (pCi cm ⁻³)	120	150

TABLE 49. DATA ON NUCLEAR EXPLOSIONS FOR PEACEFUL USES (221, 321, 607)

Event	Country	Date	Yield (kilotons)	Comments
Cratering explosions				
Sedan	USA	1962	100	Explosion in alluvium. Formation of a crater 390 m in diameter and 100 m deep
Sulky		1964	0.09	Explosion in basalt. Formation of a mound (retarc) 24 m in diameter and 8 m high
Palanquin		1965	4	Explosion in rhyolite. Formation of a crater 73 m in diameter and 43 m deep
Cabriolet		1968	2.5	Explosion in rhyolite. Formation of a crater 220 m in diameter and 73 m deep
Buggy I		1968	5.5	Explosion in basalt. First nuclear row-charge experiment (five 1.1 kt charges spaced 45.7 m apart). Formation of a crater 260 m long, 76 m wide and 20 m deep
Schooner		1968	35	Explosion in tuff. Formation of a crater 74 m in diameter and 21 m deep
T-1	USSR		0.2	Explosion in sandstone and argillite. Formation of a crater 74 m in diameter and 21 m deep
"1003"			1.1	Explosion in siltstone. Formation of a crater 124 m in diameter and 20 m deep
"1004"			> 100	Explosion in sandstone and siltstone. Formation of two water reservoirs, one inside explosion crater and one outside. The dimensions of the crater are 410 m in diameter and 100 m in depth
Contained explosions				
Gnome	USA	1961	3.1	Explosion in salt. Cavity radius: 25 m
Handcar		1964	10	Explosion in dolomite. The chimney dimensions are 42 m in diameter and 71 m in height
Gasbuggy		1967	29	Explosion in gas-bearing formation to stimulate a low producing gas field
Rulison		1969	48	Explosion in gas-bearing formation to stimulate a low producing gas field
A	USSR		1.1	Investigation of the possibility of creating an underground storage space in a salt mass—volume of the empty space: around 10,000 m ³
B			25	Investigation of the possibility of creating an underground storage space in a salt mass—volume of the cavity: 140,000 m ³
C			12.6	Detonation of three charges in two stages. Stimulation of the production in an oil field
D				Stimulation of gas production
E			30	Elimination of a runaway gas well

TABLE 50. ESTIMATES IN MILLIRADS OF WHOLE-BODY DOSES^a TO HYPOTHETICAL USERS IN LOS ANGELES BASIN OF GASBUGGY DILUTED GAS^b AND OF GAS PRODUCED IN THE SAME CONDITIONS AS GASBUGGY WITH THE NEW EXPLOSIVE DESIGN (CALCULATED FROM DATA IN REFERENCES 33 AND 285)

Source of exposure	Gasbuggy			New design ^c	
	³ H	¹⁴ C	⁸⁵ Kr	³ H	⁸⁵ Kr
<i>Domestic use^d</i>					
Nonvented heating and appliances ^e	0.09	4 10 ⁻⁴	2 10 ⁻⁴	1 10 ⁻³	1 10 ⁻⁴
All appliances vented except range	0.01	5 10 ⁻⁵	3 10 ⁻⁵	2 10 ⁻⁴	2 10 ⁻⁵
Weighted average ^f	0.02	9 10 ⁻⁵	5 10 ⁻⁵	3 10 ⁻⁴	3 10 ⁻⁵
<i>Atmosphere</i>					
At point of peak concentration	0.01	6 10 ⁻⁵	3 10 ⁻⁵	2 10 ⁻⁴	2 10 ⁻⁵
Population weighted average	2 10 ⁻³	8 10 ⁻⁶	4 10 ⁻⁶	3 10 ⁻⁵	3 10 ⁻⁶
<i>Total</i>					
Maximum exposure	0.1	5 10 ⁻⁴	2 10 ⁻⁴	1 10 ⁻³	1 10 ⁻⁴
Weighted average	0.02	1 10 ⁻⁴	5 10 ⁻⁵	3 10 ⁻⁴	3 10 ⁻⁵

^a The whole-body dose factors are taken as 1, 2.8 and 1.4 10⁻² μ rad per pCi y m⁻³ for ³H, ¹⁴C and ⁸⁵Kr, respectively.

^b The Gasbuggy gas production rate being assumed to be 28 10³ m³ d⁻¹ and the natural gas consumption rate in the Los Angeles basin being 50 10⁶ m³ d⁻¹, the dilution factor is about 1,800.

^c The production rate of ³H per kiloton of yield is assumed to be 70 times less than for the device used for Gasbuggy (358). The concentration of ⁸⁵Kr is about six times more than that of ³H and the dose from ¹⁴C is negligible compared to that from ³H and ⁸⁵Kr (647).

^d Assumes an occupancy factor of 0.7, a 90 m² residence of normal construction and an air infiltration rate of 220 m³ h⁻¹.

^e Assumes 900° C-days of heating per year.

^f Assumes nonvented heating for 10 per cent of the houses.

TABLE 51. ¹³¹I CONTAMINATION OF MILK RESULTING FROM UNITED STATES NUCLEAR CRATERING EXPERIMENTS

Cratering event	Location receiving significant concentrations of ¹³¹ I in milk	Integrated concentration ^a (pCi d l ⁻¹)	Thyroid dose to infants (mrad)	Population thyroid dose to infants (man-rads)	Reference
Sedan (July 6, 1962) ^b	{ Salt Lake City, Utah Laramie, Wyoming	20,000	230	860	383
Sulky (December 18, 1964)*		8,900	100	140	
Palanquin (April 14, 1965)	{ Helena, Montana Martin Ranch, Eureka, Nevada ^c	800	9	160	384
Cabriolet (January 26, 1968)		11,000	130	20	
Buggy I (March 12, 1968)	Mountain View Ranch, Deeth, Nevada ^c	6,300	70	10	
Schooner (December 8, 1968)	Pohlsander Ranch, Wells, Nevada ^c	5,500	60	10	
	Boyd Schena Ranch, Abraham, Utah ^c	1,000	11	2	

* Not detected.

^a The integrated concentration has been taken to be equal to 10 times the peak level concentration expressed in pCi l⁻¹ (86).

^b Five events may have contributed to the milk contamination attributed in this table to Sedan. When calculating the population dose, Sedan was assumed to account for only 16

per cent (average value of the range 2-30 per cent given by Mays (407) for Utah) of the milk contamination of Utah and Wyoming.

^c Since the milk was taken from the ranch for the radiological monitoring, it was not available for consumption by members of the public and the corresponding dose given above is hypothetical.

TABLE 52. ACTIVITY OF SELECTED LONG-LIVED ISOTOPES ($T > 8$ d) IN THE CLOUD FROM THE SCHOONER EXPERIMENT AND ESTIMATED DOSE COMMITMENTS TO THE POPULATION OF THE 40-50°N LATITUDE BAND^a

Source of irradiation	Activity (Ci)	Tissue at risk	Transfer coefficient (mrad per mCi km ²)	Dose commitment from the long-range fall-out (μrad)	Population dose commitment (man-rads)	
<i>External irradiation</i>						
Fission products:						
⁸⁸ Y	110	Whole body	4.6 10 ⁻²	1.6 10 ⁻¹	99	
¹⁰³ Ru	540		3.5 10 ⁻³	6.0 10 ⁻²	37	
¹³⁷ Cs	2.4		4.6 10 ⁻¹	3.5 10 ⁻²	22	
¹⁴⁰ Ba	910		5.1 10 ⁻³	1.5 10 ⁻¹	93	
¹⁴¹ Ce	160		4.5 10 ⁻⁴	2.3 10 ⁻³	1.4	
¹⁴⁷ Nd	130		2.3 10 ⁻⁴	9.5 10 ⁻⁴	0.6	
Activation products:						
⁵⁴ Mn	190		4.7 10 ⁻²	2.8 10 ⁻¹	170	
⁵⁷ Co	90		5.8 10 ⁻³	1.7 10 ⁻²	11	
⁵⁸ Co	540		1.2 10 ⁻²	2.1 10 ⁻¹	130	
⁷⁴ As	770		2.5 10 ⁻³	6.1 10 ⁻²	38	
¹⁸¹ W	180,000		1.3 10 ⁻⁵	7.4 10 ⁻²	46	
<i>Internal irradiation</i>						
³ H	410,000	Whole body		8.6 10 ⁻¹	3,000	
⁹⁰ Sr	1.5	Bone marrow	7.7 10 ⁻¹	3.7 10 ⁻²	23	
		Endosteal cells	1.1	5.2 10 ⁻²	32	
¹³⁷ Cs	2.4	Whole body	2.0 10 ⁻¹	1.5 10 ⁻²	9	

^a Except for ³H and ⁹⁰Sr, the activities were taken from reference 332. The ⁹⁰Sr activity was calculated assuming the ¹³⁷Cs/⁹⁰Sr ratio to be 1.6. Tritium activity was derived from the data given in table 47. The dose commitments were calculated by the Committee. Those from ³H refer to the world population.

TABLE 53. ESTIMATED NUCLEAR ELECTRIC GENERATING CAPACITY FOR THE WORLD (GW(e))^a

1980	1990	2000	Reference
216	684	1,596	419
75	390	1,200	114
250	800	2,000	476
120	430	1,030	284
350	1,600	4,300	581

^a In 1970 the nuclear generating capacity was 20 GW(e) (264).

TABLE 54. DATA ON SELECTED FISSION PRODUCTS FROM ²³⁵U FISSION IN THERMAL REACTORS (128, 567) AND FROM ²³⁹Pu IN FAST REACTORS (174, 505)

Fission product	Radio-active half-life	Fission yield (per cent)		Activity present in thermal reactors ^a operating at 20 MW(th)t ⁻¹ after 1,000 days of irradiation (Ci t ⁻¹)
		²³⁵ Pu (fission spectrum neutrons)	²³⁹ Pu (thermal neutrons)	
³ H	12.3 y	0.025	0.013	3.1 10 ²
⁸⁵ Kr	10.7 y	0.15	0.28	7.6 10 ³
⁸⁹ Sr	50.4 d	1.7	4.8	8.0 10 ⁵
⁹⁰ Sr	28 y	2.1	5.6	6.1 10 ⁴
⁹⁵ Zr	65.5 d	4.3	6.2	1.0 10 ⁶
¹⁰³ Ru	39.6 d	6.4	2.9	4.8 10 ⁵
¹⁰⁶ Ru	369 d	4.6	0.38	5.4 10 ⁴
¹²⁹ I	1.7 10 ⁷ y	3.0	0.9	1.7 10 ⁻²
¹³¹ I	8 d	4.6	3.1	5.2 10 ⁵
^{131m} Xe	12 d	0.027	0.018	3.0 10 ³
¹³³ Xe	5.3 d	5.7	6.6	1.1 10 ⁶
¹³⁷ Cs	30 y	6.8	6.2	6.4 10 ⁴
¹⁴⁴ Ce	284 d	3.2	5.6	8.6 10 ⁵

^a The values have been calculated on the basis of fission of ²³⁵U only. In practice, a substantial fraction of the fission occurring after some time in a thermal reactor arises from fissions of ²³⁹Pu resulting from activation of ²³⁸U (paragraph 340). The activities of some nuclides (e.g. ¹⁰⁶Ru) are therefore significantly different from the values given in the table.

TABLE 55. PRODUCTION OF ^3H , ^{85}Kr , AND ^{129}I FROM WORLD NUCLEAR POWER REACTORS^a

	^3H	^{85}Kr	^{129}I
Production rate (Ci (MW(e) y) ⁻¹): thermal fission of ^{235}U ..	21	510	$1.0 \cdot 10^{-3}$
fast fission of ^{239}Pu	40	270	$3.4 \cdot 10^{-3}$
Annual production (MCi): 1970	0.20	4.9	$9.7 \cdot 10^{-6}$
2000	74	740	$5.8 \cdot 10^{-3}$
Integrated amount (MCi): 1970	0.97	24	$4.6 \cdot 10^{-5}$
2000	550	$8.1 \cdot 10^3$	$3.8 \cdot 10^{-2}$
Cumulative amount (MCi): 1970	0.81	19	$4.6 \cdot 10^{-5}$
2000	420	$5.5 \cdot 10^3$	$3.8 \cdot 10^{-2}$

^a The power produced in 1970 was 9.7 GW(e) (paragraph 314). It is assumed that the growth of the nuclear power industry will follow the highest estimate in table 53 (581) and that 40 per cent of the nuclear power produced in 1990, and 70 per cent of that produced in 2000, will be from fast reactors (465). A load factor of 0.5 and a thermal efficiency of 0.3 are assumed (paragraph 338).

TABLE 56. DATA ON SELECTED ACTIVATION PRODUCTS INDUCED BY THERMAL NEUTRONS (516)

Radio-active product	Half-life	Target nuclide	Isotopic abundance (per cent)	Activation cross-section (barns)
^3H	12.3 y	^2H	0.015	0.0005
^3H	12.3 y	^6Li	7.42	950
^3H	12.3 y	^{10}B	19.7	3,800
^{14}C	5,730 y	^{13}C	1.1	0.0009
^{16}N	7.4 s	$^{16}\text{O}^a$	99.8	0.00018
^{24}Na	14.9 h	^{23}Na	100	0.53
^{41}Ar	1.8 h	^{40}Ar	99.6	0.61
^{51}Cr	28 d	^{50}Cr	4.3	17
^{56}Mn	2.6 h	^{55}Mn	100	13
^{58}Co	72 d	^{58}Ni	67.8	$0.04\text{--}0.2^b$
^{60}Co	5.3 y	^{59}Co	100	37
^{64}Cu	12.8 h	^{63}Cu	69	4.5
^{65}Zn	250 d	^{64}Zn	48.9	0.46
^{95}Zr	65.5 d	^{94}Zr	17.4	0.08
^{134}Cs	2.0 y	^{133}Cs	100	31
^{239}Pu	24,400 y	^{238}U	99.3	2.7

^a ^{16}O gives also rise to ^{13}N according to the reaction $^{16}\text{O}(\text{p}, \alpha)^{13}\text{N}$.

^b Range of values reported for fission spectrum neutrons (531).

TABLE 57. TRITIUM IN LIQUID WASTE DISCHARGED FROM WATER-COOLED REACTORS

Reactor	Power MW(e)	Annual quantity discharged (Ci)			Annual quantity discharged per unit of power generated ^a (Ci (MW(e) y) ⁻¹)			Reference
		1968	1969	1970	1968	1969	1970	
BWR								
Dresden-I, USA	200	3	6	5	0.03	0.06	0.03	155, 306, 372
Oyster Creek, USA	515		5	22		0.12	0.05	345
Nine Mile Point, USA	500			20			0.09	345
Garigliano, Italy	150	8	7	5	0.07	0.05	0.06	117
KRB Gundremmingen, Federal Republic of Germany	250	21	18		0.19	0.13		24
PWR								
Yankee Rowe, USA ^b	175	1,200	1,200	1,500	8.3	8.7	10.3	155, 306, 372
Indian Point I, USA ^b	265	790	1,100	410	4.3	5.3	9.4	155, 306, 372
San Onofre, USA ^b	430	2,300	3,500	4,800	14.9	11.1	13.1	155, 306, 372
Conn. Yankee, USA ^b	575	1,700	5,200	7,400	4.7	11.9	17.4	155, 306, 372
Ginna, USA	420			110			0.4	306
Trino Vercellese, Italy	250			135			1.0	117
Ardennes, France/Belgium.. ..	240			340			2.4	158
PHWR								
Douglas Point, Canada	210	440	1,000	950		20.4	8.9	400

^a Power generation data taken from references 143 and 263.

^b Stainless steel cladding used on fuel elements in these reactors allows greater diffusion of fission product ^3H into the coolant than the zircaloy cladding used on fuel elements in Dresden-I (BWR) and Ginna (PWR) in the United States.

TABLE 58. TRITIUM IN LIQUID WASTE DISCHARGED FROM GAS-COOLED REACTORS

Reactor	Power MW(e)	Annual quantity discharged (Ci)		Annual quantity discharged per unit of power generated ^a (Ci (MW(e) y) ⁻¹)		Reference
		1969	1970	1969	1970	
Berkeley, UK	280	61	61	0.21	0.21	146, 499
Bradwell, UK	300	180	95	0.63	0.46	146, 499
Hinkley Point, UK	500	35	19	0.08	0.08	146, 499
Trawsfynydd, UK	500	230	68	0.60	0.18	146, 499
Dungeness, UK	550	72	19	0.17	0.05	146, 499
Sizewell, UK	580	10	21	0.03	0.05	146, 499
Oldbury, UK	600	16	68	0.05	0.23	146, 499
Hunterston, UK	320	250		0.81		89
Latina, Italy	200	25	17	0.34	0.13	117

^a Power generation data taken from reference 263.

TABLE 59. ANNUAL QUANTITY (IN CURIES) OF RADIO-NUCLIDES IN LIQUID WASTE DISCHARGED FROM WATER-COOLED REACTORS

Radio-nuclide	Dresden-I, USA (BWR-200 MW(e)) (305), 1968 ^a	Humboldt Bay, USA (BWR-68 MW(e)) (374), 1970	Indian Point I, USA ^a (PWR-265 MW(e)), 1969	KRB Gundremmingen, Federal Republic of Germany (BWR-250 MW(e)) (24)		Douglas Point, Canada (PHWR-210 MW(e)) (31) 1970
				1968	1969	
⁵⁴ Mn	0.006	0.24	5			0.06
⁵⁵ Fe	0.08					
⁵⁸ Co	0.8		5	0.2	0.2	0.04
⁶⁰ Co	1.1	0.84	4	0.1	0.09	4
⁶⁵ Zn		0.12				0.04
⁸⁹ Sr	0.3	0.01	0.03	0.7	1.6	<0.0002
⁹⁰ Sr	0.03	0.01	0.002	0.02	0.09	<0.01
⁹¹ Y	0.03					
¹³¹ I	0.04	0.09	3	0.5	0.7	0.9
¹³⁴ Cs	0.07	0.24	4			4
¹³⁷ Cs	0.2	0.84	6	0.7	0.2	12
¹⁴⁰ Ba	0.2			0.2	0.2	
¹⁴⁴ Ce	0.06					
TOTAL	2.9	2.4	27	2.4	3.0	21

^a Calculated from data in reference 357.

^b Calculated from five trips during a 9-month period of study.

TABLE 60. ANNUAL QUANTITY (CURIES) OF RADIO-NUCLIDES^a IN LIQUID WASTE DISCHARGED FROM GAS-COOLED REACTORS IN THE UNITED KINGDOM, IN 1969 (89)

Radio-nuclide	Berkeley (280 MW(e))	Bradwell (300 MW(e))	Hinkley Point (500 MW(e))	Trawsfynydd (500 MW(e))	Dungeness (550 MW(e))
³² P		0.33			
³⁵ S	7.3	14	12	1.3	21
⁴⁵ Ca				0.77	
⁵⁵ Fe					2.8
⁶⁰ Co		0.56			
⁶⁵ Zn		0.086 ^b			
⁸⁹ Sr	2.4				
⁹⁰ Sr + ⁹⁰ Y	4.2		13	1.9	4.9
¹¹⁰ Ag					0.46
¹³⁴ Cs	9.7	22	35	0.039	20
¹³⁷ Cs	32	65	130	0.43	56
¹⁴⁴ Ce + ¹⁴⁴ Pr	6.4				

^a The radio-nuclides for which figures are given for a station are those which are most important radiologically and/or numerically at that station.

^b Result taken from station's monthly returns of radio-activity discharged.

TABLE 61. NOBLE GASES DISCHARGED FROM POWER REACTORS

Reactor site	Type	Net output (MW(e))	Criticality date	Annual quantity discharged (curies)				Comments	Reference
				1967	1968	1969	1970		
Dresden-I, USA	BWR	200	1959	260,000	240,000	800,000	914,000	Fission gases whose detailed composition is given in table 63. Use of 23-min hold-up line	121 305 374 535
Big Rock, USA		70	1962	264,000	232,000	200,000	277,000	30-min hold-up line	
Humboldt Bay, USA		68	1963	900,000	897,000	490,000	535,000	18-min hold-up line	
La Crosse, USA		50	1967	< 5	< 1	480	700	20-min hold-up line	
Oyster Creek, USA		515	1969			7,000	112,000	30-min hold-up line	
Nine Mile Point, USA		500	1969			55	9,500	30-min hold-up line	117
Garigliano, Italy		150	1963	29,200	82,000	140,000	275,000		
VAK, Federal Republic of Germany		15	1960	3,900	4,600	1,800	3,400	Mainly ¹³³ Xe. Storage tanks	
KRB, Federal Republic of Germany		250	1966			9,000		Mainly ¹³³ Xe. 40-min hold-up line + charcoal beds	
KWL, Federal Republic of Germany		240	1968			200,000	130,000	Mainly ¹³³ Xe. 60-min hold-up line + charcoal beds	
Tsuruga, Japan		330	1969				68,000	30-min hold-up line + 24-h decay tanks	608
Yankee Rowe, USA	PWR ^a	175	1960	2.3	0.7	4	17.2		121 305 374 535
Saxton, USA		3	1962	22	18.6	1			
Indian Point-I, USA		265	1962	23	60	600	1,750		
San Onofre, USA		430	1967	4	4.8	260	1,610		
Connecticut Yankee, USA		575	1967	0.02	3.7	190	700	¹³³ Xe(86%), ¹³⁵ Xe(12%), ⁸⁵ Kr(1.4%), ⁴¹ Ar(0.4%)	
Ginna, USA		420	1969				9,980		117 158
Trino Vercellese, Italy		250	1964	59.1			19.2		
Ardennes, France		240	1966	2.1			3		63 608
KWO, Federal Republic of Germany		300	1968			5,500	7,700	Mainly ¹³³ Xe	
Mihama, Japan		340	1970				1,200		499 158 117 608
Bradwell, UK	GCR	300	1962				7,600	⁴¹ Ar only. Annual quantity discharged calculated using a load factor of 0.8	
Hinkley, UK		500	1964				86,000		
Trawsfynydd, UK		500	1964				56,000		
Chinon, France		750	1966	23,000	16,400	12,300	8,100	Mainly ⁴¹ Ar produced by activation of the coolant	
Saint-Laurent, France		490	1969			1,900	300		
Latina, Italy		200	1962	2,500	2,500	1,500	2,500		117
Tokai, Japan		160	1966	3,400	3,000	3,400	6,300	⁴¹ Ar is the major constituent	608
NPD, Canada	PHWR	22	1962			16,000		Noble gases only. ⁴¹ Ar in the proportion of 50 per cent or less	400
Douglas Point, Canada		210	1966		40,000	100,000	160,000		

^a All PWRs are equipped with storage tanks allowing for a delay before discharge of up to 120 days.

TABLE 62. REACTOR OFF-GAS COMPOSITION AT VARIOUS DECAY TIMES (PER CENT) (61)

Isotope	Half-life	30 minutes	1 hour	8 hours	1 day	3 days	10 days	30 days	90 days	150 days
⁸⁹ Kr	3.2 min	0.3								
¹³⁷ Xe	3.8 min	0.9								
^{135m} Xe	15 min	8.0	3.0							
¹³⁸ Xe	17 min	26.7	11.8							
⁸⁷ Kr	1.3 h	15.7	18.0	1.4						
^{83m} Kr	1.9 h	2.5	3.1	0.8						
⁸⁸ Kr	2.8 h	17.4	22.9	13.6	0.7					
^{85m} Kr	4.4 h	5.8	8.1	8.9	1.0					
¹³⁵ Xe	9.2 h	17.6	25.2	50.0	38.5	2.3				
^{133m} Xe	2.3 d	0.2	0.3	0.9	1.8	2.1	0.5			
¹³³ Xe	5.3 d	5.0	7.5	24.3	57.0	95.0	98.4	91.2	0.4	
^{131m} Xe	12.0 d			0.1	0.2	0.4	0.6	1.8	0.8	0.03
⁸⁵ Kr	10.7 y				0.1	0.2	0.5	7.0	98.8	99.97

TABLE 63. AVERAGE DISCHARGE RATE OF RADIO-ACTIVE GASES FROM DRESDEN-I, IN THE UNITED STATES (305)

Isotope	Half-life	Discharge rate ($\mu\text{Ci s}^{-1}$)		Discharge/ generation ^a
		Measured	Computed for a 21-minute delay	
⁸⁹ Kr	3.2 min		140	
¹³⁷ Xe	3.8 min		320	
¹³⁷ N	10 min		450	
^{135m} Xe	15 min		370	
¹³⁸ Xe	17 min	3,000	2,800	$2 \cdot 10^{-7}$
⁸⁷ Kr	1.3 h	790	1,170	$6 \cdot 10^{-7}$
^{83m} Kr	1.9 h		220	
⁸⁸ Kr	2.8 h	740	1,250	$7 \cdot 10^{-7}$
^{85m} Kr	4.4 h	400	370	$1 \cdot 10^{-8}$
¹³⁵ Xe	9.2 h	1,250	1,310	$2 \cdot 10^{-6}$
^{133m} Xe	2.3 d	14	14	$6 \cdot 10^{-8}$
¹³³ Xe	5.3 d	510	380	$1 \cdot 10^{-5}$
⁸⁵ Kr	10.7 y	0.14	0.60	$5 \cdot 10^{-5}$

^a This column gives the quantity discharged as a fraction of the quantity generated in fuel.

TABLE 64. TRITIATED WATER AND GASEOUS IODINE DISCHARGED TO ATMOSPHERE FROM WATER-COOLED REACTORS

Radio-nuclide		Annual quantity discharged (curies)			
		Yankee Rowe, USA (PWR-175 MW(e)) (303), 1969-1970	Dresden-I, USA (BWR-200 MW(e)) (304), 1968	Douglas Point, Canada (PHWR-210 MW(e)) (400)	
				1968	1969
³ H	13		$2 \cdot 10^{-1}$	2,500	9,500
Gaseous ¹³¹ I	$< 3 \cdot 10^{-4}$		$3 \cdot 10^{-2}$	$7.3 \cdot 10^{-2}$	$1.8 \cdot 10^{-1}$

TABLE 65. ESTIMATES OF DOSE DUE TO MEASURED CAESIUM CONCENTRATIONS IN FISH

Reactor	Mean caesium concentration in fish (pCi g ⁻¹ wet)	Source of activity	Annual whole-body dose to individuals concerned per unit rate of fish consumption (rad (g d ⁻¹) ⁻¹)	Individual dose commitment, per unit of fish consumption and unit rate of power generation ^a (rad kg ⁻¹ (MW(e)) ⁻¹)	Reference
Dresden-I, USA (1968) ..	0.015	Fall-out ¹³⁷ Cs ^b			304
Indian Point I, USA (1969)	0.056	Total ¹³⁷ Cs			
	0.022	Fall-out ¹³⁷ Cs	3 10 ⁻⁷		357
	0.026	Discharged ¹³⁴ Cs		1.3 10 ⁻⁸	
	(calc.) 0.034	Discharged ¹³⁷ Cs	10 ⁻⁶		
Trawsfynydd, UK (1969) ^c .	11	Total ¹³⁷ Cs in trout			
	1.0	Discharged ¹³⁴ Cs in trout			
	25	Total ¹³⁷ Cs in perch	2 10 ⁻⁴	1.4 10 ⁻⁶	323, 426
	2.4	Discharged ¹³⁴ Cs in perch			

^a The rate of power generation in 1969 was taken from reference 263.^b Paragraph 356.^c Values for 1970 were somewhat lower than those for 1969 (427).

TABLE 66. POPULATION DOSE COMMITMENTS DUE TO DISCHARGES FROM SELECTED NUCLEAR POWER STATIONS IN THE UNITED KINGDOM CALCULATED FROM DATA IN REFERENCES 263 AND 323

Station and pathway	Critical material	Exposed population group	Daily consumption rate or annual hours of exposure	Important radio-nuclides	Whole body dose-commitment to individuals concerned per unit of power generated (rad (MW(e) y) ⁻¹)	Population dose commitment per unit of power generated (man-rad (MW(e) y) ⁻¹)
Bradwell						
Internal	Oyster	Oyster fishermen (50 persons)	75 g d ⁻¹	⁶⁵ Zn (critical) ¹³⁷ Cs ^{110m} Ag ³² P	1.1 10 ⁻⁶	5.5 10 ⁻⁵
Trawsfynydd						
Internal	Trout and perch flesh	Lake anglers (100 persons)	100 g d ⁻¹	¹³⁷ Cs ¹³⁴ Cs	5.2 10 ⁻⁵	5.2 10 ⁻³
Hinkley Point						
Internal	Fish and shrimp flesh	Local fishermen and families (100 persons)	90 g d ⁻¹	¹³⁷ Cs ¹³⁴ Cs	9.1 10 ⁻⁷	9.1 10 ⁻⁵
External	Mud/silt	Local fishermen (10 persons)	880 h y ⁻¹	¹³⁷ Cs ¹³⁴ Cs	2.3 10 ⁻⁶	2.3 10 ⁻⁵

TABLE 67. CALCULATED DOSES TO UNSHIELDED INDIVIDUALS AND POPULATIONS IN THE VICINITY OF UNITED STATES NUCLEAR POWER PLANTS
BASED ON NOBLE GASES DISCHARGED IN 1969 (188)

Reactor site	Type	Annual doses for 1969							Years of production (to December 1970)	Power produced in 1969 (263) (MW(e) y)	Dose to individuals at boundary per unit of power (rad (MW(e) y) ⁻¹)	Population dose within circle of 80 km radius per unit of power (man-rad (MW(e) y) ⁻¹)
		Dose at boundary (rad)	Within circle of 6.4 km radius			Within circle of 80 km radius						
			Population (units)	Population dose (man-rad)	Average dose (rad)	Population (thousands)	Population dose (man-rad)	Average dose (rad)				
Dresden-I	BWR	1.8 10 ⁻²	2,577	11	4.3 10 ⁻³	5,715	360	6.3 10 ⁻⁵	11	100	1.8 10 ⁻¹	3.6
Big Rock	BWR	3.2 10 ⁻³	1,430	0.57	4.0 10 ⁻⁴	100	3.64	3.6 10 ⁻⁵	8	48	6.7 10 ⁻⁵	7.6 10 ⁻²
Humboldt Bay	BWR	1.5 10 ⁻¹	18,940	68.5	3.6 10 ⁻³	101	107	1.1 10 ⁻³	8	44	3.4 10 ⁻³	2.4
La Crosse	BWR	5 10 ⁻⁴	934	0.042	4.5 10 ⁻⁵	328	0.301	9.2 10 ⁻⁷	3	9	5.6 10 ⁻⁵	3.3 10 ⁻²
Nine Mile Point	BWR	5 10 ⁻⁶	1,310	0.001	7.6 10 ⁻⁷	533	0.012	2.3 10 ⁻⁸	1	8	6.2 10 ⁻⁷	1.5 10 ⁻³
Oyster Creek	BWR	3.7 10 ⁻⁴	3,619	0.082	2.3 10 ⁻⁵	1,158	0.606	5.2 10 ⁻⁷	1	40	9.2 10 ⁻⁶	1.5 10 ⁻²
Yankee Rowe	PWR	1.1 10 ⁻⁴	1,180	0.0217	1.8 10 ⁻⁵	1,209	0.70	5.8 10 ⁻⁷	10	138	8.0 10 ⁻⁷	5.1 10 ⁻³
Indian Point I	PWR	5.5 10 ⁻⁵	38,740	0.130	3.4 10 ⁻⁶	13,324	1.94	1.5 10 ⁻⁷	8	206	2.7 10 ⁻⁷	9.4 10 ⁻³
Conn. Yankee	PWR	5 10 ⁻³	5,062	1.150	2.3 10 ⁻⁴	2,682	15.56	5.8 10 ⁻⁶	3	438	1.1 10 ⁻⁵	3.6 10 ⁻²
San Onofre	PWR	2.3 10 ⁻⁴	5,470	0.047	8.6 10 ⁻⁶	2,696	1.02	3.8 10 ⁻⁷	3	314	7.3 10 ⁻⁷	3.2 10 ⁻³
Ginna	PWR	5 10 ⁻⁶	5,001	0.0011	2.2 10 ⁻⁷	953	0.0077	8.1 10 ⁻⁹	1	17	2.9 10 ⁻⁷	4.5 10 ⁻⁴

TABLE 68. CALCULATED DOSES TO UNSHIELDED INDIVIDUALS AT THE BOUNDARY OF NUCLEAR POWER PLANTS
DUE TO NOBLE GASES DISCHARGED

Reactor site	Type	Distance from stack taken as boundary	Dose at boundary (rad y ⁻¹)	Comments on the dose calculation	Years of production (up to December 1970)	Power produced in 1970 (263) (MW(e) y)	Dose to individuals at boundary per unit of power (rad (MW(e) y) ⁻¹)
Garigliano, Italy	BWR	1,000 m	6.7 10 ⁻³	Reported dose to a group of population living at 1 km from the stack for the year 1970 (117)	7	85	7.9 10 ⁻⁵
KWL and KRB, Federal Republic of Germany	BWR	500 m	4 10 ⁻⁴	Estimated dose due to typical noble gas emission from a German BWR power plant (24)	4	174	2.3 10 ⁻⁶
KWO, Federal Republic of Germany	PWR	500 m	9 10 ⁻⁵	Estimated dose due to typical noble gas emission from a German PWR power plant (24)	2	289	3.1 10 ⁻⁷
Bradwell, UK	GCR		6.1 10 ⁻⁴	Doses calculated from the ⁴¹ Ar releases given in table 61 assuming a dilution factor of 4 10 ⁶ m ³ s ⁻¹	8	207	2.9 10 ⁻⁶
Hinkley, UK	GCR		6.9 10 ⁻³		6	238	2.9 10 ⁻⁵
Trawsfynydd, UK	GCR		4.5 10 ⁻³		6	388	1.6 10 ⁻⁵
Oldbury, UK	GCR		Nil	Doses calculated assuming that the releases given in table 61 consist of ⁴¹ Ar only and that the dilution factor is 4 10 ⁶ m ³ s ⁻¹	3	291	Nil
Chinon, France	GCR		6.5 10 ⁻⁴		5	411	1.6 10 ⁻⁶
Saint-Laurent, France	GCR		2.4 10 ⁻⁵		2	89	2.7 10 ⁻⁷
Latina, Italy	GCR		2.0 10 ⁻⁴		8	136	1.5 10 ⁻⁶
Tokai, Japan	GCR		5.1 10 ⁻³		5	98	5.2 10 ⁻⁵
NPD, Canada	PHWR	1,500 m	8 10 ⁻⁴	The ratio of the dose to the discharge is assumed to be the same for Douglas Point and NPD	8	16	5.0 10 ⁻⁵
Douglas Point, Canada	PHWR	1,500 m	8 10 ⁻³	Reported dose (400)	4	107	7.5 10 ⁻⁵

TABLE 69. RADIO-NUCLIDES IN LIQUID WASTES DISCHARGED FROM REPROCESSING PLANTS

Radio-nuclide	Quantity discharged (curies)				
	NFS, USA (393), May-October, 1969	Windscale, UK (654), 1969	Eurochemic, Belgium (625)		
			1967	1968	1969
³ H	1,700				
⁵⁴ Mn	0.0027				
⁶⁰ Co	0.20				
⁹⁰ Sr	8.3	2,500	0.16	0.13	0.24
⁹⁵ Zr	0.0046				
¹⁰⁶ Ru	52	23,000			
¹²⁵ Sb	0.59				
¹³⁴ Cs	2.0				
¹³⁷ Cs	8.0				
¹⁴⁴ Ce	0.16	14,000			
¹⁴⁷ Pm	0.092				

TABLE 70. TRITIUM IN LIQUID WASTE DISCHARGED FROM THE LAGOON SYSTEM OF THE NUCLEAR FUEL SERVICES REPROCESSING PLANT IN THE UNITED STATES (373)

Year	Quantity discharged (Ci)	Fuel processed (t)	Quantity discharged per tonne of fuel processed (Ci t ⁻¹)
1966 (from second quarter)	290	110	3
1967	4,200	120	35
1968	2,600	140	19
1969	6,000	120	50
1970 (to third quarter)	3,600	35	103

TABLE 71. PARTICULATE AND GASEOUS RADIO-NUCLIDES DISCHARGED TO ATMOSPHERE FROM THE NUCLEAR FUEL SERVICES REPROCESSING PLANT

Radio-nuclide	Average discharge ^a (Ci(MW(e) y) ⁻¹)
⁶⁰ Co	5 10 ⁻⁹
⁹⁰ Sr	3 10 ⁻⁸
¹⁰⁶ Ru	4 10 ⁻⁸
¹³⁴ Cs	2 10 ⁻⁸
¹³⁷ Cs	8 10 ⁻⁸
¹⁴⁴ Ce	1 10 ⁻⁷
²³⁸ Pu	7 10 ⁻¹⁰
²³⁹ Pu	1.5 10 ⁻⁹
³ H	5 10 ⁻²
Gaseous ¹²⁹ I ^b	2 10 ⁻⁴
⁸⁵ Kr	5 10 ⁻²

^a Calculated from data in reference 115.^b The scrubbers were not in operation during the dissolution cycles.TABLE 72. ESTIMATES OF DOSE DUE TO MEASURED ¹⁰⁶Ru AND ¹³⁷Cs CONCENTRATIONS IN AQUATIC FOOD-STUFFS

Reprocessing plant	Mean concentration (pCi g ⁻¹ wet)	Nuclide and daily consumption rate of food-stuff	Annual dose to individuals concerned at stated consumption (rad)	Dose to individuals concerned per unit of power generated (rad(MW(e) y) ⁻¹)	Reference
NFS					
1968	0.63	¹³⁷ Cs in 15 g d ⁻¹ fish (including fall-out)	2.1 10 ⁻⁴ to whole-body	7.5 10 ⁻⁸	556
	0.85	¹⁰⁶ Ru in 15 g d ⁻¹ fish	9.1 10 ⁻⁴ to gastro-intestinal tract	3.2 10 ⁻⁷	
Windscale					
1969	~ 15	¹⁰⁶ Ru in 16 g d ⁻¹ laver-bread	~ 1.7 10 ⁻² to gastro-intestinal tract	3.4 10 ⁻⁶ ^a	426
1970	~ 7		~ 8.0 10 ⁻³ to gastro-intestinal tract	1.6 10 ⁻⁶ ^b	427

^{a, b} Corresponding to population dose commitments of 8.8 10⁻² and 4.2 10⁻² man-rad (MW(e) y)⁻¹, respectively, to the gastro-intestinal tract, and 8.8 10⁻⁵ and 4.2 10⁻⁵ man-rad (MW(e) y)⁻¹ to the gonads (paragraph 389).

TABLE 73. POPULATION DOSE COMMITMENTS RESULTING FROM DISCHARGES FROM WINDSCALE TO THE IRISH SEA (UNITED KINGDOM)
CALCULATED FROM DATA IN REFERENCES 323 AND 426

Exposure pathway	Aquatic material	Exposed population group	Daily consumption rate or annual hours of exposure	Exposed organ	Radio-nuclides contributing to exposure	Dose commitment to individuals concerned per unit of power generated (rad (MW(e) y) ⁻¹)	Population dose commitment per unit of power generated (man-rad ⁻¹ (MW(e) y) ⁻¹)
Internal	Porphyra (seaweed)	Laverbread consumers in South Wales, 2.6×10^4 persons	16 g laverbread	{ Gastro-intestinal tract Gonads }	Mainly ¹⁰⁶ Ru	$3.4 \cdot 10^{-6}$ ^a $3.4 \cdot 10^{-9}$	$8.8 \cdot 10^{-2}$ ^a $8.8 \cdot 10^{-5}$ ^a
External	Estuarine silt	Fishermen (10 persons)	350 h	Total body	⁹⁵ Zr, ⁹⁵ Nb, ¹⁰⁶ Ru	$1.0 \cdot 10^{-5}$	$1.0 \cdot 10^{-4}$
Internal	Fish	Local fishermen (100 persons)	25 g fish	{ Gastro-intestinal tract Total body }	¹⁰⁶ Ru ¹³⁷ Cs	$4.0 \cdot 10^{-7}$ $1.0 \cdot 10^{-7}$	$4.0 \cdot 10^{-5}$ $1.0 \cdot 10^{-5}$ ^b
External	Fishing gear	Fishermen (100 persons)	500 h	Hands	{ ¹⁰⁶ Ru ¹⁴⁴ Ce }	$4.0 \cdot 10^{-6}$	$4.0 \cdot 10^{-4}$

^a These values are estimated from measurements made in 1969; the comparable values for 1970 are about half of these (427).

^b This value is estimated for the critical group of 100 persons; a value of $3.0 \cdot 10^{-2}$

man-rad (MW(e) y)⁻¹ is applicable for 1970, if doses from consumption of plaice caught commercially in the Irish Sea are included in the estimation. It is doubtful whether fish in the Irish Sea in 1970 had reached equilibrium with radio-caesium in sea water and therefore, this dose commitment may be an underestimate (427).

TABLE 74. LOCAL AND GLOBAL DOSES RESULTING FROM ⁸⁵Kr AND ³H DISCHARGED FROM THE NUCLEAR POWER INDUSTRY

Local (airborne ⁸⁵ Kr and ³ H)	⁸⁵ Kr	³ H
Gonad dose commitment to individuals concerned within a few kilometres of plant per unit power generated (rad (MW(e) y) ⁻¹)	$2.7 \cdot 10^{-8}$	$6.3 \cdot 10^{-10}$
Gonad population dose to population within 250 km of plant per unit power generated (man-rad (MW(e) y) ⁻¹)	$5.4 \cdot 10^{-3}$	$1.3 \cdot 10^{-4}$
Global (airborne ⁸⁵ Kr and water-borne ³ H) Gonad dose commitment per unit power generated (rad (MW(e) y) ⁻¹)	$3.1 \cdot 10^{-11}$	$4.4 \cdot 10^{-11}$

TABLE 75. SUMMARY OF ESTIMATED DOSE COMMITMENTS RESULTING FROM DISCHARGES OF RADIO-NUCLIDES BY THE NUCLEAR POWER INDUSTRY^a

	Source of radiation	Relevant tissue	Number of individuals concerned	Dose commitment, average to individuals concerned per unit of power generated by thermal reactors (rad (MW(e) y) ⁻¹)	Population dose commitment per unit of power generated by thermal reactors (man-rad (MW(e) y) ⁻¹)	Dose commitment to the world population per year of generation of electricity		Tables and paragraphs to be read in conjunction with these data	
						At the 1970 generation rate (rad) (GW(e) y)	at the estimated rate for the year 2000 of 2,150 GW(e) y ^b (rad)		
GLOBAL DOSES									
Fuel reprocessing plants	⁸⁵ Kr	Gonads	3.5 10 ⁹	3.1 10 ⁻¹¹	1.1 10 ⁻¹	3.0 10 ⁻⁷	(9.7)	4.5 10 ⁻⁵	Table 74, paragraph 396
	³ H	Whole body	3.5 10 ⁹	4.4 10 ⁻¹¹	1.5 10 ⁻¹	4.3 10 ⁻⁷	(9.7)	1.6 10 ⁻⁴	Table 74, paragraph 397
LOCAL DOSES ^c									
EXTERNAL RADIATION									
Five USA reactors (built 1959-1963)	Short-lived noble gases	Whole body	2.0 10 ⁷	4.4 10 ⁻⁸	8.8 10 ⁻¹	1.2 10 ⁻⁷	(0.46)		Table 67, paragraph 359
Six USA reactors (built 1967-1969)	Short-lived noble gases	Whole body	8.4 10 ⁸	2.5 10 ⁻⁹	2.1 10 ⁻²	1.0 10 ⁻⁸	(1.7)		Table 67, paragraph 359
Fuel reprocessing plants . .	⁸⁵ Kr	Gonads	2.0 10 ⁷	2.7 10 ⁻¹⁰	5.4 10 ⁻³	1.5 10 ⁻⁸	(9.7)	2.2 10 ⁻⁶	Table 74, paragraph 392
Doses calculated from recorded concentrations around a particular installation									
Reactor:									
Hinkley Point, UK	¹³⁴ Cs + ¹³⁷ Cs	Whole body	10	2.3 10 ⁻⁶	2.3 10 ⁻⁵	1.6 10 ⁻¹²	(0.24)		Table 66, paragraph 358
Fuel reprocessing plant:									
Windscale, UK . . .	⁹⁵ Zr— ⁹⁵ Nb, ¹⁰⁶ Ru	Whole body	10	1.0 10 ⁻⁵	1.0 10 ⁻⁴	1.4 10 ⁻¹⁰	(5.0)		Table 73, paragraph 389
INTERNAL RADIATION									
Fuel reprocessing plants . .	³ H (airborne only)	Whole body	2.0 10 ⁷	6.3 10 ⁻¹²	1.3 10 ⁻⁴	3.5 10 ⁻¹⁰	(9.7)	1.3 10 ⁻⁷	Table 74, paragraph 395
Doses calculated from recorded discharges or concentrations around a particular installation									
Reactors:									
Douglas Point, Canada	³ H (airborne only)	Whole body		7 10 ⁻⁷ ^d					Paragraph 362

Bradwell, UK	⁶⁵ Zn	Whole body	50	1.1 10 ⁻⁶	5.5 10 ⁻⁵	3.3 10 ⁻¹²	(0.21)	Table 66, paragraph 358
Hinkley Point, UK	¹³⁴ Cs + ¹³⁷ Cs	Whole body	100	9.1 10 ⁻⁷	9.1 10 ⁻⁵	6.2 10 ⁻¹²	(0.24)	Table 66, paragraph 358
Trawsfynydd, UK	¹³⁴ Cs + ¹³⁷ Cs	Whole body	100	5.2 10 ⁻⁵	5.2 10 ⁻⁸	5.8 10 ⁻¹⁰	(0.39)	Table 66, paragraphs 356-358
Fuel reprocessing plants:								
Nuclear Fuel Services, USA	¹³⁷ Cs	Whole body		7.5 10 ^{-8 e}				Table 72, paragraph 386
Windscale, UK	¹⁰⁶ Ru, ¹⁴⁴ Ce	Gonads	2.6 10 ⁴	1.6 10 ⁻⁹	4.2 10 ⁻⁵	5.9 10 ⁻¹¹	(5.0)	Tables 72 and 73, paragraphs 387-389
	¹³⁴ Cs, ¹³⁷ Cs	Whole body			3.0 10 ⁻²	4.3 10 ⁻⁸	(5.0)	Table 73, paragraph 390

^a The numbers are given with two significant figures for calculational purposes and not as an indication of accuracy.

^b The load factor for the estimated installed capacity of 4300 GW(e) in the year 2000 has been assumed to be the same as that known to apply to the installed capacity of 20 GW(e) in 1970, namely 0.5. Doses resulting from ³H and ⁸⁵Kr have been calculated for the year 2000 assuming that the quantity produced by fission (table 55) is discharged in its entirety. Doses which could result from other radio-nuclides dis-

charged are not shown for the year 2000, because the quantities likely to be discharged cannot be predicted as they depend upon waste management policy.

^c This list of local doses is incomplete; it includes only doses related to individual installations or to operations based on the total power generation rate for which either adequate data exist or reasonable assumptions can be made.

^d The calculated dose applies to hypothetical individuals at or near the site boundary.

^e The calculated dose applies to hypothetical adults eating locally caught fish.

TABLE 76. ESTIMATES OF WORLD-WIDE AVERAGE DOSE COMMITMENTS FROM MAN-MADE ENVIRONMENTAL RADIATION AND ANNUAL DOSES FROM NATURAL BACKGROUND

<i>Dose commitments (mrad)</i>							
		<i>Atmospheric tests^a</i>	<i>Cratering experiments^b</i>	<i>Electrical power production^c</i>		<i>Annual doses from natural background^d (mrad y.⁻¹)</i>	
				1970	2000		
<i>Gonads</i>							
External		84	1.7 10 ⁻²	4.5 10 ⁻⁴	0.5 10 ⁻¹	72	(79)
Internal		35	0.6 10 ⁻²	4.7 10 ⁻⁴	1.6 10 ⁻¹	21	(22)
ROUNDED TOTAL		120	2 10 ⁻²	9 10 ⁻⁴	2 10 ⁻¹	93	(100)
<i>Bone-lining cells</i>							
External		84	1.7 10 ⁻²	4.5 10 ⁻⁴	0.5 10 ⁻¹	72	(79)
Internal		95	0.6 10 ⁻²	4.7 10 ⁻⁴	1.6 10 ⁻¹	20	(20)
ROUNDED TOTAL		180	2 10 ⁻²	9 10 ⁻⁴	2 10 ⁻¹	92	(99)
<i>Bone marrow</i>							
External		84	1.7 10 ⁻²	4.5 10 ⁻⁴	0.5 10 ⁻¹	72	(79)
Internal		76	0.6 10 ⁻²	4.7 10 ⁻⁴	1.6 10 ⁻¹	17	(17)
ROUNDED TOTAL		160	2 10 ⁻²	9 10 ⁻⁴	2 10 ⁻¹	89	(96)

^a Dose commitments resulting from atmospheric tests carried out before 1971 (table 45). For ¹⁴C, only the doses accumulated up to year 2000 were taken into account. The total dose commitment to the gonads and bone marrow due to ¹⁴C is about 140 millirads, and that to cells lining bone surfaces is about 170 millirads.

^b Dose commitments resulting from peaceful nuclear explosions conducted before 1972 (paragraphs 304, 306, and 307).

^c Dose commitments per year of generation of electricity (1970 or 2000); summation of data in table 75.

^d Taken from table 20. Estimates of the 1966 report are given in parentheses.

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(c) Patients receiving multiple fluoroscopic examinations of the chest (85).

The following groups of patients, who have undergone radio-therapy, were also investigated:

- (a) Ankylosing spondylitis;
 - (b) Children receiving thymic irradiation;
 - (c) Patients treated for metropathia (33);
 - (d) Patients treated for cancer of the breast (1);
 - (e) Patients having stomach ulcers (23, 145);
 - (f) Children irradiated for ringworm (150);
 - (g) Children treated for retinoblastoma (125);
- and so were two groups of patients treated with radio-pharmaceuticals:
- (h) Patients treated with ^{131}I for hyperthyroidism (136);
 - (i) Patients treated with ^{32}P for polycythæmia vera.

6. All radiological procedures carried out on patients involve a certain degree of risk of harm which must be balanced against the value of the procedure to the patients' state of health.

7. *Genetically-significant dose.* The same definition of the *genetically-significant dose* (GSD) given in the 1958 (147) and 1962 (148) reports of the Committee will be used here. The GSD is "the dose which, if received by every member of the population, would be expected to produce the same total genetic injury to the population as do the actual doses received by the various individuals". This annual dose is the weighted population dose commitment from a year of radiological practice. It is delivered at a rate considerably higher than that of any other dose commitment received by the population from other sources.

8. The definition of GSD is based on the following assumptions and considerations that will not be discussed here but are considered in greater detail in annex E:

- (a) The relevant tissue dose is that accumulated to the gonads;
- (b) The dose-effect relationship is linear without threshold;
- (c) The rate of delivery of radiation can be neglected;
- (d) Differences in sensitivity of the gamete with age and sex are ignored.

9. The appendix to this annex gives the formulæ used to obtain the GSD from the frequency of the particular examination in a certain age group of the population, the corresponding gonad doses and the appropriate weighting factors that take into account the child expectancy of the individual, relative to the average child expectancy in the population. It is important to appreciate that many of the individuals examined may have life and child expectancies quite different from the population average, because of the effect that the diseases for which they are being examined have on these expectancies.

10. *Mean marrow dose.* Observations on the induction of leukaemia in the survivors of nuclear explosions, in patients treated with radio-therapy, and in children irradiated *in utero* have indicated a strong correlation between the incidence of leukaemia and the mean dose received by the whole body or by the

active bone marrow. If it is assumed that active bone marrow is uniformly sensitive and that the relationship between frequency of leukaemias and dose is linear, doses to any part of the bone marrow can be averaged over the whole bone marrow and the whole population to give a *per caput mean marrow dose* (CMD).

11. Certain limitations in our present knowledge should, however, be indicated:

(a) While the induction of leukaemia appears to be associated with irradiation of the active bone marrow, neither the mechanism of induction nor the specific cells, or cell stages, at risk are known;

(b) There is very little quantitative information on the distribution of bone marrow in the skeleton, the relative proportion of active relative to fatty bone marrow in the various bones and the variations of these proportions with age. Most observations have been only qualitative in nature and all the numerical information on the total marrow distribution is based on the 13 cadavers investigated by Mechanik (91) in the 1920s and the recent work of Hashimoto (54, 58, 95) on 10 Japanese cadavers. In this review it is assumed that the whole marrow is active in children and that the active-marrow distribution at age 40 applies to all adults (paragraph 75);

(c) The relevance of the concomitant irradiations of the 700 grammes of lymphocytes in the body is unknown;

(d) The effect of partial irradiation of the bone marrow may be quite different biologically from a uniform dose to the whole marrow in view of the protective and regenerative capacities of unirradiated tissue. The quantitative importance of this effect is unknown in regard to the incidence of leukaemia following irradiation in man, although it has been thoroughly demonstrated in animals.

12. The mean marrow dose to an individual i from a certain exposure j of a given type of examination x may be calculated as the average dose to the whole of the active marrow

$$d_{Mijx} = \frac{1}{W_i} \int d_{ix} \Delta w$$

where Δw is the mass element and W_i the total mass of the individual's active marrow. If the examination type x comprises k_x exposures and involves N_x patients of a total population of N individuals, the *per caput* mean marrow dose (CMD) in that population is

$$D_{Mx} = \frac{1}{N} \sum_{i=1}^{N_x} \sum_{j=1}^{k_x} d_{Mijx}$$

13. In practice the individual mean marrow dose d_M may be derived from the following relationship

$$d_{Mijx} = \sum_r \left(\frac{m}{M} \right)_r (f_s d_s)_r$$

where d_{Mijx} is averaged over the total active marrow M by summing for each fraction of marrow exposed r , the product of the fraction of active marrow exposed m/M , the fraction of the dose to the skin reaching the element of marrow f_s , and the actual skin dose d_s .

14. In a survey conducted in Japan (58) a weighting factor was applied to the calculation of the bone-marrow dose to give a "leukæmia-significant" dose. The weighting factors were based on the fact that the incidence of leukæmia in the population exposed to the nuclear explosions at Hiroshima was a function of time after exposure (paragraph 76).

15. *Radiation quantities.* In the original papers referred to in this review, various radiation quantities have been used, namely, exposure, absorbed dose, and dose equivalent. For the sake of consistency these will be converted throughout to absorbed dose on the basis of an absorbed dose of one rad corresponding to an exposure of one roentgen and to a dose equivalent of one rem. For gonad-dose measurements in the range of quantities used in diagnostic radiology, some investigators (57, 118, 119) have used a conversion of about 0.94 rad per roentgen.

16. The dosimetry of the radiation absorbed in the bone marrow is made complex by the need to take into account the fact that the marrow is enclosed in the spaces between bone trabeculae. Both the distribution of the sizes of these spaces and the thickness of the trabeculae vary in the various parts of the skeleton. The average dose to the marrow at any given site will depend on the number and energy of the photo-electrons emitted from the bone trabeculae and, therefore, on the quality of the radiation used. A conversion factor from roentgen to rad units must be based on a particular model of marrow distribution and will be a function of radiation quality. Such factors have been used in some of the bone-marrow dose surveys (25, 58).

I. Diagnostic x-ray examinations

A. GROWTH OF DIAGNOSTIC RADIOLOGY

17. The growth of diagnostic radiology must be considered in relation to the changes in its contribution to population exposure. The factors affecting the total growth are:

- (a) The number of examinations of each type being carried out;
- (b) The types of procedure being carried out;
- (c) Changes in the complexity of the procedures; and
- (d) Changes in the technical facilities available, viz. the use of image intensification, cine procedures and biplane apparatuses.

However, the changes in the GSD and the CMD will also depend on whether the doses received by the patient during the particular procedures increase or decrease. The awareness of the radiological staff of the importance of the protection of the patient is probably the greatest factor in the control of population exposure.

18. The over-all increase in the number of radiological examinations has been assessed as 4 per cent per year in New Zealand (1959-1963) (156), 6 per cent per year in Sweden (1965-1969) (152), 2 per cent per year in the United Kingdom (1958-1961) (99), whereas (21, 106) the increase was a little over 3 per cent per year in the United States during the 1960s. These figures, however, include the effect of increasing population. When this is excluded, the rate of examination appears to have increased about

3 per cent per year during the 1960s. A useful study in the United States (60) illustrates the changes in frequency and age distribution of 10 diagnostic radiation categories over the years 1963, 1966 and 1968. This survey was carried out in 228 general hospitals having patients staying for short periods. The average annual observed increment for each of the 10 categories was 1.7 per cent and the total annual increment was approximately twice this value. This study emphasizes the need to study over a period of years the variation in the age-specific frequency of a particular examination and the changes in the over-all pattern of diagnostic investigations, such as may be due to the increasing popularity of a particular examination. Such studies have been recommended by the World Health Assembly (122) to Member States and relevant data are included in the report of an expert committee on the medical uses of radiation (157).

19. *Services in developing countries.* Valid statistics from developing countries are not currently available but every indication shows that there is a great difference between the facilities provided in such countries and those available in the more technically advanced countries. Therefore such services need to be expanded with appropriate emphasis given to modern techniques and good patient protection (77). In developing countries, x-ray facilities are often only available in the main cities and even in industrialized countries there are often large but sparsely populated areas where such services are very limited. It is likely that a large proportion of the world population does not have easy access to modern x-ray facilities. It is obvious, therefore, that the rates of increase quoted in paragraph 18 are relevant only to countries in which a highly sophisticated medical care system is already in existence. In countries in which medical care and preventive medicine are not as developed, the rate of increase is expected to be many times higher during the next decade.

B. LIMITATIONS OF RADIOLOGICAL SURVEYS

20. The design of surveys for the estimation of the GSD or of the CMD received by a particular population was considered by the International Commission on Radiological Protection (ICRP) and the International Commission on Radiation Units and Measurements (ICRU) in 1955 (42) and 1959 (43) and involves the consideration of the following factors:

(a) The method of obtaining the data on the frequency of examinations and the size of the sample required for that purpose;

(b) The selection of the number of patients for whom doses are to be measured or estimated and the choice of centres at which this is to be done;

(c) The actual method of measuring or estimating the dose for each type of examination. Since examinations may involve a number of irradiated fields of differing area, focal skin distance and radiation quality, sufficient numbers must be studied to constitute a reliable average of each type of examination, particularly for those that make the greatest contribution to the GSD or the CMD;

(d) For the estimation of the GSD, the expectation of subsequent parenthood according to age within each group of patients undergoing a particular type of examination; and

(e) For the estimation of bone-marrow doses, the distribution of the active bone marrow.

21. Each of the above parameters introduces into the final result some sampling error the magnitude of which will decrease as the size of the sample increases. On the other hand, a systematic bias towards lower doses may result from the presence of an observer or from the foreknowledge of the subsequent dose estimation. An analysis of these factors is given in the following paragraphs.

1. Frequency of examinations

22. It is important to determine with the greatest accuracy the frequency of those examinations which can be judged to make the greatest contribution to the population dose. The frequency of such examinations may be low. For example, in the 1957-1958 British survey (26), obstetrical abdomen examinations contributed 24 per cent of the GSD though their frequency was only 0.6 per cent of the total yearly examinations. The main problem in comparing frequencies from one country with those from another is that the actual procedures may be considerably different for examinations similarly defined.

23. Two basic approaches have been used. The vast majority of the surveys have entailed the collection of the over-all numbers of examinations in age classes from all, or a known fraction of, hospitals, clinics and private practices over a given period of time. This period has varied from a few days to 18 months. Typical values of the percentage of the total year's work in these samples are 40 per cent in the Netherlands (14), 8 per cent in Finland (67), 6.4 per cent in Czechoslovakia (80), 3.5 per cent in New Zealand (156), 2.5 per cent in the United Kingdom (26) 1957-1958, and 2 per cent in Sweden (82). The numbers of persons undergoing examination in the radiological departments included in these surveys have been very large and typical values are 254,000 in Czechoslovakia (80), 143,000 in Finland (67) and 40,000 in New Zealand (156).

24. The second method which was utilized in the United States 1964 survey (106), depends on the selection of householders by a multistage design that permits a continuous sampling of the civilian population. After house-to-house interviews of some 31,000 people, about 3,600 of the 4,500 people who had been radiographed in the past three months were traced. Forty per cent of these, however, had been radiographed for dental examinations. About 2,200 people, therefore, provided the data on the frequency of examinations in radiological department, representing some 0.002 per cent of the radiology carried out in the United States in one year. In 1970, the United States repeated the national survey using the same methodology that was employed in the 1964 survey except that they doubled the sample size so that over 67,000 persons were interviewed in the household interview survey (21).

25. The consumption of x-ray film per year is not in itself a reliable method for estimating GSDs, because for a given film size used at a particular site, the gonad dose will depend on whether good or bad practice is followed. However, within any one institution, film consumption will follow seasonal variations in the frequency of examination as long as changes in techniques, such as the replacement of conventional radi-

ography by photofluorographic methods, do not take place. The consumption of film by month or quarter has been used in a number of surveys (26, 80), in relation to the number of examinations carried out during a sample period of the year, to obtain the yearly number of examinations.

2. Selection of patients or centres

26. The hospitals and clinics at which the measurements of gonad doses or the collection of exposure data are to be carried out are usually selected on the basis of their size and geographical location. In some surveys, however, only one or a few centres were utilized and this obviously is likely to have biased the results since the particular hospitals selected were usually the largest or leading ones in the area surveyed and hence can be expected to have a higher standard of radiological practice and of patient's protection than is common in the area. In a number of surveys no measurements were carried out and values of gonad doses published in the literature were utilized. In the United States in both the 1964 and 1970 surveys (21, 106), the centres themselves supplied exposure data on the patients selected in the frequency survey.

3. Gonad-dose measurements

27. The need to establish reliably the mean gonad dose per examination is obvious. However, for any one type of examination, the effort should be proportional to the contribution of the examination to the total dose. The difficulty, as far as sample surveys are concerned, is that, by altering the position of the edge of the beam by a few centimetres, the gonads of the patient may be just in or just out of the beam. This can change the gonad dose by a factor of ten or a hundred (100). Similarly, the use of gonad shields greatly reduces the gonad dose when the gonads are in the direct beam.

28. The determination of gonad doses may be direct or indirect. Direct measurements of male gonad doses with the dosimeter in contact with the scrotum have been made in a large number of surveys. A few surveys (119, 132) have made measurements of female gonad doses by placing dosimeters in the vagina or rectum but most surveys have relied on an abdominal skin measurement during an examination of female patients and converted it by phantom measurements to an ovary dose. In one survey (69) a multiple regression method was utilized for the conversion. In the indirect method of gonad-dose determination used in the United States for both the 1964 and the 1970 surveys (21, 106), the radiological centre returned the exposure factors together with an exposed film providing the appropriate field size and radiation quality. The data were then used in phantom experiments to derive the gonad dose.

29. The objection to the direct method is that the presence of the observer may tend to make staff use optimal operational discipline and be more aware of whether the gonads are in the beam or not. The indirect method, on the other hand, is retrospective by at least three months, and staff cannot state accurately the exact field size or precisely where the film was applied.

30. Typical numbers of actual gonad dose measurements made in the large surveys are 10,000 in Czechoslovakia (80), 3,800 in New Zealand (156),

2,200 in Yugoslavia (94) and 1,700 in Bavaria (132). Measurements of the gonad doses during examinations of children are of particular interest as there are only a few surveys which have taken these into account. When careful techniques are used, the gonad doses are smaller than those for adults. Children's gonad doses are given in a number of reports (26, 58, 134). The measurements reported in Thailand (119) are of interest since they not only reflect the result of good radiography but also show how the smaller size of the patients requires reduced exposure factors resulting in lower skin, and therefore lower gonad, doses, as long as all other factors remain constant. Several hundred measurements for a single type of examination usually give reliable distributions of doses per examination. In the Czechoslovak survey (80) the geometric mean rather than the arithmetic mean was used to correct for the small size of some samples.

31. A completely different method of dosimetry has been used in the Johns Hopkins survey (97) in the United States. The dosimeter used consisted of a transmission ionization chamber fitted close to the x-ray tube portal in the primary beam. The reading of such a chamber was, for any exposure, proportional to the integral of the area of the beam at the x-ray tube diaphragm multiplied by the exposure in roentgens, and was therefore proportional to the radiation energy projected onto the patient. This measurement was made for a large number of patients. To derive the gonad dose from such a reading of projected radiation energy, the fraction of the radiation energy falling on to the abdomen was determined for each examination type. There are difficulties and inaccuracies in translating these measurements into actual gonad doses.

4. Child expectancy

32. In the calculation of the GSD it is required to know (see appendix) (a) the child expectancy by sex and age of the patients that undergo each particular type of examination and (b) the child expectancy of the general population, also by age and sex. Data of

the first type are practically unobtainable except for a few examinations on which details are given in paragraphs 35-38. In the absence of such data, most surveys have had to assume that the child expectancy of the patient of a given age and sex is equal to the child expectancy of the average person in the population of the same age and sex. These latter child expectancies are obtained from national statistics and representative examples of them are given in table 1 for Czechoslovakia (80), Thailand (119), and New Zealand (118).

33. The values for all European countries and Japan are similar to those from Czechoslovakia; the Thailand values are probably representative of South East Asia, and the United States values are similar to those from New Zealand. The New Zealand data in table 1 are given for four periods and indicate that child expectancy is changing with time. Such changes in absolute values of child expectancy do not make as much difference in the GSD as at first might be anticipated because the same value of the indices appears in both the numerator and denominator of the formulae for the calculation of the GSD of each irradiated person. The exception to this is in the irradiation of the foetus. In this case the indices in the numerator will apply to the foetus and those in the denominator to the mother. Hence any absolute change in child expectancy will be reflected in the contribution from the foetal exposure to the GSD due to the particular examination.

34. In the New Zealand survey (118) the child expectancy in various age groups has been expressed as a percentage of the remaining child expectancy at various ages. The probit plot of figure I shows that this percentage follows a log-normal distribution and that the values derived from Norway and Sweden lie on the same line as those from New Zealand. This may not be so, however, for countries with very different demographic structures.

35. Several surveys have utilized specific data for the child expectancy of patients undergoing hysterosalpingography and for pregnancy examinations. A sur-

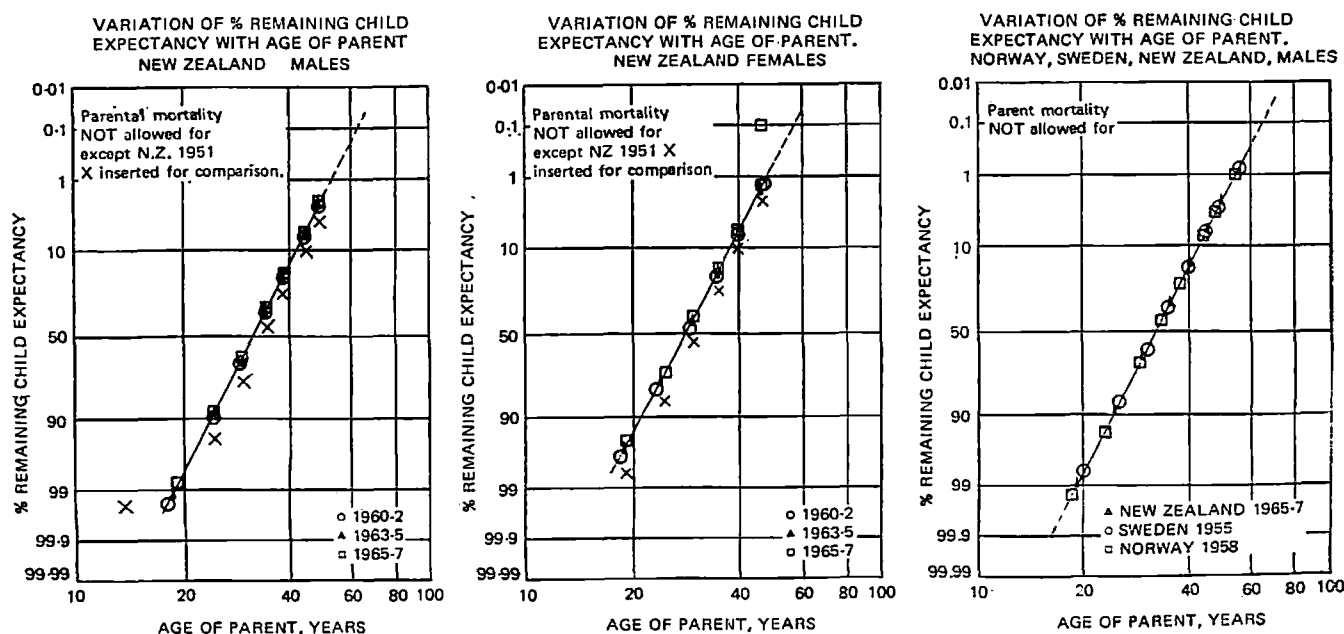


Figure I. Variation in child expectancy with age of parent (118)

vey in Brno, Czechoslovakia (80), followed up 700 women who had had hysterosalpingography examinations and showed that 25 per cent of them gave birth to live children after the examinations. This factor of 0.25 was applied to the average population statistics for the particular age class. Other surveys used different factors—0.5 in the Netherlands (14), Sweden (82), and Texas (27), and 0.1 in the United Kingdom (26).

36. For examinations connected with pregnancy, several surveys have utilized as the expected number of offspring the average population statistics for the particular age class concerned less 1 (or less 0.99) in recognition of the fact that the foetus must be considered separately with its own child expectancy. In the Dutch survey (14) a more detailed relationship by age reduction in child expectancy. It is doubtful whether this type of correction is appropriate, for it may be argued that a woman in a particular age class who is currently pregnant is more likely, rather than less likely, to have more children than the average woman in the population of that age class. This was confirmed in a survey based on the 1951 British census (98) which showed the following expectations in the different age classes:

Age class (years)	Child expectancy	
	Now pregnant	Average in population
15-19	2.78	2.207
20-24	2.23	1.733
25-29	1.84	1.017
30-34	1.60	0.462
35-39	1.47	0.157
40-44	1.38	0.030

37. A correction (9 per cent) for multiple pregnancies, twins, etc. was included in the British survey (26), as multiple pregnancy is one of the clinical indications for x-ray examination. The correction increased the number of offspring per pregnancy x-ray examination by 9 per cent.

38. The contribution from foetal irradiation during examinations not apparently connected with pregnancy, or before the pregnancy was determined, was assessed in some surveys on the basis of the number of women in the population that are pregnant at any given time. This was estimated to be 6 per cent in Finland (67) and 9 and 3 per cent in the 15-29 and 30-49 age groups, respectively, in the United Kingdom (26). In New Zealand (156) the same contribution varied with age as follows:

Age group (years)	Percentage pregnant at any one time
15-19	3.59
20-24	19.70
25-29	20.22
30-34	11.95
35-37	5.84
40-44	1.72
45-49	0.12

In the Netherlands (14), however, a further correction factor of $\frac{2}{3}$ was applied to take into account the reluctance of clinicians to request x-ray examinations of pregnant women.

C. GENETICALLY-SIGNIFICANT DOSE

1. Description of surveys

39. The 1962 report gave detailed information on surveys carried out in 12 countries or districts. The resulting GSD due to diagnostic radiology ranged from 7 to 56 millirads. These surveys were carried out during the period 1950-1961 but most of them during the last five years of that period. A summary of the results is given in table 2 which is abstracted from the 1962 report of the Committee (annex G, tables I, XVII, XXI).

40. Since 1962, a considerable number of investigations in other countries and large districts have been reported. The results of these surveys are given in table 3 and the details of each study in paragraphs 47 to 59. The GSDs range from 5 to 75 millirads and are therefore similar in magnitude to those reported in the previous decade.

41. The frequencies of radiographic examinations per year excluding mass surveys of the chest, given in tables 2 and 3 are plotted in figure II against the year of survey. This figure gives an over-all impression of the variation in the numbers of radiographs carried out in different areas of the world but attention must be drawn to the fact that different diseases and radiological techniques will alter the relative contribution of any one procedure to the over-all frequency of examinations. However, comparisons within any one country or region will be a reasonably valid indication of the growth of radiological services. Examples of this are given by the curves for New Zealand (156) and the United Kingdom (99) in figure II.

42. The frequency of radiological examinations in some industrialized countries is about one examination per person per year. From the GSDs reported in tables 2 and 3 and the annual frequency of radiological examinations in figure II a projection of the GSD has been made for each country or region assuming that the practice has increased to a frequency of one examination per person per year. These projections are shown in figure III against the year in which the original survey was conducted. This shows the variation in the GSDs arising from differences in the prevalent types of examinations in different countries, in radiological procedures and in the standards of patient protection. The main uncertainty in the value of the normalized GSDs lies in the total number of examinations reported.

43. The increase in the number of examinations need not necessarily lead to higher GSDs if the increase is accompanied by procedural improvements. Of the surveys reported in table 3, the regional survey (89) that was carried out in the United Kingdom seven years after the national survey showed a drop in the GSD from 14.1 to 8.6 millirads. The 1969 New Zealand survey (118) yielded a value not significantly higher (5 per cent) than that obtained by the 1963 survey despite an 11 per cent increase in the frequency of examinations.

44. The Dutch survey of 1967 (14) included a useful study of the dependence of the GSD on the particular values of the parameters used in the calculation. The parameters studied were the gonad dose and the frequency of the examinations. The values of gonad doses per examination used in this study were those determined in four surveys carried out in Leiden (13),

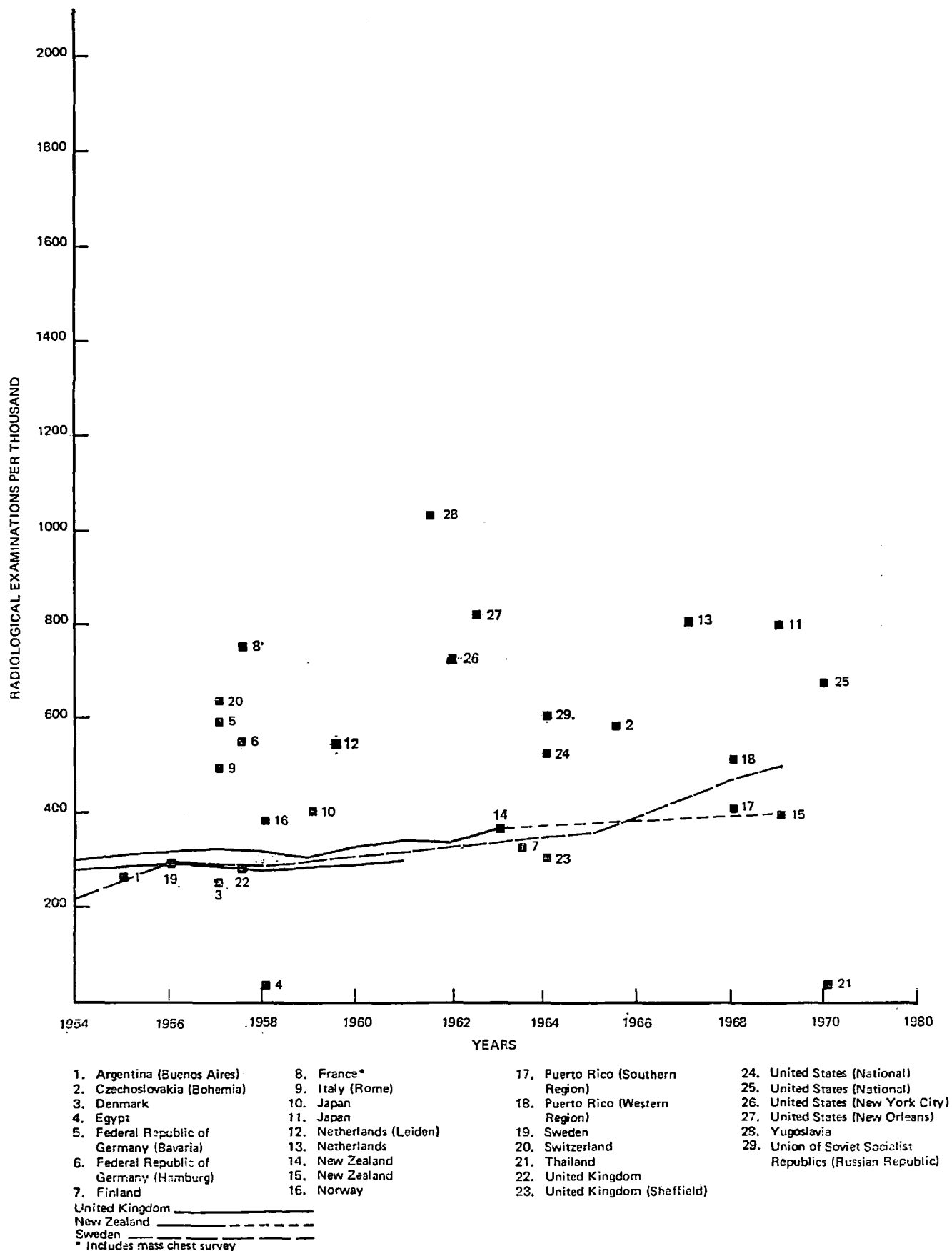


Figure II. Annual frequency of radiological examinations in the population excluding mass chest surveys

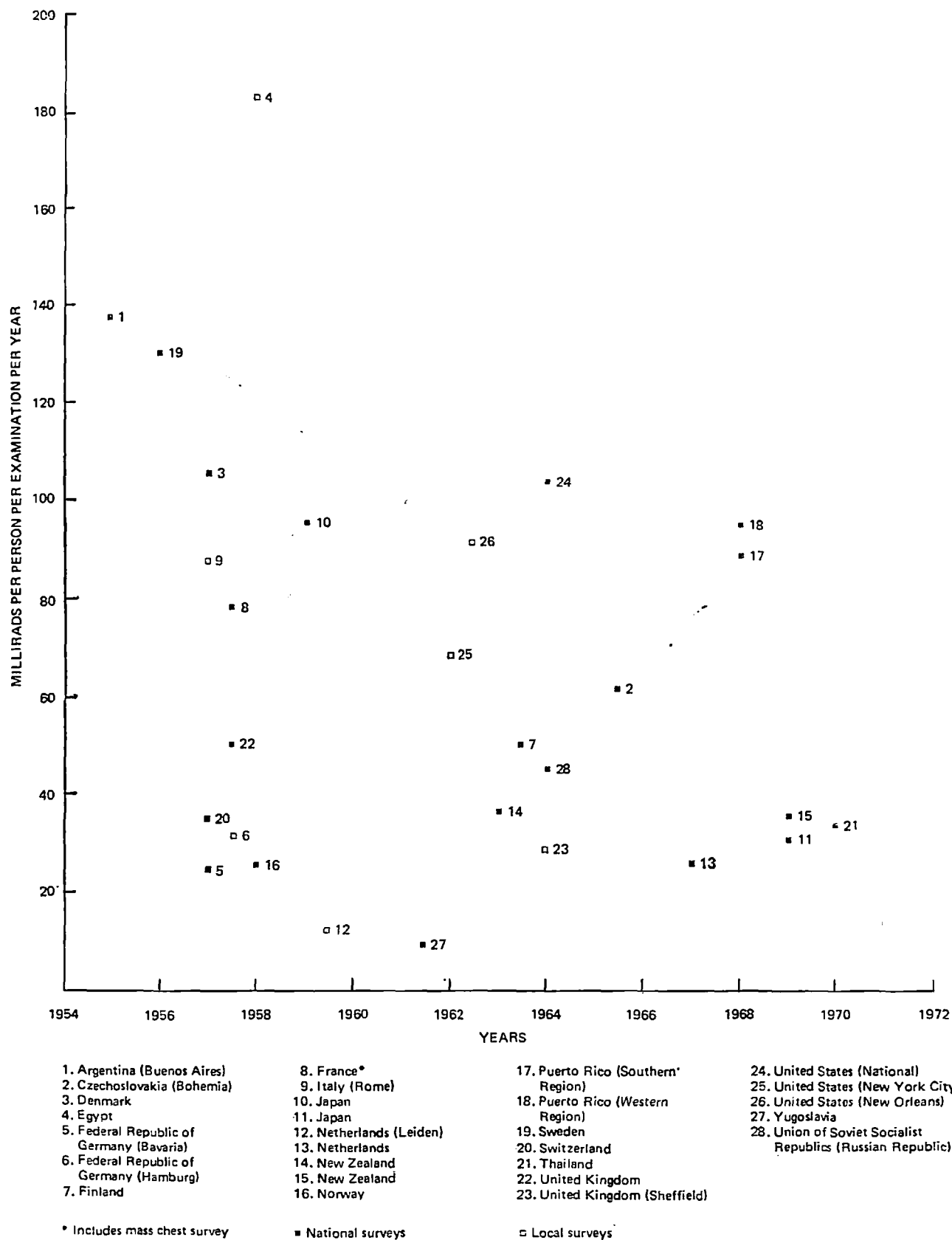


Figure III. Normalized GSD for population receiving one examination per person per year

in Denmark (53) and in Texas (27) by the same physicist (14) and in the United States national survey of 1964 (15). These were combined with one of two sets of examination frequencies obtained in the Netherlands on 1 million people (survey A) and on 5 million people (survey B), respectively (see paragraph 50). Six values of the GSD were determined using the following selections from the above data:

- Selection 1 using Leiden gonad dose data and survey A
- Selection 2 using Texas gonad dose data and survey A
- Selection 3 using Leiden gonad dose data and survey B
- Selection 4 using Texas gonad dose data and survey B
- Selection 5 using Denmark gonad dose data and survey B
- Selection 6 using U.S.A. gonad dose data and survey B

45. The six estimates of the GSD together with their male and female components were as follows:

Selection	Male	Female	GSD
1	7.8	10	17.8
2	5.6	7.8	13.4
3	7.6	9.1	16.7
4	5.4	7.4	12.8
5	9.4	7.6	17.0
6	30.6	8.9	39.5
		Mean	19.5

Comparison of 1 with 3 and 2 with 4 shows that there was little difference between the two sample populations. Comparison of 3, 4, 5 and 6 shows the difference produced by using different sets of gonad doses per examination. The four female contributions to the total were similar, but one of the male contributions was far higher than the others as a result of examinations, included in the United States national survey (106), in which the testes were exposed in the direct beam.

46. The main details of the actual surveys referred to in table 3 are presented in the following paragraphs. The results of most of the surveys are given in tables 4-17. In each of these tables the 10 examinations making the greatest contribution to the GSD are presented, with the exception that pelvimetry and obstetrical abdomen are included even though they might not rank among the top ten. In these cases they replace the ninth and tenth types of examination. The frequency of these examinations and the gonad doses are also given for each examination.

47. *Czechoslovakia, Bohemia, 1965-1966 (table 4) (80)*. The survey covered three (population 4,341,000 or 30.5 per cent of the country total) out of the 11 regions of the Czechoslovak Socialist Republic. The number of examinations carried out in all radiological and fluoroscopic units over a one-year period were collected, together with those carried out during a three-month period in all mass chest survey units and during two one-week periods in 219 out of 570 dental x-ray departments. A breakdown of the examinations by age was obtained for 253,853 examinations, i.e. for 6.4 per cent of the annual number of examinations (2.2 million radiographic and fluoroscopic; 1.4 million mass chest; 0.4 million dental). Central-axis skin-dose and gonad-dose measurements were carried out on 5,602 patients in 70 departments at 28 industrial and agricultural localities. To obtain the ovary dose, phantom measurements were carried out on each machine immediately following each exposure. The national average child expectancy in the population was used in the calculation of the GSD (table 1)

except for hysterosalpingography (paragraph 35). It should be noted that pelvimetry examinations are practically never carried out in Czechoslovakia.

48. *Finland, 1963-1964 (table 5) (67)*. All medical institutions, hospitals and private physicians in Finland were asked to supply details of all radiological examinations carried out during four weeks in 1963, together with the total number, or estimated total number, of x-ray examinations during 1963. A second survey was instituted to complete the required information. The frequency of dental examinations was estimated from film consumption. Total examinations for 1963 were 2.7 million plus 80,000 dental examinations. 143,000 examinations were recorded in the study period. Gonad dose measurements were obtained by using 1960 fluoroglass dosimeters sent to 124 hospitals. In the case of males, fluoroglass rods were in contact with the testes; in females the dosimeter was placed on the back, near the ovaries. The ovary dose was obtained by phantom measurements using a calibration factor dependent on the type of x-ray unit used. National child-expectancy figures were used in the calculation of the GSD. Six per cent of the women examined were assumed to be pregnant and a foetal dose equal to the female gonad dose was assumed.

49. *Federal Republic of Germany, Bavaria, 1956-1958 (table 6) (130-132, 134)*. Statistical data regarding the admission of patients to hospitals in Bavaria were obtained in 1956. The classification by type of examination, age and sex was obtained for a population of 0.75 million. Gonad-dose measurements were made on 1,759 patients in 10 different types of hospitals and private practices. Some 705 measurements on children and 700 on adults were also carried out at the University of Munich. The gonad doses of adult females were measured in the vagina and for female children in the rectum. The comparison of gonad doses in various clinics and hospitals and for various ages showed a wide variation depending on the procedures observed. The national child-expectancy figures were used in the calculation of the GSD.

50. *Netherlands, 1967 (table 7) (14, 107)*. The radiological examinations carried out in one year on 4.9 million people covered by 53 insurance companies were used to derive the annual total number of examinations. A subsample of nine companies which covered 1 million people was used to obtain the breakdown by age and sex. Both samples were geographically scattered. The two samples were cross-checked and found to be in reasonable agreement. The gonad-dose measurements were those obtained in a previous survey in Leiden (13) on patients and on a phantom, but other gonad-dose measurements (some by the same authors working in Texas) were used to compute various estimates of the GSD (see paragraph 44). National child-expectancy figures were used, except for the examinations of pregnant women (paragraph 35). An increase in the GSD has been reported (154) on the basis of further gonad-dose measurements at two hospitals in 1971 and on the 7 per cent per annum increase in the frequency of examination.

51. *Japan, 1969 (table 8) (57)*. The frequencies of examinations were obtained during 30 consecutive days from a number of hospitals of various sizes (number of beds) and from 1,000 physicians. Answers giving the numbers of examinations and the physical conditions used were received from 60 per cent of the hospitals approached. Gonad doses were measured

on four phantoms using x-ray units from different manufacturers operating at the particular conditions used for each examination type in the various hospitals included in the survey. The phantoms represented 8-month, 5-year and 10-year-old children and the adult. The output of some 54 x-ray generators was surveyed to obtain a mean output per unit. The child expectancies were derived from national statistics.

52. *New Zealand, 1963 and 1969 (table 9) (118, 156).* Annual figures from the Department of Health showed an increase of over-all frequencies of 21.6 per cent during the years 1963-1970. During the same time the population of New Zealand increased from 2.5 to 2.8 million. A survey in which details of 40,000 examinations were collected and analysed, sampled 3.5 per cent of the annual number of examinations. A field survey was conducted in which the gonad or skin doses were measured in 1,400 examinations and 2,460 technique forms were used to derive the gonad dose. The male measurements were carried out directly and the ovary dose was calculated from the data used in the British national survey of 1957. Child expectancies were derived from national statistics (table 1 and figure I). The 1970 survey utilized the same gonad-dose measurements and the distribution of examinations by age and sex as in the earlier survey but current data on the total frequency of examinations and child expectancy were used. The most notable changes in the frequency of examinations that took place during the 1957-1963 period regarded pelvimetry examinations, which dropped to 40 per cent of the 1957 frequency, and obstetrical abdomen examinations, which dropped to 60 per cent of that frequency.

53. *Thailand, 1970 (table 10) (4, 119).* The total number of patients radiographed in all centres was requested for the month of January 1970 and the 56 per cent return obtained represented some 45 per cent of the estimated number of examinations carried out. A very low total frequency of 30 examinations per year per 1,000 persons was reported. Gonad-dose measurements were made in one hospital during fluoroscopic procedures using thermoluminescent dosimeters placed on the scrotum of male patients and in the vagina of female patients. Phantom measurements were undertaken in five hospitals utilizing the exposure data of patients. The lower gonad dose due to the smaller size of the patients is to be noted (paragraph 30). As data were insufficient to make possible an accurate estimate of the GSD, a "most probable" value was derived. As this value seems exceptionally low, an upper limit has been estimated, referred to as "the maximum" GSD based on the "maximum" average gonad dose. The female child-expectancy data derived in 1966 by the Ministry of Public Health was used and the male fertility was deduced from it, using as a basis the relationships observed in New Zealand (figure I). It was considered that the pattern for females might be changing since the median age of the mother at childbirth had dropped from 27 years in 1966 to 25 years in 1970.

54. *United Kingdom, Sheffield, 1964 (table 11) (89).* The frequencies of the examinations in the Sheffield area (population 4.5 million) were collected in all the x-ray departments during a one-week period. This showed an increase in the frequency of radiography of 33 per cent compared to that reported in the 1957 survey. The population increase was 6.2 per cent, showing a 26 per cent increase in the frequency of

radiography *per caput*. Fluoroscopic examinations had decreased by 36 per cent *per caput* and mass chest surveys increased by 42 per cent. Gonad doses were measured using ionization chambers placed at the scrotum in males and at the level of the iliac crest in females. Over 2,000 measurements on 800 patients in 30 hospitals were made. The ovary dose was calculated using the conversion data measured on a phantom in the 1957 British survey (26, 38, 39). For changes indicated by analyses of the two surveys, see paragraph 61. The same child expectancies, based on national statistics, that were used in the earlier survey (26) were utilized in the later one.

55. *United States, 1964 national survey (table 12) (21, 51, 104, 106, 108).* The national survey was conducted on the basis of interviews of 9,653 complete households in 1964 and 21,667 in 1970, selected by a multistage sampling programme used for sampling the civilian population of the United States. The first division consisted of 357 geographically-defined primary sampling units. Within each, the ultimate subdivisions, called segments, consisted of a cluster of nine neighbouring households. Each week a random sample of approximately 90 segments (800 households) was drawn from the whole country. Interviews of these selected households over a three-month period covered just over 31,000 people of whom 4,525 had had an x-ray examination during the previous three months. (For details see paragraph 24.) The follow-up consisted of an approach to each clinic or hospital at which a selected person had had an x-ray examination, with requests for details on the examination together with a film from which the x-ray quality and the field size could be determined. The gonad doses were determined on the basis of these exposure factors by processing the results of comprehensive scatter measurements made on a phantom. These were checked by *in vivo* thermoluminescent dosimeters applied to 360 patients undergoing a variety of examinations. The mean "system-calculated" male-gonad doses ranged for particular examinations from +170 to -71 per cent of the mean dosimetric measurements. For examinations with the ovary expected to be in the direct field, the "system-calculated" values ranged from +57 to -30 per cent of the dosimetric measurements. For data regarding field size variation, see paragraph 61. Child expectancy figures were derived from national statistics.

56. *United States, Puerto Rico, southern and western regions, 1968 (table 13) (44, 45).* The average number of patients radiographed per week over the year 1968 was presented from all hospitals in the two regions of Puerto Rico. These statistics were broken down into types of examinations. An earlier investigation had been carried out in the western region in 1967 (44). The majority of the dosimetric work was carried out on one unit. Thermoluminescent dosimeters and ionization chambers were used for a limited number of *in vivo* dose measurements at one centre and agreed reasonably with phantom measurements. The average gonad doses were derived from the returns from the 47 facilities with one or more x-ray units in the southern region and from 65 facilities in the western region. The regions had a total of 83 and 75 x-ray units, respectively. In the southern region the number of x-ray units excluding dental units was 13 in 1940, 28 in 1950, 57 in 1960 and 83 in 1968, indicating a doubling period of about 10 years. The difference in the GSD estimates in the two regions may be accounted for by technically sounder practices in the southern

region. For instance, 60 per cent of the 83 units in the southern region had variable collimators compared with 22 per cent in the western region. The child-expectancy figures were derived by the Department of Health but not published.

57. *United States, other local surveys.* Four surveys have been completed in local areas of the United States since the 1962 report, in New York City in 1962 (102), in New Orleans in 1962-1963 (69), at the Johns Hopkins Hospitals in 1965 (97) and in Texas in 1963 (27). Each of these surveys have had to depend on the national child-expectancy figures. The results at the Johns Hopkins Hospitals and the survey in Texas were expressed in terms of the national frequency rate in 1960 of $8.9 \cdot 10^7$ examinations per year. The detailed results of the surveys in New York City, New Orleans and Texas are given in tables 14-16, respectively. In the New York City survey 68 out of 234 institutions took part and each reported the annual number of x-ray examinations and a breakdown by age and type for a period of a few days. Physicians' offices reported over a four-week period. In New Orleans 262 x-ray units and 144 physicians' offices, 73 per cent of those in the area, reported data for a six-month period and the details of the exposure of 8,000 patients comprising 9,000 examinations and 18,000 projections were collected and used to derive the gonad doses using relevant phantom data (41). The Johns Hopkins survey was based on the radiographic examinations of 100,000 patients and the details of the determination of the GSD is given in paragraph 31. The 220,000 examinations at the hospitals of the University of Texas over a 30-month period were used together with gonad and skin dose measurements to derive the GSD.

58. *Union of Soviet Socialist Republics, Russian Republic (1964) (75).* The results of surveys at the Moscow X-ray Radiology Research Institute concluded that 65 million x-ray examinations were carried out annually on the 82 million people in the Russian Republic (14 million radiographies, 36 million fluoroscopies and 15 million chest photo-fluorographies). The total number of fluoroscopic examinations included 10 and 22 million examinations of thoracic organs for prophylactic and clinical reasons, respectively, and 3.6 million for gastro-intestinal tract examinations. Radiography included 2.1 million investigations of thoracic organs, 0.8 million gastro-intestinal tract and 10 million examinations of knee and joint systems. Measurements of the skin dose, gonad dose and the integral dose were made for a number of x-ray examinations. The total exposure to the gonads received each year in these examinations was $220 \cdot 10^4$ man-roentgens. The *per caput* gonad exposure was calculated to be 27 milliroentgens per year of which 10 per cent was due to prophylactic examinations and the remainder to clinical examinations. The total integral dose was $845 \cdot 10^6$ kilogramme-rads of which 91 per cent was from fluoroscopy, 6 per cent from photofluorography and 3 per cent from radiography. The *per caput* annual integral dose was 10.3 kilogramme-rads which was 1.5 times natural background (150 millirads).

59. *Yugoslavia, Slovenia, 1960-1963 (table 17) (94).* During 1960, the total number of radiographic and fluoroscopic examinations was determined for all the institutions in Slovenia. Information on a 25 per cent sample of these examinations was obtained in terms of age, sex and type of examination. The gonad-

dose survey was biased towards those examinations which contribute most to the GSD. The centres to be visited were deduced on the basis of the 1960 workload. Some 2,000 gonad-dose measurements were made. The gonad dose was measured at the scrotum for male patients and at the iliac crest for female patients. The data from the British survey and some additional data were used to convert iliac crest doses to ovary doses. The child-expectancy figures were derived from national statistics. For examinations unconnected with pregnancy, the foetal contribution was taken into account, by assuming the proportion of pregnant women of a particular age group in the population and reducing this by a factor of 0.75 to take into account the reluctance of staff to subject women known to be pregnant to x-ray examination.

2. Gonad dose

60. The gonad doses received in a variety of examinations were reported in tables XVIII, XIX and XX of annex G of the 1962 report. The gonad doses reported in more recent surveys are summarized here in table 18 which shows the median of the national mean values and the range of the mean gonad doses per examination. The examinations have been classified in three categories, according to whether they involve high, medium or low gonad doses. It will be noted that, although the mean gonad doses from the same examinations tend to be lower than those reported in 1962, their range is still wide. The range of the gonad doses reported for a particular examination reflects to some extent the difference in practice in different countries, e.g. the number of radiographs that are usually taken and the physical factors used for a particular examination type. However, improvements of practice such as those recommended by Ardran (8) will ensure that the mean value for an examination approaches the lower end of the reported range.

61. The importance of strict field-size limitation, of the use of gonad shields and of filtration of the incident beam in the reduction of the gonad dose have been illustrated by the analyses presented in some of the surveys. The excess of field area over film area shown in figure IV was taken from the United States

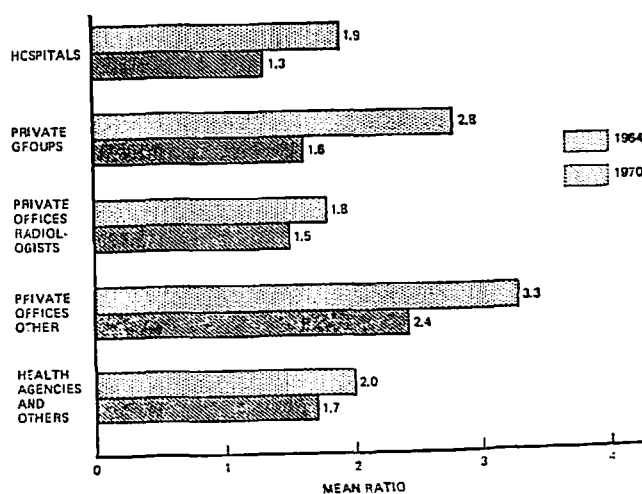


Figure IV. Estimated mean ratio of beam area to film area for radiographic examinations by type of facility, United States, 1964 and 1970 (21, 106) showing the reduction taking place during that period

national surveys (106). The 1964 survey indicated that if the field area had been equal to the film area, then the GSD would have been reduced from 55 to 19 millirads. Similarly, in the United Kingdom survey at Sheffield (89) in 1964, 67 per cent of the examinations had field sizes larger than film sizes and 8 per cent had field sizes larger than twice the film sizes. For examinations of the chest in 1957 (26) 10 per cent of males and 51 per cent of females had gonads in the direct beam but in 1964 this had been reduced to 4 and 10 per cent, respectively. In New Orleans (69), 12 per cent of the examinations were taken with units with no beam-limiting device and 30 per cent had only one large cone available. The British surveys (26, 89) indicate that gonad shields were used in examinations of 11 per cent of the male patients and 4 per cent of the female patients in 1957 but in 28 and 12 per cent, respectively, seven years later. In 1957, 24 per cent of the units had no added filtration but this was so in only 0.8 per cent of the units in 1964.

62. The radiation dose to the foetus has been studied in several surveys. In Poland an extensive survey has been carried out by Jankowski and Liniecki (70) in the city of Łódź. Reekie, Davison and Davidson (116) have also reported the doses to the foetus resulting from x-ray investigations. These surveys indicate doses to the centre of the foetus in the range of 0.1-6 rads.

63. The estimated accumulated mean gonad doses *per caput* from diagnostic medical radiology in the United States (106), assuming that examinations and dose rates were to remain constant for 30 years at the 1964 rate, would, at 15 years of age, be 160 and 50 millirads for males and females, respectively; 2,770 and 490 millirads at 30 years and 6,600 and 1,490 millirads at 45 years.

3. Genetically-significant dose by examination type

64. The contribution of the various examinations to the GSD was reported in table XXI of annex G of the 1962 report and the values reported since are contained in table 19 of the present annex in terms of their percentage contributions to the GSD. The examinations contributing most are those that involve irradiation of the pelvis and abdomen, namely, urography, lumbar spine, lumbo-sacral spine, hip and pelvis, barium meal and barium enema. The age groups contributing most to the GSDs are considered in paragraphs 66-68. The practices that are recommended to ensure that the minimum dose is received, consistent with good radiology, are referred to in paragraphs 61 and 89.

65. Particularly significant is the small contribution from examination carried out during pregnancy in some countries, e.g., in Czechoslovakia (80). In connexion with the reduction of doses by the evolution of improved techniques it is noted that in France fluoroscopic examination of the chest for mass surveys is not now allowed and that therefore radiography or photo-fluorography must be used for the chest examinations of pregnant women. In the United Kingdom (89) the number of examinations of pregnant women has greatly decreased since the 1957 survey and similarly in New Zealand (118) (paragraph 52). However, a high contribution of examinations during pregnancy is still shown by the local surveys made in the United States.

Thus, the survey by Brown and Nelson in 1963 (19) indicated that 9 per cent of all pregnancies had either a pelvimetry or obstetric abdomen examination. These examinations provided 58 per cent of the female contribution to the genetically-significant dose at New Orleans (69) in 1962-1963 and 24 per cent in New York (102) in 1962. This contribution from examinations during pregnancy is not apparent in the nationwide survey carried out in the United States (104, 106) in 1964.

4. Genetically-significant dose by sex and by age at examination

66. The contributions of examinations of males and females and of foetuses to the GSD as shown by the recent surveys are given in table 20. The foetal contribution has not always been assessed for examinations not connected with pregnancy, and sometimes that contribution is included in the female contribution. In general, the male and female contributions are about equal but in the United States 1964 survey (106) a very high male contribution, due principally to the examinations of the lumbo-sacral and lumbar spine, was recorded, 25 per cent of the male gonad doses from these examinations being in excess of five rads. The corresponding contribution to the GSD would have been reduced from 22 to 1.3 millirads, had the field sizes been reduced to the size of the films.

67. The contributions of the various age groups to the total GSD is illustrated in figure V. The fact that the examinations of the 20-30 years age group contribute about 50 per cent of the total GSD is important when considering the age group for which both gonad-dose reduction and reduction in the frequency of examinations is particularly desirable.

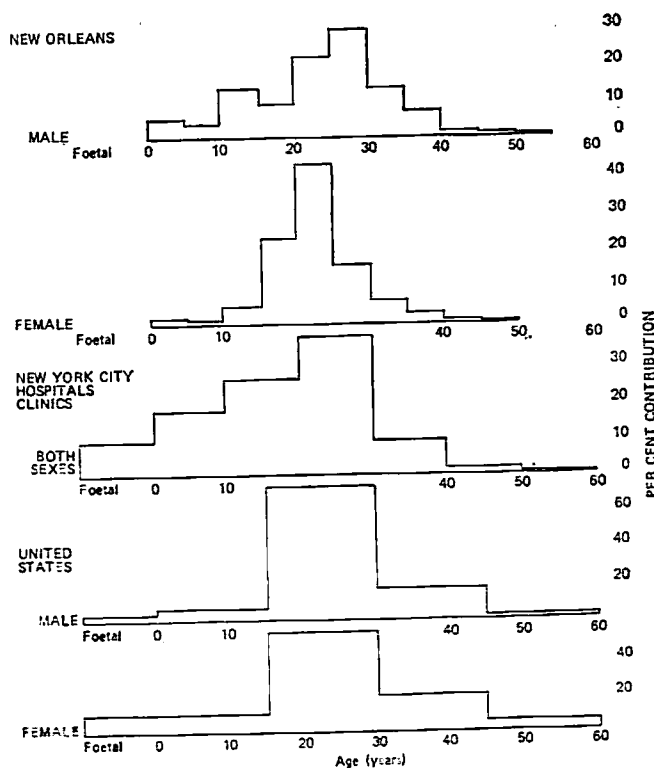


Figure V. Contribution of age groups to the genetically-significant dose

68. *Children.* The importance of reducing the gonad dose when examining children has been emphasized in several reports (26, 28, 74, 80) which have shown that such radiography needs to be carried out using careful techniques to ensure that doses smaller than those for adults are received (see paragraph 30). Otherwise gonad doses several times greater than the adult gonad doses will be received particularly from examinations of the hip, femur and of the abdomen.

5. Other investigations

69. Estimates of the GSD have now been made over a period of two decades and it is important to consider the contributions that further studies might make. Probably the most important contribution made in any country or region by the conduct of a survey is educational. Increased awareness of the need to protect the patient develops among the staff and many country-wide and regional surveys have been undertaken for this reason. Surveys have the additional advantage of bringing to light the specific practices which may be important contributors to the GSD. However, the repetition of such investigations should aim more at determining the order of magnitude of any changes in the GSD that may have taken place over, say, a 10-year period than at obtaining highly precise estimates of the GSD.

70. In countries where resources of both trained staff and finances are limited, the determination of the GSD should not rank high in the order of priorities but effort should be placed on the improvement of the facilities and on training of staff. Estimates of the GSD can be made on the basis of the studies in other countries and of data on the frequency of examination which do not require highly skilled staff for their collection.

71. As medical radiological practices change and new techniques are introduced estimates should be made of the doses to the gonads, to the skin and to other organs in the direct field. From the frequency of these investigations in a few broad age groups it should be possible to determine the importance of these practices to the GSD. Such estimates should be included in the description of the techniques in the scientific literature.

72. A number of investigations are known to be in progress, e.g., in Australia (138). In particular, a prospective survey of 20,000 patients is being undertaken in Canada (34) in which ill effects in progeny are being recorded together with radiation-dose estimates. A survey of dental radiology in the United States (30) has shown that the GSD from dental radiology is less than 0.01 millirad per year. Investigations on the doses to the body in mammography examinations (50, 101) have shown the vaginal dose per examination to be less than one millirad.

D. BONE-MARROW DOSE

73. In paragraphs 10-13 of the introduction the basic criteria have been stated for the study of the dose to the bone marrow. However, paragraph 11 emphasizes particularly the deficiencies in our present knowledge of the role of radiation in the induction of leukaemia. Only further study will elucidate whether the bone marrow is the most important organ to study or whether the reticulo-endothelial system, the lymph-

ocytes or the immune response of the body or some other factor may each have to be considered. It is important that, in considering the detailed information that is available on the dose to the bone marrow, these other factors should not be ignored. Further investigations of the bone-marrow dose delivered during particularly extensive examinations are required both as to the range of individual mean marrow doses and to their frequency throughout a population. The results of these investigations will not only help draw attention to the need to use the minimum dose consistent with good radiology but will also indicate groups of patients who may provide epidemiological information.

74. When the 1962 report was assembled, measurements of bone-marrow doses from only a few diagnostic x-ray examinations had been made. Since then the results of three comprehensive surveys have become available. Weber (153) published data for the Leiden district in the Netherlands giving a *per caput* mean marrow dose (CMD) of 30 millirads, in the United Kingdom (25) the result of the national survey for diagnostic radiology gives a figure of 32 millirads, and in Japan (58) a national survey has reported a CMD of 189 millirads. Estimates of the CMD in Czechoslovakia (81) amounted to 68 and 184 millirads, depending on which of two different approaches based on the British results were used. Other measurements were made in Japan (6, 7, 56, 127) utilizing some published data (37, 41).

75. The basic data on bone-marrow distribution which have been used in most of the surveys are very limited and are mostly derived from the figures established by Mechanik (91) in 1926 on 13 cadavers and subsequently modified by Ellis (37) to give the active bone-marrow distribution in a 40-year-old adult. This modification utilized the measurements made by Custer (29) on the distribution of the active bone marrow in the adult and its change with age. Hashimoto *et al.* (54, 58, 95) have investigated the marrow distribution in 10 Japanese cadavers by weighing each bone before and after the chemical removal of the marrow. The percentage cellularity at each site and the resultant active bone-marrow distribution were determined. Table 21 shows the percentage distribution of active bone marrow obtained by Ellis and by Hashimoto *et al.* The distribution of active marrow in children was derived by Hashimoto *et al.* from the adult distribution by taking into account the presence of active marrow in the extremities of children. The amounts of active marrow in Japanese were 765 grammes in the adult, 583 grammes in children at 8-14 years of age, 329 grammes at 3-7 years, and 162 grammes at 0-2 (derived on a body-weight basis). The corresponding adult active bone-marrow derived from the Mechanik data was 1.046 grammes. Further studies on the variation of the distribution of the active bone marrow with age are needed, and determinations of the quantitative distribution of the active bone marrow by means of radio-active tracer studies would provide a useful check of the values being currently used.

76. The use in the Japanese report (58) of a weighting factor to give a leukaemia-significant dose (paragraph 14) takes into account the shape of the time-incidence curve of radiation-induced leukaemia, and also the survival statistics for the different age groups in the population. When applied to the CMD, these factors give a "leukaemia-significant" dose of 169 millirads, about 10 per cent lower than the uncorrected CMD (table 22).

1. Variation with type of examination

77. The bone-marrow doses from the various examinations as obtained in the Netherlands (153), the United Kingdom (25) and Japan (58) are given in table 23. The examinations giving the highest doses are those involving irradiation of the trunk and particularly those, such as barium meals and barium enemas, that require long fluoroscopic exposures.

78. The active bone marrow is widely distributed in the body and therefore the factors which mainly determine the magnitude of individual mean marrow dose are the extent of the examination in terms of field area and the incident skin dose (25, 65). The latter is increased by high screening currents and long screening times during fluoroscopic examinations and by the number of radiographic exposures made. The radiation quality used has only a minor effect on the mean marrow doses received. A study of these factors and their effect on the mean marrow dose was undertaken in the British survey (25). The variation in the individual mean marrow doses for particular examinations is shown in figure VI. The variation in the foetal marrow dose dur-

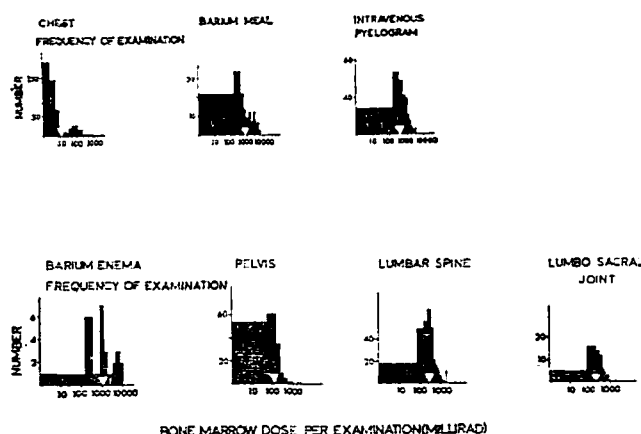


Figure VI. Histograms showing variation in bone-marrow dose with various types of x-ray examinations (male) (25) (the white triangle denotes the mean value)

ing obstetric abdomen and pelvimetry is shown in figure VII. Foetal dose studies have also been reported by Jankowski and Liniecki (70).

2. Determination of mean bone-marrow dose

79. The values of the bone-marrow dose for particular investigations have been determined by extensive phantom measurements. In the British survey (25), the percentage of the radiation at the skin was measured with a very small ionization chamber at 12 bone-marrow sites in a specially constructed phantom containing a human skeleton impregnated with wax under vacuum. For each site the doses were measured for seven radiation qualities with different focal skin distances and field areas, and for the anterior, posterior and lateral projections of the incident beam.

80. The calculation of the bone-marrow doses was based on the size of the skin field. The active bone marrow was subdivided into elements by means of a grid superimposed over the body in anterior, posterior and lateral projections. For each element so obtained, the dose contribution to the marrow arising from the

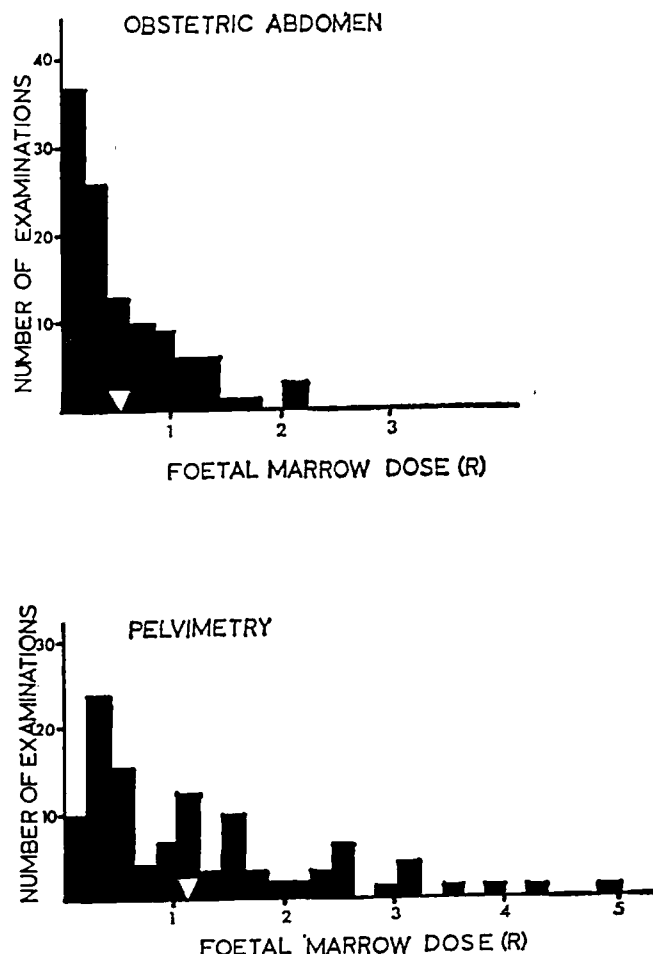


Figure VII. Variation in the foetal bone-marrow dose due to two types of examinations (25)

particular exposure conditions was calculated at each site within the element, using the results of the physical measurements and the proportion of the total active bone marrow present at that site. The doses to each element were then totalled to give the mean marrow dose. The computer programme used for these computations is available on decks of Fortran IV cards (40). A similar approach was followed in the Japanese survey (124).

3. Per caput mean marrow dose by examination type

81. Table 24 indicates the contribution of the various examinations to the CMD in the Netherlands (Leiden) (153) and the United Kingdom (25). Table 22 provides the information for Japan (58). The contribution of the various radiological techniques to the CMD and the leukaemia-significant dose in the Japanese survey (58) are given in table 25.

82. According to the British survey (25), the examinations contributing most to the population dose were mass surveys of the chest (24 per cent), barium meals (18 per cent) and barium enemas (10 per cent). The examinations that were the greatest contributors in the Dutch survey (153) were fluoroscopy of the chest, mass surveys of the chest and descending urography (27.0, 12.8 and 12.3 per cent, respectively). In Japan fluoroscopic examinations of the stomach contribute 55 per cent to the CMD. Their high frequency is due to the mass surveys carried out because of the high

incidence of stomach cancer in that country (58). These results are good examples of the contribution that bone-marrow dose surveys can make in identifying those groups of patients of importance for the epidemiological studies recommended by the ICRP/ICRU reports (42, 43) and by the UN/WHO seminar (144).

4. Dental radiography

83. Few data are available on the individual mean marrow dose from dental radiography. This dose was estimated in 1959 to be 1.8 millirads in the United Kingdom which, with an annual examination rate of 2 million dental examinations in a population of 50 million, corresponds to a CMD from dental radiography of 0.1 millirad (25, 26). However the practice in some countries is tending towards the use of wider fields and more frequent dental x-ray examinations so that the CMD from dental radiography is likely to increase. When radiographs of the whole mouth are required the use of intra-oral x-ray tubes may reduce the doses received.

E. DOSE TO THE SKIN AND OTHER ORGANS

84. The dose to the skin in the primary beam and the area of the beam are two important parameters that determine the total dose to important organs such as the bone marrow. Significant radiation may also be received by other organs and tissues of particular groups of patients. For example, young children with orthopaedic conditions may receive many radiographs of particular bones over a number of years. Such groups of people may lend themselves to epidemiological studies and the ICRP/ICRU reports (42, 43) have drawn attention to the necessity to ensure accurate dose estimates for these groups of patients.

85. Variations in the skin dose from radiographic examinations reflect the type of film and screen used and the amount of initial filtration inserted in the primary beam. For most examinations the fastest film-screen combination may be used, but where fine detail is required, as in bone radiography, fine-grain screens or no screens are often used. Table 26 gives for a number of examination types the median and the range of the average skin doses in the primary beam reported in seven surveys (8, 25, 63, 80, 123, 126, 156). Ardran (8) has drawn attention to the need to reduce the off-focus radiation and thus reduce the incident skin and gonad doses. The skin dose due to any particular examination may be much less or much more than the average values reported in table 26, depending on the number of exposures and on the exposure factors used. For example, in the British survey (25) the mean value of skin dose was 2.1 rads for pelvic examinations, but values up to 33.4 rads were recorded. In the investigations on the skin doses received during mammary radiography examinations, local doses up to 35 rads were measured (50).

86. The doses to the skin, thyroid, hypothalamus and the lens of the eye from dental radiography are not negligible. The doses delivered to the lens will be considerably reduced by the use of protective diaphragms and centring techniques. When radiographs of the whole mouth are required the use of intra-oral x-ray tubes, if correctly applied, will reduce the irradiation of the patient.

F. TRENDS WITH EXTENSIVE EXAMINATIONS

87. The main trends in diagnostic radiology have been identified in paragraph 17. The doses received during the use of image intensification and cine procedures have received attention. The incident skin-dose rate during non-intensified fluoroscopic examinations may be about 4-10 rad min⁻¹. The ICRP (114) recommends that it should not exceed 5 rad min⁻¹. When the conditions under which image intensification is carried out are optimised, for example by dark adaptation of the operators, and technical problems are overcome, the dose rate may be reduced to about 0.5-1 rad min⁻¹. However, reports indicate that when the image-intensifier tube deteriorates, the higher screening current necessary to obtain a good image may increase the skin-dose rate above that for non-intensified fluoroscopy. With cine-fluorography, very much higher skin-dose rates are used, rates of 50-100 rad min⁻¹ being delivered on thick patients. Gough, Davis and Stacey (52) report the following doses delivered during cardiac catheterization of 85 patients in the United Kingdom:

	Mean dose		Maximum dose	
	rad	mrad	rad	mrad
Skin	47		140	
Marrow	1.4		3.9	
Male gonads		25		80
Female gonads		39		100

Ardran (9) reported similar doses in another series of patients in the United Kingdom. Even higher radiation doses were reported by Gough, Davis and Stacey (52) as being delivered during pacemaker insertion—an emergency procedure. An average skin dose of 132 rads per patient was received in a group of six patients. Other surveys of the doses received during fluoroscopy have been published by Seyss (135) on 5,000 cases, and by Schoen (128).

88. The irradiation of children both for cardiac catheterization and for such examinations as voiding urethrocytography may lead to high gonad doses. Typical measurements by Kaude, Lorenz and Reed (74) give average male gonad doses of 105 millirads and ovary doses of 270 millirads, with maximum values of 570 and 690 millirads, respectively.

G. RECOMMENDATIONS FOR THE PROTECTION OF THE PATIENT IN DIAGNOSTIC RADIOLOGY

89. Because of the increasing use of diagnostic radiology (for example, an estimate in the United States (24) indicates that 50 per cent of all diagnoses are made or confirmed by diagnostic radiology), the ICRP (65, 114) and other international and national bodies have made recommendations for achieving the minimum patient dose consistent with good radiology. Similar recommendations regarding special aspects of radiology have also been published (93, 155), for example, for the examination of children (47) and for dental examinations (35).

II. Diagnostic use of radio-pharmaceuticals

90. In many countries the increase in the diagnostic use of radio-pharmaceuticals has been extremely rapid during the 1960s. The procurement of radio-pharmaceuticals has been relatively easy and their dispatch by air freight has enabled many clinics and laboratories to use radio-pharmaceuticals manufactured in a few centres. Both the number of patients investigated by

such well-established tests as the use of radio-active iodine for the study of the thyroid function and the number of radio-pharmaceuticals available for use have been increasing. This has been particularly noticeable since the column generators of short-lived radio-nuclides have been available. In industrialized countries, the introduction of large numbers of scanners into departments has also stimulated the use of radio-pharmaceuticals. The use of radio-pharmaceuticals in the developing countries is increasing and is likely to expand at a fast rate during the next decade.

91. The increase has to be judged from data that have been reported differently in various countries, e.g., comprehensive estimates of radio-nuclides distributed, but not necessarily all administered, number of orders for radio-pharmaceuticals or, better from a population-exposure viewpoint, number of patients to whom the various diagnostic radio-pharmaceuticals have been administered. Typical data are available in the reports from Australia (5), Denmark (15, 79), France (96), Japan (36, 73, 146), New Zealand (90), the United Kingdom (117) and the United States (142, 143). The basic trend observed from these data indicates a doubling of the number of investigations every three years or so. A typical growth pattern is shown by West Berlin (population 2.2 million) with a 100 per cent increase from 1963-1968 (10) and is shown in figure VIII for various radio-pharmaceuticals.

92. The information currently available on the total number of each type of investigation carried out per year is summarized in table 27. Data on the use of three main radio-pharmaceuticals in West Berlin (61) are also included in table 28. General reports from India (68) and Argentina (12) are available.

93. Even though a three- or four-fold increase in the frequency of persons exposed to diagnostic radio-

pharmaceuticals has taken place since 1958, the GSD from this source is unlikely yet to approach one millirad per year. This conclusion is based on the assumption that the average gonad dose per investigation has not radically changed. Even though increased activities of short-lived radio-nuclides have been used, those have generally replaced investigations utilizing lower activities of nuclides with longer half-lives so that the two effects on the total gonad dose have tended to cancel out.

1. Organ dose from radio-pharmaceuticals

94. A knowledge of the radiation dose to particular organs following the administration of a radio-pharmaceutical is necessary to judge the activity that may be administered to any particular patient. Useful publications giving this type of information are the booklet of the Swedish National Institute of Radiation Protection (49), Publication 17 of the ICRP (64), the series of reports produced by the Medical Internal Radiation Dose Committee (16, 20, 31, 32, 84) and other reports (78, 92, 115). These publications emphasize the fact that the dose delivered by a radio-nuclide is dependent on the metabolism of the chemical compound in which it is incorporated and that the estimates of dose per unit activity administered that they provide are mostly those for normal individuals. Variations in the doses may be caused by the particular disease of which a patient is suffering.

2. Genetically-significant dose

95. Tables XXXII and XXXIII of the 1962 report gave details on the GSD from radio-pharmaceuticals used in medical diagnosis. The GSDs varied from 0.01 to 0.03 millirad per year for Canada (72), the Federal Republic of Germany (Hamburg) (62), the United Kingdom (26) and the United States (22) in the years 1956-1958.

96. Estimates of the GSD that were made subsequently gave a value of 0.015 millirad for New Zealand in 1966 (90), 0.05 millirad for Japan (2) in 1965, 0.13 millirad for West Berlin (10) in 1968 and 0.4 millirad for Sweden (49) in 1968. The mean annual gonad dose in the Swedish survey (49) was 70 millirads. This latter dose is the average gonad dose to the population regardless of child expectancy. It is large compared with the GSD because most of the patients are in older age groups with small child expectancies. Reports from the United States (143) and the Soviet Union (103) indicate that assessments of the level of exposure of patients and of the activities administered have been made.

97. Data from New Zealand and West Berlin provide a useful breakdown of the contribution of each type of investigation. The New Zealand data (90) are given in table 29. Where more than one radio-pharmaceutical was used for a particular investigation, a mean gonad dose was derived on the basis of the frequency of use of each individual radio-pharmaceutical. The percentage contribution to the total GSD, including therapy with ^{131}I , in West Berlin (10) is given in table 30.

III. X- and gamma-ray treatments

98. In the treatment of neoplastic disease, large doses of radiation may need to be given over a period of weeks to a limited volume of the patient. The aim

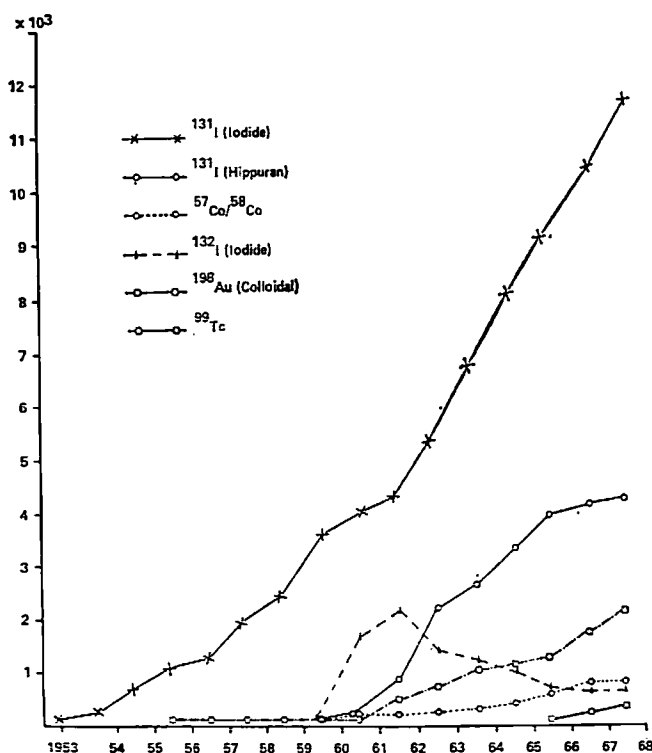


Figure VIII. Number of patients in West Berlin investigated using radio-pharmaceuticals (10)

of the treatment is, of course, to restore the health of the patient yet it is also necessary to consider the small probability of causing, during the lifetime of the patient, some deleterious effect due to the radiation, either to the individual or to any subsequent offspring. For the treatment of non-neoplastic disease alternative forms of therapy not involving radiation have been recommended for some disorders (26) so as to reduce the incidence of somatic effects over the long subsequent life expectancy of these patients.

99. In many industrialized countries about one-half of the new cancer cases arising each year are treated with radio-therapy. This proportion has not changed appreciably even though the use of chemotherapy has been increasing. Technological developments in the form of linear accelerators, betatrons and telecurie units and 14-MeV neutron therapy units are likely to maintain the current régimes of radio-therapy in the industrialized countries. Elsewhere, the treatment of cancer will rise in importance as other causes of death such as malnutrition, malaria and tuberculosis are gradually eliminated by the improvement in living conditions and the availability of medical care.

1. Genetically-significant dose

100. Tables XXV to XXVIII of annex G of the 1962 report showed the average gonad doses received by patients during treatment for non-neoplastic diseases, together with the GSDs arising from these treatments.

101. These were 2.2 millirads in the Federal Republic of Germany (62), 3.1 millirads in France (110), 3.1-12.1 millirads in the Netherlands (129) and 4.47 millirads in the United Kingdom (26) with additional contributions from the treatment of neoplastic disease of 0, 2.5, 1.0 and 0.52 millirads, respectively.

102. In Japan (95) in 1962 the GSD from therapeutic irradiation was estimated to be 0.9 millirad. A further survey in 1971 (59) has been carried out and utilizes a range of child-expectancy factors for patients by age and disease. A value of GSD of 0.97 millirad was obtained. From unpublished reports in the United Kingdom it appears that the frequency of treatments of non-neoplastic diseases has tended to decrease and that the use of x-rays of lower kilovoltage for the treatment of many skin diseases has tended to reduce the GSD.

2. Bone-marrow dose

103. The results of the British survey (25) on bone-marrow doses from the treatment of non-neoplastic diseases and on the subsequent contribution to the population dose in terms of man-rads were issued in 1966. The method of calculation of the bone-marrow dose was based on that described in paragraphs 79 and 80.

104. Table 31 gives the mean marrow dose per treatment course in those patients who were treated on the head and trunk only, and also the average for all patients treated for a particular condition, including those that were treated on the limbs and whose bone marrow was therefore not exposed since no active marrow is present in the adult limbs. The first set of data can then be used for calculating marrow doses to individuals or populations known to have been treated on the head and trunk, the second set to obtain population doses in groups of patients treated for a

particular condition, assuming that the distribution of treatment sites is the same in the study population as in the British survey (25).

105. Table 32 gives the total annual radiation load in man-rads from radio-therapy of non-neoplastic disease. This is 617,000 man-rads per year in the United Kingdom (25). The authors of the original report considered that this radiation load to the population could not justifiably be expressed as a *per caput* mean marrow dose (CMD) since only 1.2 persons per thousand in the population receive such treatment in any one year. However, expressed as CMD, it would amount to 11 millirads.

106. The three procedures making the greatest contributions to the total radiation load are the treatment of skin conditions (41 per cent), that of ankylosing spondylitis (25 per cent) and the induction of artificial menopause (20 per cent). The contribution from the treatment of skin conditions arises from a large number of irradiated patients receiving each year mean marrow doses of about 3.3 rads. On the other hand, the treatment of ankylosing spondylitis and the induction of artificial menopause are carried out on relatively small populations, each receiving mean marrow doses of 50-100 rads.

107. The marrow doses resulting from the treatment of neoplastic disease were also considered in the British survey (25). Estimates per treatment course for the main conditions are given in table 33. The estimates were made for treatments carried out at 250 kVp (2mm Cu HVT). No estimates seem to have been made of the bone-marrow dose received from treatments by supervoltage equipment. It is estimated, however, that such treatments will not appreciably increase the bone-marrow doses since similar integral doses are received from 250 kVp therapy and supervoltage therapy for the 100-400 cm² fields that are used in the treatment of neoplasms 6 to 9 centimetres deep.

108. An extensive survey of the bone-marrow dose from the radio-therapy of neoplastic disease has been carried out in Japan in 1971 (59). The CMD for the population amounted to 206 millirads. Utilizing a weighting factor to give a "leukæmia-significant" dose (paragraphs 14 and 76) a value of 37 millirads was obtained.

3. Doses to other organs

109. The radiation dose received by the skin, or, in the case of supervoltage radiation, by the tissues lying just beneath the skin surface, will be of the same order as the doses to the main treatment volume. By increasing the number of fields the superficial doses can be reduced. Nevertheless, significant radiation may be received by organs such as the lung, the kidney and the tissues of the nervous system and the gastro-intestinal tract which are in a direct beam. The radiation doses received by stomach, pancreas and œsophagus during the treatment of ankylosing spondylitis are currently being estimated in the United Kingdom as part of a study of the cancers occurring in these organs, which are heavily irradiated during the treatment of the spine.

IV. Therapeutic use of radio-pharmaceuticals

110. The two most important radio-nuclides administered to patients for therapy are ¹³¹I for thyroid

treatment and ^{32}P for polycythæmia vera. ^{198}Au and ^{90}Y are used in the local treatment of effusions and ^{131}I -lipidol for endolymphatic therapy.

111. GSDs due to the therapeutic use of radio-pharmaceuticals were presented in table XXXII of annex G of the 1962 report. The annual doses were 0.40 millirad in Canada (72), 0.18 millirad in the Federal Republic of Germany (Hamburg) (62), 0.15 millirad in the United Kingdom (26) and 0.24 millirad in the United States (22). The only further information available is from New Zealand (90) where the dose in 1966 was estimated to be 0.047 millirad, from West Berlin (10) where the use of ^{131}I for therapy contributed 0.014 millirad in 1968, and from Japan (2) where ^{131}I was estimated to contribute 0.047 millirad in 1965.

112. Typical values of the gonad doses per millicurie administered for therapy are 0.45-0.6 rad for ^{131}I (17) and 2.6-7.0 rads for ^{32}P (90). The bone-marrow doses per millicurie in the treatment of thyroid cancer has been estimated as 1.7 rads (83) and for intravenously administered ^{32}P the bone-marrow dose is 30 rads per millicurie (64). The use of colloidal gold in malignant diseases and rheumatoid arthritis leads to local doses at the site of injection but to insignificant gonad and bone-marrow doses as long as there is no transport away from the injection site. Endolymphatic therapy is a relatively infrequent form of treatment and the dose to the lung per millicurie administered is about 10 rads (64).

113. Sealed sources of radio-nuclides are also used in the treatment of patients. These sources emit either beta rays, as with ^{90}Sr surface applicators, or gamma rays as with ^{137}Cs tubes and needles inserted into the patient. The gonad and bone-marrow doses received will depend on the distance of the gonads or the bone marrow from the area under treatment, the radio-nuclide used and the total dose delivered. For a typical treatment of cancer of the cervix using sealed gamma-ray emitters the gonad dose will be 1,800 rads and the individual mean marrow dose about 260 rads (25).

V. Conclusions

114. The aim of medical radiology being to provide maximum benefit to the population served, any increase in frequency of radiological examinations must be justified, particularly in the developing countries. The Committee has examined data on the frequency of diagnostic radiological examinations and noted that in the 10 years since its last review of the subject (148) there has been an increase by a few per cent per year in this frequency in a number of technically advanced countries and that considerably larger increases may have occurred in developing countries. The Committee has also reviewed information on the attendant doses and concluded that an increase in the frequency of x-ray examinations need not be accompanied by a proportionate rise of the population dose.

115. The results of surveys carried out in the various countries are sufficiently in agreement to make it possible to assess within an order of magnitude the average doses resulting from particular examinations. It therefore appears to be questionable whether emphasis should continue to be placed on the need to carry out dose surveys alone or whether more attention should not be given to other means of achieving the minimum practicable dose to the patient commensurate with the needs of diagnostic radiology.

116. Three basic approaches can contribute variously to this improvement depending, in any particular case, on the availability of funds and trained staff—educational programmes, surveys of the frequency of examination and of the doses received, and administrative control measures. Educational programmes can be aimed at (a) the radiation staff in the conduct of their day-to-day work; (b) the clinical staff that prescribe investigations involving radiation; (c) the development in the general public of an awareness of the need for radiation protection. The provision of educational training programmes and the establishment of some administrative control may be much more important than dose surveys, particularly where resources are limited.

APPENDIX a

1. A general definition of genetically significant dose has been given in paragraph 9 above.^a Approximations must be made to calculate this dose, the most obvious being consideration of groups rather than individuals. It is convenient to start with the approximate definition*

$$D = \frac{\sum_j \sum_k (N_j^{(F)} w_{jk}^{(F)} d_{jk}^{(F)} + N_j^{(M)} w_{jk}^{(M)} d_{jk}^{(M)})}{\sum_k (N_k^{(F)} w_k^{(F)} + N_k^{(M)} w_k^{(M)})} \quad (1)$$

where

D = (annual) genetically significant dose,

N_{jk} = (annual) number of individuals of age-class k , subjected to class j exposure,

N_k = total number of individuals of age-class k ,

^a Reprinted from annex G of the 1962 report of the Committee (148).

^b This definition is reproduced in paragraph 7 of the present annex B.

* The degree of approximation involved in the use of formula 1 depends on the definition of classes j . In theory, there need be no approximation since the classes may be made so restrictive as to include only one individual per class.

w_{jk} = future number of children expected by an exposed individual of age-class k subsequent to a class j exposure.

w_k = future number of children expected by an average individual of age-class k ,

d_{jk} = gonad dose per class j exposure of an individual of age-class k .

(F) and (M) denote "female" and "male" respectively.

2. For the practical work, formula 1 can be simplified considerably, the first step being to replace the denominator by $w \cdot N$, where

$$w = \frac{N^{(F)}}{N} \cdot w^{(F)} + \frac{N^{(M)}}{N} \cdot w^{(M)} \quad (2)$$

and

$$w^* = \frac{1}{N^*} \sum_k w_k^* N_k^* \quad (3)$$

In the last expression, $*$ denotes the sex. N is the total number of individuals of the population. It should be noticed that $w \cdot N$ is about twice the future number of children expected by the present population even though the value of w may be as low as 0.8.

3. As formula 1 has w^* in both the numerator and denominator, the numerical value of w has no direct relevance, and all terms can be expressed by help of the ratio w_{jk}/w . For understanding of the demographic background, however, it is valuable to realize that w must be calculated from the sum of the age-group products $w^* N^*$ for a population, which

means that an assumption has to be made regarding the expected future number of children (w^*) of an individual in any specified age-group.

4. The assumption could be that the average individual will have a future annual child-expectancy expressed by the present specific annual birth rate. This makes it possible to calculate, by summation, the total future expected number of children of an individual of any age, and hence also the mean for any age-group. If significantly less than unity, the probability of an individual of age a to reach age t should also be considered. This gives

$$w^* = \sum_{a=t}^{\infty} c^* \cdot \Delta t \cdot P^*(t) \quad (4)$$

where

w^* _{a} = expected future number of children of an individual of age a . With knowledge of the function w^* of age, the average w^* for any age-group k can be calculated,

c^* _{t} = age-specific annual birth rate, i.e., annual expected number of children of an individual of age-group t ,

Δt = number of years included in age-group t .

P^* _{a} (t) = probability of an individual of age a to reach age (group) t .

5. It must be noted that c^* may have a tendency to change considerably before an average individual of a specified age has reached the age-group in question. As it is, however, difficult to predict the values for the future, c^* has been assumed not to vary with time.

6. $W^* = w^*$ _{$a \rightarrow 0$} is the number of children expected by the average individual during his whole life. The range of w^* is normally 0.8-2, and the range of W^* is 2-4 for most developed countries. The ratio W^*/w ranges from 1.5 to 3.

7. The female and male contribution to the genetically significant dose can both be written

$$D^* = \frac{1}{wN} \sum_j \sum_k N^* w^* d^*_{jk} \quad (5)$$

8. If the gonad dose due to an examination of type j is nearly uniform for all age-classes k , then

$$d^*_{jk} = d^*_j \quad (6)$$

approximately for all k , and formula 5 reduces to

$$D^* = \frac{1}{wN} \sum_j d^*_j \sum_k N^* w^*_{jk} \quad (7)$$

or

$$D^* = d^*_j \cdot \frac{1}{wN} \sum_k N^* w^*_{jk}$$

where D^*_j is the contribution from type j examination of the

specified sex to the genetically significant dose. This again can be written as

$$D^*_j = d^*_j \cdot \frac{N^*_j}{N} \cdot \frac{w^*_j}{w} \quad (8)$$

which is the expression for numerical calculations.

9. The necessary information to make it possible to calculate D^*_j by help of formula 8 is:

- (a) d^*_j = the mean gonad dose per individual undergoing class j examination;
- (b) N^*_j/N = the relative frequency of class j examination, i.e., the number of examinations *per caput*, per year;
- (c) w^*_j/w = the relative child-expectancy of the average individual undergoing class j examination.

The formula is applicable also to foetal exposure ($w_j = W$) which must not be overlooked.

10. Often d_j varies considerably from hospital to hospital. Most of the uncertainty in estimates of D_j is probably due to the difficulty of estimating a reliable average of d_j for a population.

11. If there are no data on the child-expectancy of the patients, an approximate estimate of D^*_j may be made, under the assumption that the child-expectancy is not influenced by the nature of the condition for which the patient is examined. w^*_j can then be calculated from the age-distribution of the patients and the normal child-expectancy for each age-group,

$$w^*_j = \frac{\sum_k w^*_{jk} N^*_{jk}}{N^*_j} \approx \frac{\sum_k w^*_k N^*_k}{N^*_j} \quad (9)$$

where w^* can be taken from formula 4. If w^*_j/w is not given in the primary material, it may be recalculated from N^*_j/N , d^*_j and this approximation of D^*_j , but will in that case reflect only variations in the age-distribution of the patients examined and not indicate any dependence of child expectation on type of examination.

12. In the case where the age-distribution in an examination class is not known, a yet more simplified assumption may be used, namely

$w^*_k = W^*$ for all persons below mean age of child-bearing,

$w^*_k = 0$ for all persons above mean age of child-bearing.

If n is the total number in the population below the mean age of child-bearing, it follows from formula 3 that

$$w^* = \frac{n^*}{N^*} \cdot W^* \quad (10)$$

which is also, indirectly, a definition of the "mean age of child-bearing". Formula 8 reduces approximately to

$$D^*_j = \frac{n^*_j}{n} \cdot d^*_j = \frac{N}{n} \cdot \frac{n^*_j}{N} \cdot d^*_j \quad (11)$$

TABLE 1. CHILD EXPECTANCY IN THE POPULATION BY AGE AND SEX

New Zealand (118)								
Age group	1951		1960-1962		1963-1965		1965-1967	
	Male	Female	Male	Female	Male	Female	Male	Female
Fœtus	—	—	3.897	—	3.598	—	3.271	—
0-14	3.171	3.396	3.710	4.084	3.420	3.776	3.109	3.432
15-19	3.185	3.332	3.686	3.967	3.391	3.631	3.075	3.272
20-24	3.010	2.785	3.385	3.213	3.077	2.880	2.773	2.557
25-29	2.364	1.767	2.487	1.913	2.229	1.696	1.978	1.473
30-34	1.457	0.863	1.390	0.871	1.248	0.786	1.077	0.662
35-39	0.744	0.314	0.652	0.303	0.588	0.282	0.493	0.237
40-44	0.325	0.068	0.270	0.062	0.239	0.060	0.194	0.052
45-49	0.128	0.005	0.101	0.004	0.089	0.004	0.068	0.004
50+	0.02	—	0.013	—	0.012	—	0.004	—

Czechoslovakia 1965 (80)			Thailand 1966 (119)		
Age group	Male	Female	Age group	Male	Female
0-1	2.37	2.32	0-14	4.58	4.93
1-5	2.41	2.34	15-19	4.53	4.65
5-10	2.42	2.35	20-24	4.18	3.73
10-15	2.43	2.35	25-29	3.34	2.61
15-20	2.43	2.35	30-34	2.29	1.55
20-25	2.42	2.14	35-39	1.42	0.61
25-30	1.85	1.17	40-44	0.76	0.15
30-35	0.98	0.50	45-49	0.30	0.0
35-40	0.43	0.17	50+	0.03	—
40-45	0.16	0.04	Male values estimated on basis of female values		
45-50	0.06	0.002			
50-55	0.02	—			
55-60	0.004	—			
60-65	9.6 10 ⁻⁴	—			
65-70	1.4 10 ⁻⁴	—			

TABLE 2. ANNUAL FREQUENCIES OF X-RAY EXAMINATIONS

(Surveys reviewed in the 1962 report)

Country or area	Year	Population (millions)	Annual number of x-ray examinations per 1,000 of total population				Genetically-significant dose in millirads		Reference
			Diagnostic		Mass surveys		Diagnostic examinations	Mass surveys	
			Radio-graphy	Fluoro-scropy	Radio-graphy	Fluoro-scropy			
Argentina									
Buenos Aires	1950-1959	6	270		80		37.0	1.90	105
Denmark	1956-1958	4.5	260		140		27.5	0.05	53
Egypt									
Alexandria	1956-1960	1.4	36		4		7.0	0.09	86
Cairo	1955-1961	2.6	40		5		7.0	0.07	87
Federal Republic of Germany									
Hamburg	1957-1958	1.8	560		130		17.7	0.05	62
France	1957-1958	42	150		40	570	58.2 ^a	0.02 ^b	111-113
Italy									
Rome	1957	1.9	500		80		43.4	0.93	18
Japan	1958-1960	90	410		320		39.0	0.08	121
Netherlands									
Leiden	1959-1960	0.1	350	200	130		6.8	0.02	13
Norway	1958	3.5	390		210		10.0	0.08	48
Sweden	1955-1957	7.3	290		140		37.8	0.40	82
Switzerland	1957	5.2	310	330	130	60	22.3	0.12	158
United Kingdom	1957-1958	50	280		95		14.1	0.01	26

^a From radiographic mass survey.^b Includes fluoroscopic mass survey.

TABLE 3. ANNUAL FREQUENCIES OF X-RAY EXAMINATIONS AND GENETICALLY-SIGNIFICANT DOSE
(Recent surveys)

Country or area	Year	Population (millions)	Annual number of x-ray examinations per 1,000 of total population				Genetically-significant dose millirads per caput y ⁻¹		Reference
			Diagnostic		Mass surveys		Diagnostic examinations	Mass surveys	
			Radiog- raphy	Fluoro- scopy	Radiog- raphy	Fluoro- scopy			
Czechoslovakia									
Bohemia	1965-1966	4.3	517	79	331		37.0	0.44	80
Federal Republic of Germany									132, 134
Bavaria	1956-1958	9.6	601 ^a		267		13.7 (15.1) ^b	0.05	130, 131
Finland	1963-1964	4.5	334		266		16.8		66, 67
Japan	1969	105	610	191	628		25.7	0.8	57
Netherlands	1967	12.6	810				20.0		14, 107
New Zealand	{ 1963	2.5	366		113		13.1		156
	{ 1969	2.8	400		113		13.7		118
Puerto Rico									
Southern region	1968	0.5	414				36.4		45
Western region	1968	0.4	512				48.6		44
Thailand	1970	34.7	39				5.2-1.3		4, 119
United Kingdom									
Sheffield	1964	4.5	310				8.6		89
United States									
National surveys	1964	187	475	56	87		55.0		51, 104, 106, 108
	1970	200	580	65	45				21
Local surveys									
New York City	1962	8	630	100			50.0		102
New Orleans	1962-1963	0.9	825				75.3		69
Johns Hopkins	1965						20.3		97
Texas	1963						16.0		27
Union of Soviet Socialist Republics									
Russian Republic	1964	82	171	439	183		27.0 ^c		75
Yugoslavia									
Slovenia	1960-1963	1.5	594	436			9.1		94

^a One examination in this case = one radiograph.

^b Later figure to include special children's clinics.

^c Mean gonad dose per year rather than GSD.

TABLE 4. GENETICALLY-SIGNIFICANT DOSES IN CZECHOSLOVAKIA, 1958-1966 (80)

Type of examination	Frequency (N _j [*] /N) 1,000		Gonad dose (d _j [*]) mrad		GSD (D _j [*]) mrad			Total GSD (D _j) mrad	
	Male	Female	Male	Female	Male	Female	Faetal	Total	Percentage
Hip	13	17	430	200	4.24	2.46		6.70	18.3
Lumbosacral spine	9	8	490	1,580	2.63	3.80		6.43	17.6
Femur	2	1	2,430	930	4.55	0.43		4.98	13.6
Upper gastro-intestinal tract	15	10	18	670	0.29	3.43		3.72	10.2
Urography (descending) ..	4	4	380	1,110	2.14	1.52		3.66	10.0
Pelvis	2	2	1,770	700	2.01	0.58		2.59	7.1
Abdomen	5	5	130	540	0.64	0.88		1.52	4.2
Cholecystography	3	8	100	380	0.72	0.80		1.52	4.2
Thorax	11	6	35	65	0.51	0.40		0.91	2.5
Obstetrical abdomen		1		330		0.06		0.06	0.2
Other examinations	424	371						3.04	8.3
Faetal contribution							1.39	1.39	3.8
TOTAL	488	432			18.74	16.39	1.39	36.52	100

TABLE 5. GENETICALLY-SIGNIFICANT DOSES IN FINLAND, 1963 (67)

Type of examination	Frequency (N_j^*/N) 1,000		Gonad dose (d_j^*) mrad		GSD (D_j^*) mrad			Total GSD (D_j) mrad	
	Male	Female	Male	Female	Male	Female	Fatal	Total	Percentage
Abdomen	8	8	44	790	0.13	1.62	0.72	2.47	14.7
Lower gastro-intestinal tract	3	4	100	1,140	0.27	1.20	0.45	1.92	11.4
Lumbar spine	5	5	200	730	0.40	1.08	0.36	1.84	11.0
Pelvimetry		1		520		0.60	1.03	1.63	9.7
Chest	56	54	13	20	0.52	0.53	0.12	1.17	7.0
Fluoroscopy	17	15	18	93	0.17	0.67	0.15	0.99	5.9
Urography (descending) ..	2	3	320	270	0.23	0.53	0.08	0.84	5.0
Obstetrical abdomen		2		113		0.22	0.40	0.62	3.7
Lower leg and foot	17	14	29	13	0.41	0.18	0.02	0.61	3.6
Dorsal spine	5	5	150	110	0.30	0.18	0.07	0.55	3.3
Other examinations								4.16	24.7
TOTAL	302	299			4.23	8.69	3.88	16.80	100

TABLE 6. GENETICALLY-SIGNIFICANT DOSES IN THE FEDERAL REPUBLIC OF GERMANY (BAVARIA), 1957 (130-132, 134)

Type of examination	Frequency (N_j^*/N) 1,000		Gonad dose (d_j^*) mrad		GSD (D_j^*) mrad			Total GSD (D_j) mrad	
	Male	Female	Male	Female	Male	Female	Fatal	Total	Percentage
Pelvis	12		1,020	710	2.88	1.65		4.53	33.1
Urography (descending and ascending)	7		740	470	1.07	0.91		1.98	14.4
Hip and upper half of the femur	10		1,100	350	1.76	0.14		1.90	13.9
Middle and lower half of the femur			1	1					
Stomach and small intestine	54		16	120	0.31	1.23		1.54	11.2
Sacrum lumbo sacral spine	39		65	73	0.69	0.54		1.23	9.0
Dorsal spine									
Large intestine	6		550	1,200	0.44	0.79		1.23	9.0
Abdomen	8		480	57	0.92	0.11		1.03	7.5
Obstetric						0.01	0.02	0.03	0.2
Other examinations	498				0.13	0.10		0.23	1.7
TOTAL	634				8.20	5.48	0.02	13.70	100

TABLE 7. GENETICALLY-SIGNIFICANT DOSES IN THE NETHERLANDS, 1967 (14, 107)

Type of examination	Frequency (N_j^*/N) 1,000		Gonad dose (d_j^*) mrad		GSD (D_j^*) mrad			Total GSD (D_j) mrad	
	Male	Female	Male	Female	Male	Female	Fatal	Total	Percentage
Hip, upper femur	5	6	1,200	180	4.06	0.14		4.20	21.0
Urography (descending) ..	13	11	290	600	1.90	2.10		4.00	20.0
Lumbo sacral spine	19	15	240	560	1.05	2.15		3.20	16.0
Lower gastro-intestinal tract	11	13	230	750	0.48	2.33		2.81	14.0
Pelvis	12	14	190	110	0.71	0.54		1.25	6.2
Stomach and duodenum ...	31	21	88	180	0.57	0.54		1.11	5.6
Urethrocytography	<1	1	330	1,390	0.14	0.74		0.88	4.4
Lumbar spine	8	6	250	230	0.47	0.30		0.77	3.9
Obstetrical abdomen		1		370		0.40		0.40	2.0
Pelvimetry		<1		700		0.03		0.03	0.2
Other examinations	345	278			0.62	0.73		1.35	6.7
TOTAL	444	366			10.0	10.0		20.0	100

TABLE 8. GENETICALLY-SIGNIFICANT DOSES IN JAPAN, 1969 (57)

Type of examination	Frequency (N_j^+/N) 1,000		Gonad dose (d_j^+) mrad		GSD (D_j^+) mrad		Total GSD (D_j) mrad	
	Male	Female	Male	Female	Male	Female	Total	Percentage
Intestine	10	8	800	400	3.9	2.7	6.6	24.9
Stomach	157	96	11	130	0.96	5.5	6.46	24.4
Hip joint	7	7	460	120	2.0	0.32	2.32	8.7
Lumbo sacral spine	5	3	530	180	2.0	0.26	2.26	8.5
Lumbar spine	19	10	70	220	0.84	0.88	1.72	6.5
Bladder	3	2	990	160	1.2	0.12	1.32	5.0
Pelvis	2	2	830	200	1.1	0.20	1.30	4.9
Chest	484	408	0.2	0.6	0.73	0.43	1.16	4.4
Obstetrical abdomen		2		250		0.67	0.67	2.5
Pelvimetry		1		460		0.25	0.25	0.9
Other examinations	127	76			1.38	1.10	2.48	9.3
TOTAL	814	615			14.1	12.4	26.5	100

TABLE 9. GENETICALLY-SIGNIFICANT DOSES IN NEW ZEALAND, 1963 (156), 1969 (118)

Type of examination	Frequency (N_j^+/N) 1,000		Gonad dose (d_j^+) mrad		GSD (D_j^+) mrad						Total GSD (D_j) mrad		
	Male	Female	Male	Female	Male		Female		Fetus		Total 1963	Total 1969	Percentage 1969
					1963	1969	1963	1969	1963	1969			
Pelvis													
Lumbar spine	16	32	220	280	1.70	1.78	1.16	1.20	0.13	0.11	2.99	3.09	22.5
Lumbo sacral spine													
Obstetrical abdomen		2		390			0.67	0.69	1.11	1.33	1.78	2.02	14.7
Urography (descending)	4	8	140	380	1.11	1.14	0.62	0.65	0.06	0.05	1.79	1.84	13.4
Abdomen	7	15	380	130	0.75 ^a	0.78	0.32	0.33	0.03	0.03	1.10	1.14	8.3
Barium enema	2	6	310	1,260	0.13	0.14	0.83	0.85	0.11	0.09	1.07	1.08	7.9
Pelvimetry		1		590			0.33	0.34	0.39	0.56	0.72	0.90	6.6
Hip, upper femur	2	5	630	110	0.40	0.42	0.06	0.06			0.46	0.48	3.5
Barium meal	10	18	19	252	0.05	0.05	0.35	0.36	0.04	0.03	0.44	0.44	3.2
Other examinations	165	107			0.52	0.55	0.13	0.14	0.02	0.01	0.67	0.70	5.1
TOTAL	206	194			4.66	4.86	4.47	4.62	1.89	2.21	11.02	11.69	85.2
Chiropractics											1.92	1.92 ^b	14.0
Dental radiography											0.10	0.10 ^b	0.7
Mass miniature radiography											0.02	0.02	0.1
GRAND TOTAL											13.06	13.73	100

^a Corrected 1963 figure.^b Upper limits.

TABLE 10. GENETICALLY-SIGNIFICANT DOSES IN THAILAND, 1970 (4, 119)

Type of examination	Frequency (N_j^+/N) 1,000		Gonad dose (d_j^+) mrad		GSD maximum (D_j^+) mrad				GSD most probable (D_j^+) mrad			
	Male	Female	Male	Female	Male	Female	Total	Per- centage	Male	Female	Total	Per- centage
Plain urological	1.4	0.8	300	300	0.86	0.37	1.23	23.8	0.26	0.11	0.37	29.6
Pelvis												
Lumbar spine	0.5	0.4	300	420	0.64	0.27	0.91	17.6	0.10	0.08	0.18	14.4
Lumbo sacral spine												
Urography (descending)	0.3	0.2	400	900	0.56	0.19	0.75	14.5	0.06	0.09	0.15	12.0
Abdomen	0.6	0.6	100	200	0.16	0.40	0.56	10.8	0.04	0.08	0.12	9.6
Hip, upper femur	0.4	0.2	700	200	0.40	0.08	0.48	9.3	0.28	0.03	0.31	24.8
Upper gastro-intestinal tract	0.5	0.3	30	60	0.23	0.13	0.36	7.0	0.01	0.01	0.02	1.6
Pelvimetry		<0.1		600		0.14	0.14	2.7		0.02	0.02	1.6
Obstetric abdomen		0.1		300		0.08	0.08	1.5		0.01	0.01	0.8
Other examinations	17.9	14.6			0.39	0.27	0.66	12.8	0.03	0.04	0.07	5.6
TOTAL	21.6	17.2			3.24	1.93	5.17	100	0.78	0.47	1.25	100

TABLE 11. GENETICALLY-SIGNIFICANT DOSES IN THE UNITED KINGDOM (SHEFFIELD), 1964 (89)

Type of examination	Frequency (N_j^*/N) 1,000		Gonad dose (d_j^*) mrad			GSD (D_j^*) mrad			Total GSD (D_j) mrad	
	Male	Female	Male	Female	Fetus	Male	Female	Fatal	Total	Percentage
Hip, upper femur	3	3	1,220	250	250	2.04	0.29	0.08	2.41	28
Pelvis, lumbo sacral joint, lumbar spine	6	6	150	470	470	0.58	1.22	0.27	2.07	24
Abdomen obstetrical		1		230	200		0.30	0.62	0.92	11
Urography (descending) .	3	2	460	310	310	0.53	0.29	0.05	0.87	10
Pelvimetry		0.2		440	710		0.16	0.40	0.56	7
Abdomen	3	3	31	180	180	0.06	0.27	0.05	0.38	4
Barium enema	1	1	95	690	690	0.03	0.20	0.12	0.35	4
Barium meal	3	2	5	200	200	0.01	0.12	0.07	0.20	3
Urography (retrograde) .	0.1	0.20	730	390	390	0.13	0.03		0.16	2
Others		173				0.33	0.34	0.03	0.70	7
TOTAL		310				3.71	3.22	1.69	8.62	100

TABLE 12. GENETICALLY-SIGNIFICANT DOSES IN THE UNITED STATES OF AMERICA, 1964 (51, 104, 106, 108)

Type of examination	Frequency ^a (N_j^*/N) 1,000		Gonad dose (d_j^*) mrad			GSD (D_j^*) mrad			Total GSD (D_j) mrad	
	Male	Female	Male	Female	Fetus	Male	Female	Fatal	Total	Percentage
Lumbar spine }	15		2,550	420	240	21.4	0.6		22.0	40.3
Lumbo sacral spine }										
Barium enema	23		1,585	810	810	6.5	2.9		9.4	17.2
Urography (retrograde de- scending)	24		2,090	410	450	5.1	1.4	0.1	6.6	12.1
Pelvis	No data		720	40	80	3.8		0.2	4.0	7.3
Abdomen	21		250	290	290	2.0	0.4	0.5	2.9	5.3
Lower extremities	54		96			2.6			2.6	4.8
Upper gastro-intestinal tract ..	30		140	560	540	1.0	1.4		2.4	4.4
Pelvimetry	No data			No data						
Obstetric abdomen	No data			No data						
Other examinations	364					3.0	1.6	0.1	4.7	8.6
TOTAL		531				45.4	8.3	0.9	54.6	100

^aDeduced by Committee.

TABLE 13. GENETICALLY-SIGNIFICANT DOSES IN PUERTO RICO, 1968 (44, 45)

Type of examination	Frequency (N_j^*/N) 1,000		Gonad dose (d_j^*) mrad		Southern region GSD (D_j^*) mrad				Western region GSD (D_j^*) mrad			
	Male	Female	Male	Female	Male	Female	Total	Percent- age	Male	Female	Total	Percent- age
Lumbar spine	13	7	160	1,190	2.0	7.5	9.5	26.3	0.8	7.9	8.7	17.9
Gastro-intestinal tract	7	9	180	690	1.1	5.7	6.8	18.8	0.5	7.4	7.9	16.9
Urography (descending)	6	6	1,150	760	2.1	4.5	6.6	18.7	3.1	7.6	10.7	22.0
Abdomen	11	16	360	530	1.7	3.0	4.7	13.0	1.3	2.5	3.8	7.8
Barium enema	1	2	1,240	880	1.4	1.5	2.9	8.0	7.6	2.3	9.9	20.4
Pelvimetry		1		1,030		1.1	1.1	3.0		<0.1	<0.1	
Hip	2	2	780	280	1.5	0.4	1.9	5.3	1.6	1.0	2.6	5.4
Pelvis	3	4	760	64	1.4	0.2	1.6	4.4	3.3	0.5	3.8	7.8
Cholecystography	3	7	9	190		0.9	0.9	2.5	0.1	1.0	1.0	2.1
Chest	104	109	1	1	0.1	0.1	0.2	0.5	0.1	0.1	0.2	0.4
Other examinations	64	64										
TOTAL		441			11.2	25.0	36.2	100	18.3	30.3	48.6	100

TABLE 14. GENETICALLY-SIGNIFICANT DOSES IN NEW YORK, 1962 (102)

Type of examination	Frequency (N_j^*/N) 1,000		Gonad dose (d_j^*) mrad		GSD (D_j^*) mrad			Total GSD (D_j) mrad	
	Male	Female	Male	Female	Male	Female	Fetal	Total	Percentage
Hip	1	1	1,330	580	13.7	1.6		15.3	30.6
Lumbo sacral spine	2	2	2,020	1,780	9.1	3.1		12.2	24.4
Pelvis	1	1	890	350	9.6	1.0		10.6	21.2
Lumbar spine	No data		190	930	1.1	1.1		2.2	4.4
Upper gastro-intestinal tract	7	7	65	830	0.3	1.7		2.0	4.0
Barium enema	3	4	350	1,110	0.4	1.3		1.7	3.4
Urography (descending)	No data		17	690	0.4	1.3		1.7	3.4
Pelvimetry	No data		1,010		3.6			3.6	7.2
Obstetrical abdomen									
Other examinations	701				0.3			0.7	1.4
TOTAL	730				34.9			50.0	100

TABLE 15. GENETICALLY-SIGNIFICANT DOSES IN NEW ORLEANS, 1963 (69)

Type of examination	Frequency (N_j^*/N) 1,000		Gonad dose (d_j^*) mrad		GSD (D_j^*) mrad			Total GSD (D_j) mrad	
	Male	Female	Male	Female	Male	Female	Fetal	Total	Percentage
Pelvimetry	6		1,600		23.3			23.3	31.0
Obstetrical abdomen									
Urography descending, retrograde, cystography	25	25	750	580	5.97	9.00		14.97	19.9
Lower spine	35	25	580	660	11.36	3.58		14.94	19.8
Pelvis			400		10.76			12.15	16.1
Hip									
Barium enema	13	10	380	670	1.70	2.74		4.44	5.9
Upper gastro-intestinal tract	18	19	90	230	0.59	1.63		2.22	3.0
Chest, including mass miniature radiography	240	182	3	9	0.72	1.26		1.98	2.6
Other examinations	124	103			0.40			1.30	1.7
TOTAL	455	370			31.5			75.3	100

TABLE 16. GENETICALLY-SIGNIFICANT DOSES IN TEXAS, 1963 (27)

Type of examination	Frequency (N_j^*/N) 1,000		Gonad dose (d_j^*) mrad		GSD (D_j^*) mrad			Total GSD (D_j) mrad	
	Male	Female	Male	Female	Male	Female	Fatal	Total	Percentage
Region									
Lower abdomen					5.5	6.8		12.3	68.0
e.g., Lumbar spine	7	7	230	—					
Pelvis	4	4	260	180					
Urography	12	13	260	340					
Abdomen	8	8	260	300					
Barium enema	11	11	120	850					
Pelvimetry									
Hysterosalpingography									
Upper abdomen					1.7	2.3		4.0	22.0
Upper gastro-intestinal tract	14	12	55	170					
Chest	113	113	1	2	0.3	0.9		1.2	7.0
Extremities, hip	6	5	520	360	0.4	0.1		0.5	3.0
Other examinations	75	75							
TOTAL	250 ^a	250 ^a			7.9	10.1		18.0	100

^a Assumed equal.

TABLE 17. GENETICALLY-SIGNIFICANT DOSES IN YUGOSLAVIA (SLOVENIA), 1960-1963 (94)

Type of examination	Frequency (N_j/N) 1,000		Gonad dose (d_j) mrad		GSD (D_j) mrad			Total GSD (D_j) mrad	
	Male	Female	Male	Female	Male	Female	Fetal	Total	Percentage
Pelvis	17	19	200	200	3.27	2.37	—	5.64	62
Lumbo sacral spine }									
Urography, descending retrograde	5	5	220	290	0.60	0.88		1.48	16
Femur	4	2	230	30	0.48	0.05		0.53	6
Chest (not mass miniature radiography)	227	188	1.4	2.7	0.12	0.28		0.40	4
Hand and wrist	38	18	6	2	0.14	0.01		0.15	2
Cystography	1	1	520	61	0.07	0.06		0.13	1
Hysterosalpingography		2	—	150	—	0.13		0.13	1
Pelvimetry		1	—	500	—	0.01		0.01	1
Other examinations	267	237			0.34	0.32		0.66	8
	558	472							
TOTAL		1,030			5.02	4.11		9.13	100

TABLE 18. MEAN GONAD DOSE PER EXAMINATION IN RECENT SURVEYS

	Male		Female	
	Median value mrad	Range of mean values mrad	Median value mrad	Range of mean values mrad
<i>High gonad dose group</i>				
Barium meal	30	5-230	340	60-830
Urography (descending)	430	15-2,090	590	270-1,160
Retrograde urography ..	580	150-2,090	520	85-1,390
Abdomen	250	12-480	210	57-790
Colon, barium enema ..	300	95-1,590	870	460-1,750
Pelvis	300	100-1,020	230	40-710
Lumbar spine	210	26-2,270	410	230-1,190
Lumbo sacral spine	300	65-2,019	340	73-1,780
Upper femur	920	230-1,710	240	58-680
Obstetrical abdomen ...			300	110-1,600
Pelvimetry			620	230-1,600
Hysterosalpingography ..			1,270	275-2,700
<i>Medium gonad dose group</i>				
Cholecystography	8	1.3-39	120	14-380
Femur lower two thirds	92	1.1-290	1	1-13
<i>Low gonad dose group</i>				
Mass survey chest	0.4	0.2-1.3	3	0.9-11
Chest, heart, lung	0.7	0.1-13	2	0.2-8
Head	Less than 10 ^a		Less than 10 ^a	
Dental	0.6	0.5-0.7	0.06	0.03-0.1
Extremities	Less than 10 ^a		Less than 10 ^a	
Mammography			Less than 10 ^b	

^a Reference 65.^b Reference 50.

TABLE 19. PERCENTAGE CONTRIBUTIONS TO THE GENETICALLY-SIGNIFICANT DOSE

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	Mass survey chest	Chest, heart, lung	Cholecystography	Stomach barium meal	Urography (descending)	Retrograde Pyelography	Abdomen	Obstetrical abdomen	Pelvimetry	Colon barium enema	Pelvis	Lumbar spine	Lumbo sacral spine	Upper femur, hip	Femur	Tonography chest	Hysterosalpingography	Chiropractics	Fatal	Dental	Others	Total percentage	Total mrad
Czechoslovakia	1.2	0.4	4.2	10.2	10.0	0.4	4.2	0.2		2.7	7.1		17.6	18.3	13.6	1.0	0.3		3.8	0.3	5.5	100	36.52
Finland	0.9	7.0	2.7	0.6	5.0	1.0	14.7	3.7	9.7	11.4	2.8	11.0	2.2	3.1	0.6		3.0		(23.1)	0.01	21.6	100	16.8
Federal Republic of Germany, Bavaria				11.2	—14.4—		7.5	0.2		9.0	33.1	—9.0—	—13.9—								1.7	100	13.7
Netherlands				5.6	20.0	4.4		2.0	0.2	14.0	6.2	3.9	16.0	21.0							6.7	100	20.0
Japan	3.0	1.4		24.4	—6.6—		2.6	2.5	0.9	24.9	4.9	6.5	8.5	8.8	1.4						3.6	100	26.5
New Zealand (1969)	0.1			3.2	13.4		8.3	14.7	6.6	7.9	—22.5—			3.5			14.0		0.7	5.1	100	13.73	
Puerto Rico																							
Southern region ..		0.5	2.5	18.8	18.2		13.0		3.0	8.0	4.4	26.3		5.3								100	36.2
Western region ..		0.4	2.1	16.2	22.0		7.8			20.4	7.8	17.9		5.4								100	48.6
Thailand				1.6	12.0	29.6 ^a	9.6	0.8	1.6		—14.4—			24.8							5.6	100	1.25
United Kingdom																							
Sheffield				3	10	2	4	11	7	4	—24—			28					(5.1)		7	100	8.6
United States				4.4	—12.1—		5.3			17.2	7.3	—40.3—							(0.9)		13.4	100	54.6
New York City ..				4.0	3.4			—7.2—		3.4	21.2	4.4	24.4	30.6							1.4	100	50.0
New Orleans	—2.6—			3.0	—19.9—			—31.0—		5.9	16.1	—19.8—									1.7	100	75.3
Texas		7.0		22.0					68.0					3.0								100	18.0
Yugoslavia, Slovenia	1	4.0			—16.0—						—62—				6						11	100	9.1

^a Plain urological examinations.

TABLE 20. GENETICALLY-SIGNIFICANT DOSES BY COUNTRIES AND SEX CONTRIBUTIONS

	<i>GSD mrad</i>				<i>GSD percentage</i>			
	<i>Male</i>	<i>Female</i>	<i>Fatal</i>	<i>Total</i>	<i>Male</i>	<i>Female</i>	<i>Fatal</i>	<i>Total</i>
Czechoslovakia, Bohemia	18.74	16.39	1.39	36.52	51	45	4	100
Finland	4.23	8.69	3.88	16.80	25	52	23	100
Federal Republic of Germany, Bavaria	8.20	5.48	0.02	13.70	60	40	1	100
Netherlands	10.0	10.0	—	20.0	50	50		100
Japan	14.1	12.4	—	26.5	53	47		100
New Zealand (1969)	4.86	4.62	2.21	13.73 ^a	42	39	19	100
Puerto Rico								
Southern region	11.2	25.0		36.2	31	69		100
Western region	18.3	30.3		48.6	38	62		100
Thailand	3.24	1.93		5.17	63	37		100
United Kingdom, Sheffield	3.7	3.2	1.7	8.6	43	37		100
United States	45.4	8.3	0.9	54.6	83	15	2	100
New York City	34.9	15.1		50.0	70	30		100
New Orleans	31.5	43.8		75.3	42	58		100
Johns Hopkins	11.9	11.2		23.1	52	48		100
Texas	7.9	10.1		18.0	44	56		100
Yugoslavia, Slovenia	5.02	4.11		9.13	54	46		100

^a Includes 2.04 mrad not allocated.

TABLE 21. PERCENTAGE DISTRIBUTION OF ACTIVE BONE MARROW

	<i>Adult, 40 years (57)</i>	<i>Adult (57)</i>	<i>Child, 3-7 years (57)</i>
Head	13	7	7
Upper limb girdle	8	7	6
Sternum	2	3	3
Ribs	8	14	13
Cervical vertebræ	4	3	3
Thoracic vertebræ	14	13	12
Lumbar vertebræ	11	11	10
Sacrum	14	9	8
Lower limb girdle	26	33	31
Extremities			7
TOTAL	100	100	100

TABLE 22. *Per capit* MEAN BONE-MARROW DOSE (JAPAN) (58)

(mrad per person per year)

		Mean bone-marrow dose				Leukemia-significant dose			
		Male	Female	Total	Percentage	Male	Female	Total	Percentage
Skull		0.49	0.25	0.74	0.4	0.42	0.24	0.64	0.4
Cervical spine		0.55	0.28	0.83	0.4	0.50	0.26	0.76	0.5
Shoulder	R	0.38	0.17	0.55	0.3	0.35	0.16	0.51	0.3
	F	0.30	0.19	0.48	0.2	0.39	0.18	0.57	0.3
Thorax	R	0.22	0.16	0.38	0.2	0.20	0.15	0.35	0.2
	F	0.44	0.24	0.68	0.4	0.43	0.24	0.67	0.4
Chest	R	1.6	0.90	2.5	1.3	1.4	0.82	2.22	1.3
	F	5.4	2.2	7.6	4.0	4.4	2.0	6.4	3.8
	PF	10.2	10.0	20.2	10.7	9.4	9.5	18.9	11.2
Esophagus		0.68	0.49	1.7	0.9	0.57	0.4	1.0	0.6
Stomach	R	11.4	6.1	17.5	0.3	10.2	5.5	15.7	9.3
	F	60.0	40.6	100.6	53.2	53.2	36.5	89.7	53.0
		3.6	3.0	6.6	3.5	3.0	2.7	5.7	3.4
Cholecystography	R	0.59	0.5	1.1	0.6	0.52	0.42	0.9	0.5
	F	3.8	2.2	6.0	3.1	3.5	2.1	5.6	3.3
Abdomen		0.41	0.34	0.75	0.4	0.35	0.30	0.65	0.3
Barium enema	R	0.66	0.58	1.24	0.7	0.59	0.53	1.1	0.7
	F	4.7	4.4	9.1	4.8	4.05	4.00	8.05	4.7
Dorsal spine		0.50	0.46	0.96	0.5	0.45	0.41	0.86	0.5
Lumbar spine		2.9	1.5	4.4	2.3	2.5	1.4	3.9	2.3
Lumbo-sacral spine		0.49	0.32	0.81	0.4	0.43	0.28	0.71	0.4
Pelvis		0.16	0.15	0.31	0.2	0.14	0.13	0.27	0.1
Urography	R	0.44	0.33	0.77	0.4	0.39	0.31	0.70	0.4
	F	0.34	0.12	0.46	0.2	0.30	0.10	0.40	0.2
Bladder		0.12	0.057	0.13	0.1	0.10	0.05	0.15	0.1
Pelvimetry		—	0.13	0.13	0.1	—	0.10	0.10	0.1
Hysterosalpingography	R	—	0.042	0.042	—	—	—	—	—
	F	—	0.37	0.37	0.1	—	0.36	0.36	0.2
Obstetrical abdomen		—	0.17	0.17	0.1	—	0.16	0.16	0.1
Hip		0.22	0.21	0.43	0.2	0.20	0.19	0.39	0.2
Femur		0.013	0.007	0.02	—	0.01	—	0.01	—
Lower leg		0.008	0.005	0.013	—	0.01	—	0.01	—
Other examinations		1.40	0.73	2.13	1.1	1.0	0.76	1.7	1.2
TOTAL		112	77	189	100	99	70	169	100

R = radiography.

F = fluoroscopy.

PF = photofluorography.

TABLE 23. BONE-MARROW DOSE (mrad) PER EXAMINATION

	Japan (58)	Netherlands (153)	United Kingdom (25)		Epp (37, 41)	
			Male	Female	Antero- posterior projection	Lateral projection
Head	29	90	32	39		
Cervical spine	43	8	54	49	10	3
Barium swallow	140	50	1,300	590		
Arm and hand						
Clavicle and shoulder	18		38	81		
Dorsal spine	140	105	200	220	30	90
Whole chest	9	R 10 F 40	12	13	1,3 ^d	4.5
Thorax (ribs and sternum)	34	6	180	37		
Barium meal	210	80	510	800		
Cholecystography	73	36	150	150		
Abdomen	59	93	120	130		
Abdomen (obstetric)	72	56		210 ^a		
Descending urography	110	433	580	450		
Retrograde urography		257	440	330		
Salpingography	50	282		210		
Placentography						
Pelvimetry	170			280 ^b		
Cystography	37	168	170	940		
Barium enema	210	359	530	1,060		
Pelvis	70	138	130	140	70	180
Lumbar spine	150	140	270	270	50	180
Lumbo-sacral joint	92	651	290	220		
Hip and upper femur (upper 1/3) ..	43	47	57	60	35	
Rest of femur	8					
Leg and foot						
Dental			1.8	1.8		
Angiography (head)			130	130 ^c		
Angiography (abdomen)			380 ^c	380		
Tomography (chest)			360	390		
Cardiac catheterization			190 ^c	190		
Bronchogram			31	31		
Mass survey chest	35	47	61	101		
Mass survey stomach	60					

^a Foetal contribution 500 mrad.^b Foetal contribution 1,100 mrad.^c Assuming equal frequencies of male and female examinations.^d Postero-anterior projection.

R = radiography.

F = fluoroscopy.

TABLE 24. *Per caput* MEAN BONE-MARROW DOSE CONTRIBUTION FROM EXAMINATION TYPE
(mrad per person per year)

	Netherlands (153)		United Kingdom (25)			
	Total male and female (mrad)	Per-cent-age ^a	Male (mrad)	Female (mrad)	Total (mrad)	Per-cent-age ^b
Head	1.14	3.8	0.275	0.258	0.533	
Cervical spine	0.06	0.2	0.155	0.089	0.244	
Barium swallow	0.12	0.4	0.752	0.450	1.202	3.7
Arm and hand						
Clavicle and shoulder			0.097	0.153	0.250	
Dorsal spine	0.3	1.0	0.250	0.342	0.592	
Whole chest: (a) Fluoroscopy	8.1	27.0				
(b) Radiography	1.11	3.7	1.010	0.827	1.837	5.7
Thorax (ribs and sternum)	0.03	0.1	0.329	0.046	0.375	
Barium meal	2.52	8.4	2.394	3.580	5.974	18.5
Cholecystography	0.48	1.6	0.192	0.326	0.518	
Abdomen	0.57	1.9	0.375	0.395	0.770	
Abdomen (obstetric)	n ^c	n ^c	0.400 ^d	0.729	1.129	3.5
Descending urography	3.69	12.3	1.375	0.915	2.290	7.1
Retrograde urography	0.27	0.9	0.143	0.133	0.276	
Salpingography	0.09	0.3		0.043	0.043	
Placentography						
Pelvimetry			0.210 ^d	0.315	0.525	
Cystography	0.24	0.8	0.021	0.067	0.088	
Barium enema	3.12	10.4	0.569	1.590	2.159	6.7
Pelvis	0.9	3.0	0.214	0.057	0.271	
Lumbar spine	1.05	3.5	0.999	0.046	1.465	4.5
Lumbo-sacral joint	2.19	7.3	0.645	0.080	0.725	
Hip and upper femur (upper ½) ..	0.18	0.6	0.107	0.172	0.279	
Other examinations			0.593	0.445	1.038	
General diagnostic radiology			11.105	11.478	22.583	
Other hospitals					1.9	
Mass miniature radiography	3.84	12.8			7.8	24.2
TOTAL	30	100			32.3	100

^a Mean value of HVL and kV determination.

^b Contributions greater than 3 per cent.

^c Negligible.

^d Foetal contribution.

TABLE 25. *Per caput* MEAN BONE-MARROW DOSE (mrad y⁻¹) IN JAPAN (58)

	Radiography	Photofluorography	Fluoroscopy	TV-fluoroscopy	Total
Male	23	14	56	19	112
Female	14	13	35	15	77
TOTAL	37	27	91	34	189

Leukæmia-significant dose (mrad y⁻¹ per person)

	Radiography	Photofluorography	Fluoroscopy	TV-fluoroscopy	Total
Male	20	13	49	17	99
Female	13	12	32	13	70
TOTAL	33	25	81	30	169

TABLE 26. AVERAGE SKIN DOSE (rad) IN PRIMARY BEAM

	Per exposure		Per examination	
	Median value	Range of average values	Median value	Range of average values
<i>High skin dose group</i>				
Barium swallow R			1.4	
Barium swallow F	6.4 ^a		8.5	
Barium meal R	0.9	0.9-2.2	1.7	
Barium meal F	4.4 ^a		2.1	6-25
Barium enema R	0.7	0.4-1.0	1.5	
Barium enema F	4.9 ^a		20	5-26
Whole chest R	0.02	0.006-0.09	0.14	0.07-0.15
Whole chest F	2.0 ^a		12	3-22
Mammography			15	10-22
Pelvimetry	2	0.8-3.8	8	6-10
Lumbo sacral spine	2.7	0.5-2.9	5	5-6
Lumbar spine	1.5	0.7-2.9	4.5	
Cardiac catheterization			47	
<i>Medium skin dose group</i>				
Head	0.4	0.3-1.5	1.5	1.4-1.9
Cervical spine	0.3	0.03-0.8	1.5	0.6-1.9
Clavicle and shoulder	0.9		0.3	0.3-0.4
Dorsal spine	1.8		2.8	2.0-4.7
Thorax	0.4		0.8	0.6-0.9
Cholecystography	0.8	0.2-1.2	2.2	1.5-2.8
Abdomen	0.2	0.15-1.3	1.2	1.0-1.4
Abdomen (obstetric)	2.0	0.4-3.9	3.2	2.7-3.8
Urography (descending)	1.2		3.2	1.7-5.0
Urography (retrograde)			2.9	1.4-2.4
Salpingography R			1.2	
Salpingography F			3.4	
Placentography			3.0	
Cystography	0.2		3.1	
Pelvis	1.4	0.4-1.7	3.3	2.1-4.5
Hip and upper femur	1.1	0.4-1.7	1.4	1.1-3.0
Dental	0.4		2.5	1.6-3.4
Angiography (head)			1.0	
Angiography (abdomen)			3.3	
Tomography (chest)			1.1	0.8-1.4
Mass survey chest	0.9		1.0	0.6-1.4
<i>Low skin dose group</i>				
Arm and hand	0.1		0.3	0.1-1.7
Chest	0.02	0.006-0.09	0.14	0.07-0.15
Femur (lower two thirds)	0.03		0.4	
Leg and foot	0.1		0.4	0.3-0.4

^a R min⁻¹.

R = radiography.

F = fluoroscopy.

TABLE 27. ANNUAL NUMBER OF INVESTIGATIONS WITH RADIO-PHARMACEUTICALS
PER 1,000 PERSONS

Country	Year	Investigations per thousand	Reference
Australia	1967-1968	5.6	5
	1966-1967	3.3	5
Denmark	1968	7.1	79
	1967	5.7	79
Japan	1968	1.7	73
New Zealand	1966	2.4	90
Sweden	1968	6.1	49
	1970	7.2	152
United States	1966	9.2	22, 142, 143
West Berlin	1960	1.9	10, 11, 60
	1968	10.1	10, 11, 60

TABLE 28. ANNUAL NUMBER OF DIAGNOSTIC INVESTIGATIONS WITH RADIO-PHARMACEUTICALS BY AGE AND SEX
IN WEST BERLIN (60)

Age group (years)	Percentage total population		Number of investigations per 1,000 persons					
	Male	Female	¹³¹ I Thyroid ^a		¹³¹ I Hippuran ^b		¹⁹⁸ Au Colloide ^c	
			Male	Female	Male	Female	Male	Female
0-6	3.6	3.4	0.09	0.10	0.09			
7-14	3.5	3.2	0.10	0.49	0.27	0.88		
15-20	3.0	2.9	0.64	7.05	0.53	1.35	0.11	
21-25	4.0	3.5	2.68	12.0	1.22	1.30	0.08	
26-30	4.5	4.1	2.92	15.1	1.07	2.15	0.28	0.08
31-35	3.1	3.0	1.46	13.7	1.16	1.93	0.94	0.11
36-40	2.5	2.7	2.56	15.7	2.18	2.36	0.26	0.47
41-45	2.0	3.2	3.38	14.4	2.08	2.03	0.97	1.12
46-50	1.9	3.3	3.99	12.2	1.83	2.51	1.00	1.07
50	15.4	27.4	2.71	5.96	3.01	2.56	2.24	1.59
TOTAL	43.0	57.0	2.28	7.90	1.77	2.11	1.04	0.95
GRAND TOTAL	100		5.5		1.96		0.99	

^a Thyroid function test.

^b Kidney function test.

^c Liver function test.

TABLE 29. ANNUAL GENETICALLY-SIGNIFICANT DOSE (microrad) DUE TO DIAGNOSTIC USE
OF RADIO-PHARMACEUTICALS IN NEW ZEALAND (90)

Test	Male	Female	Fetus	Total	Percentage
Thyroid uptake and scan	2.4	1.8	0.16	4.4	29.0
Brain scan	3.3	1.4	0.22	4.9	32.2
Liver scan	0.23	0.76	0.04	1.03	6.8
Kidney scan	0.04	0.056		0.096	0.7
Schilling test	0.024	0.044	0.004	0.072	0.5
Renogram	0.003	0.88	0.25	1.13	7.5
Blood volume	0.012	1.7	1.2	2.9	19.0
Red cell survival	0.032			0.032	0.2
Bone scan		0.052		0.052	0.3
Lung scan	0.008	0.024		0.032	0.2
Exchangeable sodium	0.012	0.028		0.040	0.2
Miscellaneous	0.044	0.45	0.024	0.52	3.4
TOTAL	6.1	7.2	1.9	15.2	100

TABLE 30. GENETICALLY-SIGNIFICANT DOSE DUE TO RADIO-PHARMACEUTICALS
IN WEST BERLIN 1968 (10)

Product	Percentage
¹³¹ I therapy	10.0
¹³¹ I diagnostic	23.5
⁷⁵ Se methionine	23.2
¹⁹⁸ Au colloid	11.6
¹³¹ I macro-aggregate of human serum albumin	9.9
⁵⁷ Co ⁵⁸ Co B-12 vitamin	5.3
¹⁹⁷ Hg ²⁰³ Hg neohydrin	4.6
¹³¹ I Hippuran	4.0
^{99m} Tc	2.7
⁵¹ Cr	2.5
⁵⁹ Fe	2.4
¹³² I	0.3
GSD=0.14 mrad	100

TABLE 31. RADIO-THERAPY OF NON-NEOPLASTIC DISEASE: MEAN MARROW DOSE PER TREATMENT COURSE^a (25)

Condition treated	Head and trunk only								All cases							
	Children				Adults				Children				Adults			
	Males		Females		Males		Females		Males		Females		Males		Females	
	No.	Mean dose rad	No.	Mean dose rad	No.	Mean dose rad	No.	Mean dose rad	No.	Mean dose rad	No.	Mean dose rad	No.	Mean dose rad	No.	Mean dose rad
1. Skin conditions																
Growths	27	14.6	21	10.0	52	4.8	80	7.6	91	4.3	125	1.7	110	2.3	185	3.3
Allergic and inflammatory	10	10.8	13	23.3	201	10.4	230	7.9	26	4.2	18	16.8	600	3.5	578	3.2
Ringworm	5	92.0	1	62.5	2	36.0	—	—	6	76.0	2	31.3	4	18.0	3	18.0 ^b
Others	1	49.0	1	5.6	38	6.9	38	4.3	1	49.0	1	5.6	65	4.0	115	1.4
2. Glandular enlargements	—	—	2	6.2	7	5.5	1	5.9	—	—	2	6.2	7	5.5	1	5.9
3. Ankylosing spondylitis	—	—	—	—	70	83.6	14	59.5	—	—	—	—	70	83.6	14	59.5
4. Arthritic and rheumatic	—	—	—	—	23	27.1	29	22.0	—	—	—	—	33	18.9	42	15.1
5. Artificial menopause	—	—	—	—	—	—	74	51.5	—	—	—	—	—	—	74	51.5
6. Deafness	5	9.4	2	8.6	7	3.5	10	3.7	5	9.4	2	8.6	7	3.5	10	3.7
7. Other non-malignant	1	2.6	2	282.0	15	20.9	35	27.6	1	2.6	2	282.0	23	13.6	37	26.2

^a The computer programme was adapted to make an approximate estimate of the bone-marrow dose from small treatment areas which receive high doses.^b Assumed male value in absence of data.

TABLE 32. RADIO-THERAPY OF NON-NEOPLASTIC DISEASE:
TOTAL PATIENT-RADS EXPOSURE PER YEAR (25)^a

X-ray treatments	Patient: rads per year ($\times 10^3$)				Total	Per-centage
	Contribution					
	Male		Female			
	Children	Adults	Children	Adults		
1. Skin conditions						
(a) Growths, etc.	9.8	5.5	6.1	12.2	33.6	5.4
(b) Allergic and inflam- matory etc.	4.3	72.6	14.6	80.5	172	27.8
(c) Ringworm	20.8	1.8	1.2	3.7	27.5	4.5
(d) Others	4.3	8.5	1.2	3.7	17.7	2.9
2. Glandular enlargements etc.	n ^b	n	n	n	n	n
3. Ankylosing spondylitis .	—	133	—	22	155	25.1
4. Arthritic and rheumatic, etc.	n	16.5	n	17.1	33.6	5.5
5. Artificial menopause ...	—	—	—	126	126	20.4
6. Deafness	2.4	n	1.8	n	4.2	0.7
7. Any other non-malignant conditions	n	9.8	12.8	25	47.6	7.7
					617.2	100

^a This total exposure in patient-rads per year is obtained by multiplying the mean marrow dose per treatment course with the number of patients treated per year.

^b n=less than 10^3 patient-rads.

TABLE 33. RADIO-THERAPY OF NEOPLASTIC CONDITIONS:
MEAN MARROW DOSE PER TREATMENT COURSE (25)

Malignant conditions	Marrow dose (rad)
Buccal cavity and pharynx	114
Esophagus	320
Stomach	157
Small intestine	77
Large intestine	70
Rectum	31
Other digestive	106
Nose, etc.	47
Larynx	40
Trachea, etc.	399
Other respiratory	392
Breast: male	10
female	19
Cervix ^a	{ Radium 260 } { X rays 208 } 468
Other uterus	276
Ovary	198
Prostate	94
Testis	476
Kidney	79
Bladder	223
Eye	13
Brain	109
Thyroid	62

^a For the treatment of the cervix uteri a standard Manchester technique irradiation of 9100 mghrs has been assumed in addition to two supplementary fields to the parametrium. The marrow dose from the radium treatment was deduced from Holodny *et al.* (61a).

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Annex C

DOSES FROM OCCUPATIONAL EXPOSURE

CONTENTS

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Introduction

1. In its 1962 report (72) the Committee discussed the contribution made by occupational exposure to the population dose. At that time it was concluded that the genetically-significant dose (GSD) from this source was unlikely to exceed a value of 0.5 millirem per year. The 1962 report also presented information on the numbers of workers in various countries, and on the doses being received by workers in various categories of work involving exposure to radiation.

2. The purpose of the present annex is to present new information with which the 1962 report can be updated.

I. Sources of information

3. Surprisingly little information on occupational exposure has been published in the scientific literature, although a considerable body of data is reported in sources of limited availability, such as annual reports of various organizations. Some of the information in this report has been submitted to the Committee as unpublished data. Much of the submitted data has needed to be reprocessed by the Committee in order for it to be put into the form required for the report. It is to be hoped that the presentation of such a considerable amount of unpublished data will encourage the publication of similar information through the normal scientific channels.

II. Limitations of the data

4. Most of the data that the Committee has used in this report were originally obtained for other purposes, and, in particular, in personnel monitoring programmes that either were designed to check that the exposures of radiation workers do not exceed some specified level, or were required by law. For reasons described below, the data were not always suitable for deriving estimates of dose in the form required by the Committee.

5. Accurate assessment of dose at the lower exposure levels is severely limited by the fact that in personnel monitoring it is usual to ignore doses below either a

minimum detectable level, or below an "investigation level"¹ selected for monitoring purposes. Because the exposures of most radiation workers are in this low range, there are few precise data on the actual doses received by them. The difficulties of selecting a representative dose value for this lower range are described in paragraph 34.

6. Another factor tending to limit the use of monitoring data for the Committee's assessment of dose is that the proportion of workers who have been supplied with personal monitoring devices varies considerably from place to place. In some establishments the staff, including those not likely to be exposed to radiation, are provided with such a device, while in others only those workers whose exposures might exceed three tenths of the annual dose limit are so monitored (see also paragraphs 16 and 17).

7. A major problem in using the results of personnel monitoring programmes to make dose estimates is concerned with the meaning of the term "dose" itself. With external radiation, irradiated personal monitoring devices undergo some change which is usually compared with the amount of change occurring in similar devices exposed under calibration conditions. In most instances the calibration devices indicate the exposure (in its strict physical sense) in the device itself, and seldom can it be said that the so-called "dose" in the test device is a true absorbed dose. Similarly, with the monitoring device worn by a worker, the change produced by irradiation, after being compared with a standard, is usually reported as a "dose", although it is not strictly an "absorbed dose".

8. Of more significance, however, is the fact that the "dose" estimated for the monitoring device is usually assumed to represent the "dose" in tissue in the person wearing the device. At the low dose levels encountered by most radiation workers it is not usual to assess the actual absorbed dose in tissue by taking account of factors such as depth, direction, and energy of the radiation; instead, for radiation protection pur-

¹ For a description of this concept see reference 24.

poses, the rough assumption is made that the "dose" in the monitoring device is the same as the dose in the underlying tissues. While this is a satisfactory procedure for radiation protection, difficulties arise when the reported results are used to estimate the actual dose in tissue, and particularly the whole-body dose.

9. It is therefore not surprising that practice varies as to whether the results of personnel monitoring programmes are reported as exposures (R), absorbed doses (rad) or dose equivalents (rem). The dose equivalent is frequently used since it is in terms of this quantity that the International Commission on Radiological Protection (ICRP) expresses the maximum permissible doses for occupational exposure, thus taking account of differences in the biological effectiveness of different radiations. The dose equivalent (H) is the absorbed dose (D) expressed in rads multiplied by a quality factor (Q) determined from the linear energy transfer (LET ∞) of the radiation (22). However, in many instances it is not possible to know which quantity was originally determined, and the Committee has therefore decided, for the purposes of this report, to use the term "recorded dose", for want of a better term. In keeping with its previous practice, the Committee has adopted the procedure of using the rad as the unit for this quantity. However, in instances where the recorded dose may contain a significant component of high-LET radiation (such as neutron exposures), it becomes necessary to draw special attention to this fact.

10. With external monitoring there is seldom much information available about the actual doses received by the various tissues. Individual workers rarely wear more than one dosimeter, the exposure of which may or may not give a true indication of the doses received by the various parts of the body (1). However, when only a single dosimeter is used, it is frequently worn at the position of highest exposure, in which case the dose in more distant parts of the body will generally be lower than in the dosimeter. Exceptions to this may occur with localized high exposures of parts of the body, an extreme example of this being with narrow beams from x-ray crystallographic machines.

11. For various reasons, therefore, it is probable that the direct use of data about individual doses from personnel monitoring programmes will tend to overestimate population doses for the various tissues of interest, but, at the low levels currently involved, this is not considered to be a serious problem.

12. With personal monitoring for internal exposure the position is even more complex. In work places the ambient levels of radio-activity are usually maintained at low values, and therefore significant internal exposures of radiation workers seldom occur. Intakes of radio-activity occur, however, on occasion from minor mishaps or incidents, and monitoring procedures may thus often be discontinuous. Whilst they are entirely adequate to ensure compliance with prescribed intake limits, they may involve considerable uncertainty for dose estimates at the very low levels occurring. Available information suggests that when higher levels occur they are limited to very few workers. Exposure to tritium is, however, an exception, and appreciable whole-body doses frequently occur in workplaces where this nuclide is used. Another exception is the exposure of the lungs of workers engaged in underground uranium mining.

III. Results

13. The main function of this annex is to present estimates of the population dose resulting from occupational exposure to radiation. With a few exceptions information about population doses was not submitted to the Committee, so that estimates of the population dose had to be made from other available data. In addition, it was felt that it would be useful to present data on the numbers of radiation workers per thousand population for comparison with the 1962 report, on the distribution of dose in certain ranges and on the annual mean dose for various occupational categories.

A. THE NUMBERS OF RADIATION WORKERS

14. With the increasing use of radiation sources and radio-active substances it becomes increasingly difficult to define what is meant by "radiation workers". There is no clear border-line between the group of workers who are directly engaged in manipulating radiation sources and those workers who are less actively engaged in such work but who are nevertheless exposed to ionizing radiation in the course of their work. Often a "radiation worker" is merely a worker who might receive radiation doses of such magnitude that dose monitoring is justified (see paragraphs 15-17). Hence, the actual number of radiation workers in different countries may sometimes differ merely as the result of different administrative practices.

15. In the 1962 report the term "occupational exposure" was considered to apply to all activities involving exposure of individuals in the course of their work, regardless of whether or not they were directly engaged in radiation work. At that time it was customary, for radiation protection purposes, to make a distinction between individuals who were regularly, and those who were occasionally, exposed in the course of their work. In addition there was a large group of individuals, such as typists, cleaners, etc., who worked in radiation establishments, but who were not considered to be occupationally exposed to radiation. However, in 1966 the ICRP introduced (23) the concept of a single category of occupational exposure, namely, the radiation exposure received by any worker in the course of his work.

16. In its 1966 recommendations the ICRP also noted that for administrative purposes it was convenient to consider two conditions under which workers are exposed, namely, conditions such that the resulting doses might exceed three tenths of the annual dose limit, and conditions in which they are most unlikely to exceed this value. The ICRP recommended that personal monitoring and health supervision should be applied in the former case, but indicated that they were not generally required in the latter.

17. The anticipated result of this recommendation was that a considerable number of workers, employed under conditions such that their exposures were most unlikely to exceed three tenths of the dose limits, would no longer be subject to personal monitoring, and consequently would not be included in the records of monitoring programmes. In this case, unless steps had been taken to include information on this latter category, any use of data derived from personal monitoring programmes would underestimate the actual number of radiation workers. However, the impact

of the 1966 recommendation of ICRP has not been fully realized in practice and, in the words of one report (15), "it is difficult to advocate any radical pruning of the numbers of workers subjected to film or other forms of monitoring". Thus, it is not possible to say to what extent the reported numbers of monitored persons may underestimate the actual number of radiation workers.

18. Table 1 presents data on the numbers of radiation workers per thousand population in various countries. It will be seen that the total is approximately the same in most countries, a representative figure being between 1 and 2 per thousand, with a somewhat higher figure for the United States. The high value for Norway (2.7 per thousand) may be accounted for by the particularly large number of dentists and dental assistants in that country. It is not clear whether the figures for other countries include dental assistants or not. In general, the number of workers in the medical field has not changed since the time of the 1962 report, being still about 0.3-0.5 per thousand.

19. However, in industry there are indications (Australia, the German Democratic Republic, Sweden) that there has been a considerable increase over the previously reported value of about 0.06 per thousand. There has also been an increase in the reported number of workers in education and research.

B. THE DISTRIBUTION OF RECORDED DOSES IN CERTAIN DOSE RANGES

20. A number of countries supplied data on the distribution of recorded individual doses in certain dose ranges for various types of work. With the exception of exposures resulting from irradiation by tritium, ^{131}I and some bone-seeking nuclides, which will be dealt with later, all information about the doses relates to external exposures. It needs to be emphasized that the numbers of persons in the lowest dose ranges will depend on the numbers of workers supplied with personal dosimeters.

21. The recorded dose ranges varied somewhat, and for the purposes of this report the following ranges, in rads per year, have been selected: 0-0.5; 0.5-1.5; 1.5-5; >5.

22. Tables 2-10, showing the percentages of monitored workers in different dose ranges must be read with some caution since the numbers are dependent on the somewhat arbitrary selection of the group of "radiation workers" being monitored. For example, an increase in the monitoring programme would be expected to raise the percentage number in the lowest dose range and decrease the percentage number in the highest dose range.

23. Table 2 shows the percentages of monitored workers in the various ranges in five countries. It will be seen that most workers are reported as receiving less than 0.5 rad per year, and that very few receive recorded doses of more than five rads per year.² Data from Sweden (64) show that a large proportion of workers receive no detectable exposure in a year.

² It should be pointed out that under the ICRP recommendations, a worker may exceptionally receive a whole-body dose up to 12 rems in a single year provided that his average exposure does not exceed 5 rems per year (23).

24. Tables 3 and 4 show the trend of exposure with time in Poland and New Zealand. In both countries it is seen that a considerable decrease in recorded dose has occurred. This is particularly evident in New Zealand, for which data covering a period of 16 years are available on monitoring films exposed to gamma rays and x rays above 150 kV. Table 4 shows the percentage of monitoring films exposed in selected ranges, and demonstrates the marked change that occurred between 1954 and 1958, which has been maintained since then.

25. A similar trend is shown in table 5, which illustrates the experience in the gynaecological department of a large Swedish medical centre in which radium is used extensively. Over the period 1961-1968 there was a marked shift of exposures towards the lower dose ranges, as a result of intensive efforts to reduce the irradiation of the staff.

26. Exposures of medical workers using radium tend to be higher than for those exposed to other radio-nuclides and x rays, as exemplified by data from the German Democratic Republic for 1966 (table 6).

27. Information was received from the United States about the results of film-badge monitoring of a sample of workers using radio-active materials (table 7). The recorded dose ranges differ slightly from those used previously but they confirm that, in general, the great majority of exposures lies in the lower dose ranges. Two significant exceptions may be noted: the first concerns the large percentages of waste-disposal workers with exposures in the high dose ranges, and the second shows the same trend, although to a much lesser extent, among industrial radiographers.

28. Information from India (table 8) also shows that most exposures are in the lowest range. However, in contrast with the data for the United States (table 7) workers in industry, and especially in reactor work, show a higher proportion of exposures in the range 0.5-5 rads.

29. Data about the exposure of atomic energy workers are shown in table 9. Most of the data refer to atomic energy research establishments, but the data from Canada's NPD reactor and from the United Kingdom are for workers in nuclear power stations. The figures from the United Kingdom are for seven nuclear power stations of the Central Electricity Generating Board.

30. An extensive review (14) of occupational exposure in the United Kingdom during the three-year period 1963-1965 confirms the observations made in other countries about the smallness of the doses received by most workers, 91-100 per cent of workers being reported as receiving less than 1.5 rads per year. Workers in medical radio-therapy, luminizing and industrial radiography received the highest doses, although less than 1 per cent of these received more than an average of five rads per year. However, a more recent analysis (2) has been made in the United Kingdom of the exposures of industrial radiographers working in factory conditions, and in the field (e.g., construction sites, gas pipelines). This showed that 5 per cent of factory radiographers and 11.5 per cent of site radiographers received doses greater than an average of five rads per year. For the period 1965-1970 the average annual recorded dose for factory radiographers was 0.9 rad, whereas for site radiography it was 2.7 rads.

The analysis concludes that the standard of radiological protection for workers engaged in site radiography is significantly lower than for workers employed in factory conditions. Nevertheless, the good results obtained by some firms in both groups suggest that, if the necessary precautions are taken, the process of industrial radiography can be carried on without workers receiving doses greater than those permitted by the national regulations.

31. Observations over a period of six years (1962-1967) made in the Federal Republic of Germany (8) showed that the percentage of workers with exposures over five rads was nearly constant from year to year, and mostly below 1 per cent, although the total number of workers doubled in the same period of time.

32. In Japan, in contrast with other countries, exposures of medical workers in 1968 were rather greater in the higher dose ranges, but very few recorded doses exceeded five rads (table 10).

C. THE MEAN ANNUAL DOSE BY TYPE OF WORK

33. Table 11 shows the mean annual recorded dose in rads for monitored workers in various types of work involving external exposure. In some cases the values shown are those reported by the country in question. In the remaining cases no value was given and it had to be estimated. For this purpose it was necessary to select a representative dose from the information supplied about the numbers of workers in various dose ranges.

34. The selection of an appropriate value for the mean annual dose for the range 0-0.5 rad has to take account of the well-known skewed distribution within this range. The value of the mean dose will depend critically on how many more-or-less unexposed workers were actually monitored. A Swedish analysis (64) shows that, for persons wearing monitoring films that were all reported as being exposed below the practical threshold value, the mean annual recorded dose was about 20 millirads. The mean annual recorded dose when films were reported as falling in the range 0.05-0.5 rad was about 150 millirads. For the purposes of this report, therefore, the value of 0.1 rad was selected as the mean dose for the reported range 0-0.5 rad. The use of this value probably results in an over-estimate of the dose contribution from this range; for example, the use of this value, if applied to the data in table 2, results in contributions from the recorded dose range 0-0.5 rad of about 50 per cent to the total calculated man-rads in each category of work, the actual proportion varying from 12 to 83 per cent. Because the calculated mean doses are generally low in relation to the dose limits, this is not considered to be a serious drawback.

35. For the ranges 0.5-1.5 and 1.5-5 rads, representative values were selected at one rad and three rads, respectively. The Swedish data referred to in the previous paragraph gave values for these ranges of 0.8 rad and 2.5 rads, respectively. For recorded doses greater than five rads, representative values were chosen at the arithmetic mean when ranges were given, or were arbitrarily allotted the value of seven rads when the only information was that there were exposures greater than five rads.

36. A fairly consistent pattern emerges from table 11, indicating that the mean recorded dose in medical work and in industry usually lies between about 0.2

and 0.6 rad per year, and that in other work the dose is lower. Data from Australia, New Zealand and the United Kingdom show higher mean doses in medical radio-therapy than in medical radio-diagnosis, this apparently being mainly caused by exposure to sealed radio-active sources. This is confirmed by data from the German Democratic Republic (7) from which it can be calculated that medical workers exposed to radium and radio-active cobalt sources received an annual mean dose of 0.79 rad, while those working with x ray machines (diagnostic and therapy) received 0.13 rad.

37. Data concerning certain hospitals in Paris for the year 1971 (51) show that in spite of the introduction of up-to-date equipment, exposures in radiological departments were still far from negligible, over 1 per cent of workers receiving more than 2 rads per year. In certain specialized radiological work up to 10 per cent of the workers received more than 2 rads per year; this particularly applied to angiography and to radiological procedures conducted during surgery and brachytherapy. The increasing use of medical radiology, and in particular, its use during surgery and in specialized procedures such as angiography, emphasizes the importance of adequate protection for all those involved in this work.

38. Swedish data (65) show that medical workers exposed to x rays (unspecified as to whether diagnostic or therapeutic) received a mean recorded dose of 0.11 rad per year and that those using radio-nuclides received 0.34 rad. A point of interest is the relative contribution to the doses received by radio-isotope workers from sealed and unsealed sources. More than 90 per cent of the mean recorded doses received by this group was from exposure to brachytherapy sources (64). Reference has already been made (paragraph 25) to the exposures in a large Swedish medical centre using radium (38). From data summarized in table 5 it was calculated that the annual mean recorded dose to workers in this centre was steadily reduced from a value of about two rads in 1961 to less than one rad in 1968.

39. The mean annual dose to the trunks of veterinary workers, as reported in the United Kingdom for 1964 (14) was 0.24 rad. This can be compared with an assessment of the dose in 1969 (50): in this study a special evaluation of low doses was made, and the mean annual doses were estimated to be 0.04 rad in women and 0.07 rad in men.

40. The data from New Zealand, which are presented in table 4, have been used to estimate the mean exposure from gamma rays and x rays above 150 kV. In 1954 the mean exposure of monitoring films was 2.4 roentgens, and by 1958 it had been reduced to 0.4 roentgen. Since 1958 the mean exposure has remained steady, at just below 0.4 roentgen.

41. The information presented in table 7, showing the distribution of recorded dose in the United States, can be used to calculate mean recorded doses in the various types of work. These show general agreement with the results shown in table 11, but in the case of waste-disposal workers the annual mean recorded dose was 1.84 rads. Industrial radiographers had a mean recorded dose of 0.50 rad (54).

42. Amongst other industrial workers, luminizers in the United Kingdom were reported to have received an average recorded dose of 0.59 rad in 1964; these luminizers worked at that time mainly with radium-

activated luminous compound "in rather primitive working conditions" (14). Luminizing is now tending to be done with tritium- rather than radium-activated compounds, with a consequent reduction in external exposure. The occupational exposures from tritium luminizing are from internal radiation and are discussed in paragraphs 51 and 52.

43. Information about the doses received by atomic energy workers, whether in research establishments or in nuclear power stations, are not generally available in the scientific literature. The data included in this report were made specially available to the Committee, and in some cases the original data had to be changed into a form suitable for the Committee's purposes. The annual mean recorded doses of workers in research atomic energy establishments varied considerably, ranging from 0.06 rad in Israel to 0.69 rad in the United Kingdom. The latter figure is for workers employed by the United Kingdom Atomic Energy Authority. Among this group, those working on nuclear-fuel reprocessing were reported as receiving a mean annual dose of 1.5 rads (41). A value of 0.11 rad per year in 1968 was reported from the Oak Ridge National Laboratory in the United States (47).

44. Data were provided on doses received by workers in seven nuclear power stations operated by the Central Electricity Generating Board in the United Kingdom (49). In 1969 these ranged from mean recorded doses of 0.84 rad in the oldest station to 0.17 rad in the newest. In the same year, the mean recorded dose in three nuclear power stations in the United States ranged from 0.6 to 1.3 rads (54).

45. Information about a number of nuclear power stations makes it possible to calculate the ratio of total staff dose to output of electricity, expressed as man-rads per megawatt-year of electricity. This quantity, whilst not of importance for the individual workers, is of relevance to the total dose incurred by the population. The results are shown in table 12. These results only apply to the doses received by workers within nuclear power stations; however, in the case of the British nuclear power programme an estimate can also be made of the total occupational dose contributed at present by the reprocessing of the nuclear fuel (including waste management) used in the power reactors. The available data indicate that, for the two years 1968-1969, the occupational exposures contributed by fuel reprocessing (41) and by work in the nuclear power stations (49) were:

Fuel reprocessing	1.6 man-rads per megawatt-year
Power stations	0.7 man-rad per megawatt-year
Total	2.3 man-rads per megawatt-year

46. Only limited information is so far available on the dose related to electrical output, but the data indicate that, at the present time, for a fairly-well-established nuclear power programme, electricity can be produced at a rate of two or three man-rads per megawatt-year, of which the dose contributed by fuel reprocessing appears to form the major part. Improved technology, and the trend towards the construction of power reactors with greater electrical output, in which the staff exposures are not likely to raise proportionately, are expected to result in lower values of man-rads per megawatt-year, as indicated in table 12. Technical developments in reprocessing plants which are likely to be greatly expanded in the next decades are expected to result in a reduction of the total occupa-

tional dose per megawatt-year. In the United Kingdom, for instance, nuclear power generation is expected to reach about 90 GW y (46) by the year 2000 and the contribution of occupational exposure to the total population dose is still likely to be relatively small compared with the natural radiation background (population doses from environmental contamination by nuclear power stations are discussed in annex A of this report).

47. During the first six months of 1971 the exposure of the crew of the N.S. *Otto Hahn* was at the rate of 0.5 man-rad per megawatt-year (thermal) (71): this cannot be compared directly with the estimates of dose per megawatt-year for nuclear power stations for which the power output is expressed as megawatt-year (electrical).

48. The data that have so far been referred to come mainly from the more developed countries, in which, as has been seen, average annual doses are now usually much less than one rad. A report from Pakistan (43) on 600 persons monitored by means of film badges, representing 20-30 per cent of all radiation workers in that country, showed average weekly exposures of about 34 milliroentgens, corresponding to approximately 1.5 rads per year. Five per cent of the films were reported as showing exposures greater than 100 milliroentgens per week, or five rads per year. The Pakistani report states that in organizations having a "local radiation-safety facility" the average weekly dose was 10 milliroentgens and that 2 per cent of the films exceeded 100 milliroentgens per week; the report does not state what proportion of workers in these organizations were supplied with film badges.

49. All the preceding results relate to external exposures. Data are available from Canada (56) on the whole-body doses from tritium uptake by workers at the Chalk River Nuclear Laboratories, where tritium monitoring is performed only when it is suspected that a tritium intake has occurred. Among individuals monitored in this way the average recorded whole-body dose in 1968 was 0.24 rad. The dose from the uptake of tritium may be compared with the dose from external gamma radiation, which averaged 0.70 rad among those workers receiving detectable exposures.

50. At the Canadian heavy-water reactors, occupational exposure to tritium accounts for 12-26 per cent of the dose (table 12).

51. Estimates of the dose received by workers using tritium in industry have also been reported in the United Kingdom (33). These workers were employed in the luminous-paint industry, and in filling gas in capsules used as self-luminous warning signs etc. The doses received by the workers were derived from the measured concentration of tritiated water in their urine. Table 13 shows the distribution of doses reported in the original paper, and a calculated value of the mean doses for the years 1963-1969.

52. Data on annual mean doses are also available for luminizers using tritium in France and the Federal Republic of Germany. A group of French workers, numbering from 15 to 35, was reported to have received mean doses of 0.17-0.86 rad in the four years 1968-1971 (51). The results of a survey of luminizers in the Federal Republic of Germany are shown in table 14. It will be seen that over the period 1962-1969 there was a steady improvement, due to an energetic programme of radiation protection. Tritium-energized luminous paint was introduced to reduce

population exposures from radium in wrist watches. Its increasing use in consumer products, and the problems of monitoring the internal exposures of workers, emphasize the need for stringent control of its use in industry, especially after the recent publication of two fatalities among tritium workers in Germany (61).

53. Contamination by tritium from watches at wholesale importers, retailers and refiners has been reported. A dose of 0.5 rad in a year was estimated to have been received by an individual working in a firm of wholesale importers which handled 200 Ci per year and which had poor ventilation. Contamination was negligible in retail establishments. Watch repair-men and refiners had negligible internal contamination (6).

54. Several investigations of medical and paramedical personnel working with radio-nuclides have been reviewed (62). Individuals working with iodine radio-nuclides received higher doses than those working with other radio-nuclides (^{99m}Tc , ^{133}Xe , ^{137}Cs , ^{74}As , ^{22}Na , ^{68}Ge); 70 per cent of individuals working with ^{125}I showed contamination of their thyroid glands, with an average activity of 5 nanocuries, and a maximum level of 20 nanocuries. The degree of contamination appeared to be related to the quantity of material handled, and not to the professional category of the worker. Only 15 per cent of persons working with ^{131}I showed the presence of the nuclide in their thyroid glands, the maximum amount being four nanocuries. These lower levels with ^{131}I were attributed to the availability of pre-packaged forms of this nuclide for diagnostic purposes, improved procedures for radio-nuclide handling and administration, and increased emphasis on radiological protection.

55. Data were submitted from Argentina (3) on the dose to the thyroid gland among workers at the Comisión Nacional de Energía Atómica involved in the production of ^{131}I and of compounds labelled with this nuclide. In 1969 57 per cent of the workers accumulated less than 0.6 rad, 25 per cent received 0.6-3 rads, 3 per cent received 3-6 rads, and 15 per cent received a dose in the 6-30 rads range. None had a total dose greater than 30 rads, the maximum permissible dose for the thyroid gland.

56. At the same establishment 93.5 per cent of workers exposed to bone-seeking radio-active materials (enriched uranium and ^{32}P) had an annual intake, by inhalation, of less than 2 per cent of the maximum permissible, and 6.5 per cent had intakes between 2 and 10 per cent of the annual maximum permissible (3).

57. A special case of internal exposure involving also some workers who are not usually recognized as radiation workers, is the exposure to radon and its radio-active daughter products in underground mines. Inhalation of radon and its daughter products in various types of underground mines has been reported, particularly in the mining of uranium (20, 68), thorium (45), fluorspar (13), tin (15) and hæmatite (15). In some uranium mines considerable practical difficulties have been experienced in keeping the concentrations of radon below currently recommended limits; for example, in Argentina in 1970, 24 per cent of about 150 uranium miners were exposed to an integrated concentration of "equilibrium equivalent radon" greater than 60 nCi h 1^{-1} (3) which corresponds to the maximum permissible concentration in air recommended by ICRP, inhaled for 2,000 hours. In Swedish metal mines in

1969-1970 40 per cent of 4,700 workers were exposed to average concentrations greater than 30 pCi 1^{-1} (66).

58. In some mines where men were exposed to high concentrations of radon and its daughter products an increased incidence of lung cancer has been reported (40). An increased incidence of lung cancer has also been reported in fluorspar (13) and hæmatite (15) mines. Because of the difficulty in assessing lung dose from inhalation of radon, no attempt has been made here to assess a population dose from occupational exposure in mines. Estimates of the risk of developing lung cancer as a result of exposure to radon and its daughter products are discussed in annex H of this report.

59. The risk of cancer in underground miners has presented one of the major problems in radiation protection. However, during recent years there has been a marked improvement in working conditions in mines, with a subsequent lowering of the exposure to radon and its daughter products.

D. THE POPULATION DOSE RESULTING FROM OCCUPATIONAL EXPOSURE

60. The Committee's 1962 report contained estimates of the genetically-significant doses (GSD) resulting from occupational exposure, and it was concluded that 0.5 millirem represented an upper limit to those doses; this conclusion was based on data from three countries.

61. The policy adopted by the Committee for calculating average population doses is described in detail in annex A, paragraphs 5 to 13.

62. To make a precise estimate of the GSD, however, requires knowledge of the actual gonad doses, the size of the groups receiving such doses, and the child expectancy of such groups. Only Japan and New Zealand have used these factors, and both conclude that the total value of the GSD was 0.07 millirad in the particular year studied. For New Zealand an estimate was also made of the corresponding *per caput* dose to the whole population, which was approximately twice the value of the GSD. The contributions to the GSD are shown in table 15.

63. For countries where the required data are not available, the table also shows over-all population doses. In one case (Australia) allowance was made for the dose actually received by the gonads and for the ages of the exposed individuals. The remaining population doses were simply determined as a *per caput* dose to the entire population of the particular country. Since the latter doses were obtained from personal monitoring, and did not allow for depth dose or child expectancy, they are likely to be over-estimates. Nevertheless, the available data strongly indicate that the population dose is unlikely to exceed 0.5 millirad per year, and that in many cases the actual value may be less than 0.1 millirad per year.

IV. Some special problems

64. In addition to the occupational exposures that have been considered in this chapter there are a number of categories of radiation work that may present special problems for radiation protection. These include radiation exposure of television maintenance men; a survey concludes that "occupational x-radiation exposure of television repair-men and assemblers is

virtually non-existent" (59). This conclusion is supported by a study of the exposure of television repair shops in Baltimore, United States, in which it was found that negligible doses were received (74). A survey of 30 aircraft-instrument repair shops in the United States revealed many cases of significant radium contamination resulting from repair and stripping operations on radium luminous dials (60).

65. Additional categories of radiation work about which it would be valuable to have information or associated radiation doses include exposure of radar operators to x rays emitted from klystrons and magnetrons; exposures in educational institutions, especially in schools for x-ray technologists; exposures of transportation workers; exposures of aircraft maintenance workers; and exposures of radio-pharmaceutical manufacturers.

66. Consideration is given in annex A of this report to the exposure of the crews of supersonic aircraft. The total galactic cosmic-ray dose equivalent rate at supersonic altitudes is estimated to be about 1 mrem h⁻¹, which is approximately double the rate at subsonic altitudes. The annual dose to be received by crews of supersonic aircraft might be about 1 rem per year, depending on the length of time spent at supersonic altitudes. This may be compared with the exposure of crews in current subsonic jet aircraft, who are estimated (42) to receive about 0.5 rem per year. In addition, crews of supersonic aircraft may be exposed to solar flare radiation, but it is expected that appropriate measures will ensure that the dose contribution from this source will be small.

67. Astronauts in space can be exposed to a fairly constant background of 30-50 millirads per day from primary galactic radiation and its secondaries (34). In addition, they can also be exposed to periodic solar flares and magnetically-trapped radiations, in which the dose rates have been estimated to vary from a fraction of a rad per hour up to 20 rads per hour, and the duration from minutes to days (34). The total dose for space missions up to six months' duration has been estimated to range up to 2,000 rads, depending upon the phase of the solar cycle (34).

V. Accidents

68. Occasionally, radiation injuries occur in persons occupationally exposed to ionizing radiation. These can usually be attributed to severe over-exposures resulting from failures of safety procedures or from carelessness. A number of injuries have been reported in x-ray analytical work (37), and in industrial radiography (4, 5).

69. In addition to the few accidents that have resulted in radiation injury, there has been a number of incidents, some of which have involved exposures in excess of currently accepted limits, but which have not resulted in injury (11). A survey of lost-time accidents in operations of the United States Atomic Energy Commission and its associates over the period 1943-1970 (73) showed that during that period over 4 10⁹ man-hours were worked. Lost-time injuries attributable to all causes amounted to 17,934, of which 9,147 occurred in AEC operations. Only 38 of the 9,147 lost-time injuries were caused by nuclear radiation; these included three fatalities shortly after exposures received as a result of criticality accidents in the early days of atomic energy (three additional

deaths caused by the explosion of the SL-1 reactor not being included). A report (76) has reviewed 400 incidents involving radium, most of which involved loss of radium sources from medical establishments, with approximately one third of the sources not being recovered. No injuries were reported in this review. The total contribution to the population dose from all these accidents is likely to have been very small.

70. Two reports from Thailand emphasize the hazards of the hand-held fluoroscope. A prolonged exposure (about 30 minutes) with a poorly protected hand-held fluoroscope resulted in injury to a hand of an examining physician and to the foot of his patient (57). The absorbed dose in the skin of the patient's foot was estimated to be greater than 6,000 rads. Another instance of severe injury occurred in the hand of a physician using a mobile x-ray machine and a hand-held fluoroscope (58). The dose to the physician's hand was estimated to be between 3,000 and 6,000 rads. No injury was reported as developing in the patient, in whom the dose was calculated to be 10-15 per cent of that received by the physician. An investigation has revealed the existence of 30 additional hand-held fluoroscopes in the same country.

VI. Summary

71. Data assembled since the Committee's 1962 report indicate that the total number of radiation workers has remained at about 1-2 per thousand of total population.

72. The majority of radiation workers receive very low exposures, and very few exceed the recommended maximum permissible doses recommended by the International Commission on Radiological Protection. The mean annual recorded dose for most types of radiation worker lies in the range of 0.2-0.6 rad per year. In particular types of work, notably industrial radiography and medical work involving the use of radium, higher exposures have been reported. Mean annual recorded doses as high as 2.7 rads per year have been reported for industrial radiographers working on site radiography.

73. The integrated dose among occupationally-exposed persons involved in the production of electricity by nuclear power is at present about 2-3 man-rads per megawatt-year, most of the dose apparently being received during the reprocessing of nuclear fuel. Improved technology is expected to result in lower values of man-rads per megawatt-year.

74. The genetically-significant dose from occupational exposure has been estimated in two countries to be 0.07 millirad in a year, with a corresponding *per caput* dose of about twice this value. Other estimates of the *per caput* dose range as high as 0.8 millirad in a year. This may be compared with the 1962 estimate of 0.5 millirem as being the likely upper limit of the genetically-significant dose from occupational exposure.

75. Over-exposures and injuries are now extremely rare in most kinds of radiation work. There are, however, several types of radiation work in which accidental high exposures and injuries are still not uncommon. Chief among these are industrial radiography and x-ray crystallography, in which careless operating procedures are nearly always the cause of reported injuries. The use of the hand-held fluoro-

scope for the examination of patients has led to a number of reported injuries, both in patients and in the examining physicians.

76. Difficulty is being experienced in a number of underground mines (and, in particular, uranium mines) in maintaining the inhalation exposures of miners below currently recommended limits. Abnormally high incidences of lung cancer have been reported in various groups of underground miners exposed to levels much above those recommended

by the International Commission on Radiological Protection. Much effort is currently being put into reducing the exposures of underground miners.

77. There has also been some initial difficulty in the luminizing industry, when there has been a change from the use of radium to tritium in the luminous compound, in preventing excessive uptake of tritium by the workers. Experience shows that special care needs to be taken if the exposures of the staff are to be kept well below the recommended limits.

TABLE 1. NUMBER OF RADIATION WORKERS PER THOUSAND POPULATION

	Type of work									Total	Reference
	Medical	Diagnosis	Therapy	Dental	Chiro-practic	Veter-inary	Indus-trial	Research and education	Atomic energy		
Argentina											
1969									0.08		3
Australia											
1966-1967		0.41	0.11	0.40	0.02	0.02	0.14	0.25	0.08	1.5	67
Belgium											
1968	0.4			0.01			0.1	0.2	0.02	0.7	18
Denmark											
1968	0.8			0.2		0.03	0.03	0.2	0.2	1.5	17
Federal Republic of Germany											
1969	0.14						0.09	0.12	0.07	0.4 ^a	9
Finland											
1967				0.27						0.9	69
France											
1969-1970	0.85			0.30			0.32	0.11	0.49 ^b	2.1	51
German Democratic Republic											
1966	0.9						0.2	—0.2—		1.5	7
Italy											
1966		0.27	0.06	0.20		<0.01	0.04	0.05	0.07	0.7	52
Japan											
1968		—0.28—					0.06	0.05	0.02	0.4	19
Netherlands											
1969		—0.7 ^c —					0.1		0.02	0.8	75
New Zealand											
1969		0.32	0.10	0.55	0.04	0.07	0.05	0.13	0	1.3	48
Norway											
1968		0.51	0.05	1.8 ^d		0.01	0.08	0.12	0.19	2.7	30
Poland											
1966	0.38						0.07	0.07		0.5	39
Sweden											
1968	0.5			1.0		0.01	0.13	0.16	0.15	2	36
Thailand											
1970										<0.1	58
United Kingdom											
1968-1969						0.07			0.36 ^b		41, 49, 50
United States											
1970	1.33			0.87				1.55		3.7	42

^a Does not include x-ray workers.

^b Includes nuclear power stations.

^c Includes research and education.

^d Includes a value of 0.8 for dental assistants.

TABLE 2. PERCENTAGE OF WORKERS IN RECORDED DOSE RANGES

Dose range (rad y ⁻¹)	Czechoslovakia, 1966 (12)		Federal Republic of Germany, 1969 (9)			Finland, 1967 (69)		German Democratic Republic 1966 (7)			Poland ^a 1966 (32)		Research and other
	Medical	Industry	Medical	Industry	University and research	Medical and research	Industry	Medical	Industry	University and research	Medical	Industry	
0-0.5	87.2	73.7	88.9	87.3	89.0	89.8	99.0	96.2	97.2	92.0	78.8	94.7	95.5
0.5-1.5	9.8	14.8	10.8	12.4	10.4	7.2	0.5	2.5	2.1	4.6	14.4	3.9	3.3
1.5-5	2.2	10.4	0.2	0.3	0.4	3.0	0.5	1.3	0.7	3.0	6.3	1.4	1.2
>5	0.7	1.0								0.4	0.4		

^a These data refer only to persons engaged in work with radio-nuclides.

TABLE 3. PERCENTAGE OF POLISH WORKERS IN RECORDED DOSE RANGES (26-28)

Dose range (rad y ⁻¹)	1966	1967	1968	1969
<0.1	85.5	89.5	91.1	92.0
0.1-0.4	9.3	7.0	6.3	5.6
0.4-1.2	3.3	2.2	2.0	1.7
1.2-5	1.3	0.9	0.5	0.5
>5	0.7	0.4	0.2	0.1

TABLE 4. PERCENTAGE OF MONITORING FILMS EXPOSED^a IN SELECTED EXPOSURE RANGES IN NEW ZEALAND (55)

Exposure range (R y ⁻¹)	1954	1958	1963	1969
0-0.5	24.0	84.0	86.0	88.8
0.5-1.5	30.0	10.8	9.5	6.4
1.5-5	29.5	4.0	3.6	3.2
>5	16.5	1.2	0.9	1.6

^a Exposure to gamma rays and to x rays over 150 kV.

TABLE 5. PERCENTAGE OF WORKERS IN RECORDED DOSE RANGES (GYNECOLOGY DEPARTMENT, RADIUMHEMMET, STOCKHOLM, SWEDEN) (38)

Dose range (rad y ⁻¹)	1961	1962	1963	1964	1965	1966	1967	1968
≤1	51.6	60.4	62.7	69.4	69.3	64.7	77.2	80.2
1-2	17.2	12.1	15.5	6.9	9.3	20.6	15.3	17.0
2-5	19.4	17.4	17.6	17.5	17.3	14.0	7.4	2.8
>5	11.8	10.1	4.2	6.3	4.0	0.7	0	0

TABLE 6. PERCENTAGE OF MEDICAL RADIATION WORKERS IN RECORDED DOSE RANGES (GERMAN DEMOCRATIC REPUBLIC, 1966) (7)

Dose range (rad y ⁻¹)	X ray	Radium	Radio-nuclides other than radium
0-0.5	98.1	64.1	86.8
0.5-1.5	1.4	19.3	7.4
1.5-5	0.4	15.7	5.4
>5	0.1	0.8	0

TABLE 7. PERCENTAGE OF WORKERS IN RECORDED DOSE RANGES IN LICENSED INSTALLATIONS^a (United States, 1968) (54)

Dose range (rad y ⁻¹)	Academic	Medical ¹	Major processor	Industry general	Industry radiography	Waste disposal	Fuel processing and reprocessing	Power and research reactors	All other
0-0.5	96.5	87.9	88.0	91.7	75.0	46.2	86.1	95.7	94.6
0.5-1	2.1	7.1	4.0	3.4	10.5	6.6	5.4	2.4	3.4
1-5	1.4	4.7	6.8	4.7	14.0	33.8	7.4	1.7	1.8
>5	0	0.2	1.2	0.2	0.5	13.3	0.1	0.2	0.2

^a The data in this table apply to facilities licensed under the United States Atomic Energy Act, and do not include those workers exposed to machine-produced radiation exclusively.

TABLE 8. PERCENTAGE OF WORKERS IN RECORDED DOSE RANGES (INDIA, 1969) (31)

Dose range (rad y ⁻¹)	Medical	Industry	Research and education	Fuel reprocessing	Waste disposal	Power and research reactors
0-0.5	92.1	77.6	97.4	93.4	89.1	68.9
0.5-1.5	5.4	15.7	1.8	5.4	8.1	16.6
1.5-5	2.2	4.7	0.6	1.2	2.7	14.4
>5	0.4	1.9	0.2	0	0	0.1

TABLE 9. PERCENTAGE OF ATOMIC ENERGY WORKERS IN RECORDED DOSE RANGES
(All external, except tritium)

Dose range (rad y ⁻¹)	Argentina, CNEA, 1970-1971 (3)	Canada, AECL, 1968 (56)	Canada, ^a NPD, 1969 (77)		France, CEA (25) 1968	India, BARC (31), 1969	United Kingdom, ^b CEGB (49), 1968	United States, ORNL (47), 1968
			External	Tritium				
0-0.5	98.4	88.6	86.4	84.4	97.6	75.1	75.4	93.8
0.5-1	1.1							3.6
0.5-1.5		7.0	10.3	11.8	2.2	14.0	22.2	
1-5	0.5							2.6
1.5-5		4.4	3.3	3.8	0.2	10.4	2.5	
>5	0	0	0	0	0.01	0.4	0	0

^a Nuclear power demonstration station.

^b Seven nuclear power stations.

TABLE 10. PERCENTAGE OF JAPANESE WORKERS IN RECORDED DOSE RANGES (1968) (19)

Dose range (rad y ⁻¹)	Medical	Industrial	Research and education	Atomic energy
0-0.5	84.3	92.8	98.2	96.1
0.5-1	9.4	3.4	1.1	2.5
1-5	5.9	3.3	0.6	1.4
>5	0.3	0.4	0.1	0

TABLE 11. MEAN ANNUAL RECORDED DOSE (rad) BY TYPE OF WORK (EXTERNAL EXPOSURE)

	Type of work								Reference
	Medical	Diagnosis	Therapy	Dental	Chiropractic	Veterinary	Industrial	Research and education	
Australia 1966-1967		0.19	0.34	0.02	0.03	0.07	0.25	0.07	67 (1969)
Belgium 1968	0.29			0.08			0.66	0.48	18
Brazil 1969	0.23						0.42	0.16	10
Czechoslovakia ^d 1966	0.34						0.62		12
Denmark ^d 1968	0.18			0.005		0.03	0.36	0.05	17
Federal Republic of Germany 1969	0.31						0.37 ^a	0.34 ^a	9
Finland ^d 1967							0.21		69
France 1969-1970				0.075			0.11	0.03	51
German Democratic Republic ^d 1966	0.17						0.15	0.26	7
India ^d 1969	0.21						0.62	0.06	31
Israel 1969	0.07			0.07			0.08	0.04	16
Italy 1966		0.20					0.08		52
Japan 1968	0.38						0.29	0.09	19
Netherlands 1969							0.40		75
New Zealand ^d 1969		0.08	0.34	0.07	0.09	0.06	0.42	0.16	48
Poland ^d 1966	0.44						0.18	0.17	39
Sweden 1968	0.15						0.10	0.02	64
Thailand 1969	0.33 ^b						0.86 ^c		58
United Kingdom 1964		0.35	0.49	0.27		0.24 ^e	0.30— 0.59		14 (1969) 41
United States ^d 1969-1970	0.34			0.12			0.16		70

^a Includes atomic energy.

^b Including dental.

^c Including medical therapy.

^d Values calculated by the Committee.

^e But see special estimate referred to in paragraph 39.

TABLE 12. RECORDED STAFF DOSE IN RELATION TO ELECTRICAL OUTPUT FOR SELECTED NUCLEAR POWER REACTORS

Reactor	Reactor type	Rated power (12) (MW(e))	Years surveyed	Total electrical output (MW y)	Total staff dose (man-rads)	Man-rads per MW(e) y	Notes	Reference
Berkeley (United Kingdom) ..	GCR	276	1965-1969	1,401	2,027	1.4	Annual range 1.4-1.5 man-rad per MW y	49
Bradwell (United Kingdom)...	GCR	300	1965-1969	1,436	1,269	0.9	Annual range 0.8-1.2 man-rad per MW y	49
Chinon 1, 2, 3 (France)	GCR	750	1962-1969	1,059	647	0.6	Man-rads apply to reactor staff only	21, 25
Dungeness (United Kingdom).	GCR	550	1965-1969	1,803	915	0.5	Annual range 0.3-0.8 man-rad per MW y	49
Hinkley Point (United Kingdom)	GCR	500	1965-1969	2,245	1,526	0.7	Annual range 0.6-0.8 man-rad per MW y	49
Latina (Italy)	GCR	200	1962-1969	965	590	0.6	Man-rads include doses received during refuelling and in large maintenance operations	21, 52
Marcoule (G-2, G-3) (France)	GCR	80	1958-1969	571	219	0.4	Man-rads apply to reactor staff only	21, 25
Oldbury (United Kingdom)...	GCR	600	1968-1969	624	156	0.2	Annual range 0.2-0.3 man-rad per MW y	49
Sizewell (United Kingdom) ..	GCR	580	1965-1969	1,423	360	0.3	Annual range 0.3-2.1 man-rad per MW y	49
Tokai (Japco-1) (Japan)	GCR	160	1965-1969	318	703	2.2		21, 44
Trawsfynydd (United Kingdom)	GCR	500	1965-1969	1,564	653	0.4	Annual range 0.3-0.9 man-rad per MW y	49
Indian Point (United States)...	PWR	265	1962-1969	1,033	1,386	1.3	Annual range 0.5-5.3 man-rad per MW y	53
Shippingport (United States) .	PWR	90	1965-1969	255	893	3.5	Annual range 1.0-8.7 man-rad per MW y	54
Trino Vercellese (Italy)	PWR	247	1964-1969	386	250	0.6	Man-rads include doses received during refuelling and in large maintenance operations	21, 52
Big Rock Point (United States)	BWR	70	1962-1970	305	1,217	4.0		63
Dresden (United States)	BWR	200	1960-1970	1,223	2,038	1.7	Annual range 0.8-4.0 man-rad per MW y	35
Garigliano (Italy)	BWR	150	1963-1969	645	750	1.2	Man-rads include doses received during refuelling and in large maintenance operations	21, 52
N Reactor (United States) ..	LWGR	790	1966-1969	1,248	1,446	1.2	Annual range 0.8-3.7 man-rad per MW y	21, 54
Douglas Point (Canada)	PHWR	208	1967-1969	155	1,386	8.9	Tritium contributes 12 per cent of dose	21, 77
Pickering 1, 2 (Canada)	PHWR	1,080	1971	338	198	0.6	Tritium contributes 26 per cent of dose	77

TABLE 13. PERCENTAGE OF WORKERS USING TRITIUM IN RECORDED DOSE RANGES (UNITED KINGDOM) (33)

Year	Workers monitored	<0.1 rad	0.1-1.5 rad	1.5-5 rad	>5 rad	Mean dose rad
1963	43	62.8	34.9	2.3	0	0.38
1964	56	51.8	44.6	3.6	0	0.58
1965	47	61.7	38.3	0	0	0.34
1966	42	19.0	71.4	11.9	0	0.93
1967	56	39.3	58.9	0	0	0.49
1968	56	41.1	58.9	0	0	0.49
1969	82	31.7	59.8	6.1	2.4 ^a	1.43

^a Two individuals, with doses of 7 rads and 55 rads.

TABLE 14. PERCENTAGE OF LUMINIZERS USING TRITIUM, IN RECORDED DOSE RANGES (FEDERAL REPUBLIC OF GERMANY) (29)

<i>Year</i>	<i>No. of supervised persons</i>	<i><0.1 rad</i>	<i>0.1-1.5 rad</i>	<i>1.5-5 rad</i>	<i>>5 rad</i>	<i>Mean dose rad</i>
1962	1	0	0	0	100	88
1963	2	0	0	0	100	44
1964	4	0	25.0	0	75.0	8
1965	18	28.7	66.5	5.4	0	0.69
1966	108	34.3	36.1	16.6	13.0	0.87
1967	89	33.7	58.4	7.9	0	0.41
1968	108	28.7	52.7	16.7	1.9	0.49
1969	99	26.3	61.6	11.1	1.0	0.39

TABLE 15. CONTRIBUTIONS TO THE POPULATION DOSE (mrad y⁻¹)
(All per caput doses except Japan and New Zealand)

	<i>Type of work</i>									<i>Total</i>	<i>Reference</i>
	<i>Medical</i>	<i>Diagnosis</i>	<i>Therapy</i>	<i>Dental</i>	<i>Chiro-practic</i>	<i>Veter-inary</i>	<i>Indus-trial</i>	<i>Research and education</i>	<i>Atomic energy</i>		
Australia 1966-1967										0.1	67
Federal Republic of Germany 1969	0.04						0.05 ^a	0.05 ^a		0.14	9
Finland 1967	0.14						0.01			0.15	69
German Democratic Republic 1966										0.2	7
Israel 1969										0.07	16
Japan ^b 1968	0.044						0.024	0.001	0.005	0.07	19
New Zealand ^b 1969		0.016	0.022	0.017	0.002	0.003	0.009	0.006		0.07	48
Norway 1968										0.05	30
Poland 1966										0.01	39
Sweden 1968	0.07						0.01	0.004	0.02	0.1	64
United Kingdom 1968-1969									0.23 ^c		41, 49
United States 1970	0.4			0.1			—0.3—			0.8	70

^a Includes atomic energy.

^b Calculated as genetically-significant dose.

^c UKAEA (1969): 0.20; CEGB (1968): 0.03.

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Annex D

MISCELLANEOUS SOURCES OF IONIZING RADIATION

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Introduction

1. The general population may be exposed to a wide variety of miscellaneous sources of ionizing radiation. These sources can be classified in two categories. The first category includes sources intended for industrial, medical, military or research purposes which, as a result of transportation accident, loss, theft, incorrect use or disposal may escape control and find their way to the public at large, or contaminate the environment. The second category consists of products containing natural or man-made radio-nuclides nominally sealed and which can be acquired by the general public, referred to in this annex as consumer products.

I. Radiation sources not normally available to the general public

2. About 100 transportation incidents involving radio-active material have been reported throughout the world from 1954 to 1968 (58, 60). Fourteen accidents involved aircraft carrying nuclear weapons or components of nuclear weapons (58). Two of those accidents, which resulted in appreciable contamination of the environment, are discussed in annex A (paragraphs 243-244). Other publicized accidents include the disappearance of two nuclear submarines and the burn-up in the upper atmosphere of a ^{238}Pu isotopic generator. More common incidents involve loss or theft of radio-active material during ground transportation. A number of such incidents have been reported in which injuries of varying degrees of severity have resulted for members of the public coming in contact with lost or stolen radio-active sources (3, 19, 33).

3. Among the sources commonly used for industrial, medical, or research purposes, radium deserves special

attention as it has been widely utilized since the turn of the century and is one of the most hazardous radio-nuclides. In the United States alone, about 2,000 curies of ^{226}Ra have been processed and imported for use in medical and industrial sources (50). Manufacturer sales data indicate over 1,300 curies of ^{226}Ra (including 550 curies of luminous compounds) has been sold or leased. Estimates based on state licensing and registration programme data can account for about 475 curies of industrial and medical radium at this time. (This estimate does not include Federal use, devices not subject to licensure or registration, and luminous compounds.) Most of the remaining radium not accounted for can be attributed to the disposal of luminous compounds and devices and radium returned to the manufacturer (45). In the medical field, reports of 442 radium incidents occurring since 1905 had been collected by 1 January 1970 in the United States (8). Detailed analysis of 115 radium incidents which occurred during 1966 through 1969 show that 55 per cent of all radium incidents are losses (72 per cent of medical incidents) and that 75 per cent of these losses occur during patient treatment and source removal. However, for 299 incidents involving lost or stolen radium, 66 per cent of the sources were recovered (49).

4. In the case of major transportation accidents, extensive decontamination, when feasible, was carried out and the doses were kept to a minimum (paragraphs 243-246 of annex A). With other incidents, even if the dose to some individuals was high, the number of exposed persons has been very small. The population dose from these sources is certainly negligible when compared to natural background.

II. Products available to the general public

A. RADIO-ACTIVE NUCLIDES ADDED TO CONSUMER PRODUCTS

5. Radio-active materials, either natural or man-made, are often incorporated into consumer products. A list of such products, which does not pretend to be comprehensive, is presented in table 1 (13). The use of radio-nuclides to produce luminosity appears at present to be the largest single application of radio-nuclides in products available to the general public. Quantitative data on the doses resulting from the distribution of such products are scarce but it is estimated that the contribution of radio-luminous timepieces, which is relatively well documented, amounts to more than half of the average gonad dose from all consumer products containing radio-active materials (45).

1. Radio-luminous timepieces

6. Several studies on doses arising from radio-luminous timepieces were conducted around 1960, when ^{226}Ra predominated as the activating material (12, 25, 31, 34, 51, 52). The alpha activity of such a source is the main means of producing fluorescence, while the beta activity and accompanying gamma rays give rise to the external radiation exposure of the wearer. The radium content of self-luminous timepieces was found to vary considerably, depending upon many factors such as size of hands and dials, and radium concentration in the luminous paint. In a summary of the investigations, Seelentag and Schmier (52) reported that the average radium content of men's wrist watches containing radium as a luminizing material varied from 0.014 to 0.36 microcurie, with a maximum observed value of 4.5 microcurie.

7. The actual dose received by a wearer will depend on a number of factors such as the amount of radium in the watch, the length of time that the watch is worn during the day, and the habits of the wearer. It has been estimated (52) that the annual gonad dose to males wearing a watch only during waking hours (16 hours per day) might be about one fifth of the 24-hour dose, and might be about 15-30 millirads per year, normalized to a watch activity of one microcurie.

8. Radium-dial pocket watches, which are worn in relatively close proximity to the gonads, are potentially a greater genetic hazard than wrist watches with equal amounts of ^{226}Ra (43). However, they are not worn overnight, and measurements on a phantom indicated that the annual dose to the testes is about 60 mrad μCi^{-1} , which is lower than the average annual dose from a wrist watch of the same activity worn 24 hours a day (27). As regards self-luminous alarm clocks, Joyet and Miller (25) estimated the average gonad dose from that source to be only one tenth of the gonad dose from luminous wrist watches.

9. Estimates of the genetically-significant dose from radium in watches around the year 1960 are shown in table 2. On average, the genetically-significant dose was 2 mrad y^{-1} and, in all cases, less than 4 mrad y^{-1} .

10. The fraction of ^{222}Rn leaking out of the watches was reported to vary widely (12). The radon content measured after a build-up of 10 hours in an airtight box was found to vary from around 0.1 to 30 nanocuries per microcurie ^{226}Ra for new, watertight watches and for loosely sealed, old watches, respectively. The

dose to the lung after inhalation of ^{222}Rn and its decay products depends on the size and ventilation rate of the room in which the watch is used but can be estimated to be in most cases a small fraction of the contribution of natural background.

11. It was already clear in the early 1960s that, probably because of radiation regulations, the average content of ^{226}Ra in self-luminous wrist watches, as well as the annual production of such watches, was decreasing (52). At the same time, efforts were also made to use beta-active sources of low energy, which emit a small amount of gamma radiation or none at all, such as ^3H or ^{147}Pm , to eliminate the external radiation exposure. For a period ^{90}Sr was used but has now been discontinued on account of the beta radiation and Bremsstrahlung escaping from the watch and the hazard for the workers involved. In 1967, the ENEA and the IAEA jointly recommended that only ^3H , ^{147}Pm and ^{226}Ra should be used as activating radio-nuclides in luminous paint for dials and hands of timepieces and that ^3H or ^{147}Pm should be preferred as far as possible (18). Average and maximum recommended values of the radio-nuclide content to be used per timepiece were also indicated.

12. In recent years, ^{226}Ra in watches has tended to be replaced by ^3H and, to a lesser extent, ^{147}Pm . In 1968, the annual United States production and importation of timepieces activated by ^{226}Ra was estimated to be about 3 million whereas 6 to 7 million timepieces contained ^3H or ^{147}Pm (45).

13. Although the use of ^3H eliminates the risk of external irradiation, experience has shown that tritiated water, or a simple tritiated organic molecule, evolves from the self-luminous compound (26, 63) and leakage of ^3H from watches has been found to result in annual doses to wearers of the order of one millirad (65).

14. The Committee is not aware of any recently-published survey on radiation doses resulting from the use of self-luminous timepieces. However, taking into account the increased use of nuclides giving rise to smaller exposure and the development of performance standards, it seems very likely that the genetically-significant dose has considerably decreased since 1960.

2. Self-luminous devices other than timepieces

15. Although nowadays radio-luminous phosphors are usually activated by ^3H , radium has been extensively used, primarily by the aircraft industry and the military. During World War II, the major United States manufacturer of luminous markers used several hundred curies of radium in production for the armed forces. Some of those products find their way into consumer outlets as government surplus (48).

16. The dose resulting from the normal use of the majority of self-luminous devices is probably very low but the possibility always exists that persons receive greater exposure than expected because of the release of the radio-nuclide during accidents, fire or unconventional use of the product. However, the probability of such circumstances occurring will normally be small (13).

3. Other products

a. Radio-active gold rings

17. It has been reported that spent gold-encased radon seeds, originally intended to be implanted into

tumours, have occasionally been used in the manufacture of gold rings (4, 56). In one instance irradiation from long-lived daughter products of radon that became incorporated in the gold caused sufficient damage to adjacent skin to necessitate amputation of the affected finger.

b. Heart devices

18. Owing to its high ratio of power output to weight and volume, and to its long half-life, ^{238}Pu is used as a power source for isotopic generators. In the medical field, about 10 ^{238}Pu sources were in use in patients in March 1972 as batteries for heart pacers. This practice has been introduced to avoid the surgical replacement of the conventional electrical batteries in heart pacers each 18 months. ^{238}Pu is also envisaged as a power supply for a mechanical pump which would totally replace the human heart. If all the technological problems can be overcome, there might be as much as 100 megacuries of ^{238}Pu committed to this use by the turn of the century (29).

19. In the present state of technology, the dose equivalent received by someone staying continuously near the patient would be of the order of one rem per year for an artificial heart and of one millirem per year for a heart pacer (15). The dose to the adjacent tissue in a person wearing a pacemaker would be very much higher but is essentially a matter of medical concern only.

c. Radio-active substances in patients released from hospitals

20. Members of the families of patients who have been released from hospitals after having been treated with radio-active substances may receive some exposure from radio-active nuclides still retained in the patients. The practices concerning the amount of activity permitted in patients leaving hospitals vary from country to country but often reflect current international recommendations (22) intended to limit the dose received by other persons than the patient to less than 0.5 rad per year.

d. Radio-active materials used in schools

21. Pupils in schools sometimes use radio-active materials in science classes. Recommendations for the protection of pupils exposed to radiations used in schools have been given by the ICRP (21).

e. Radio-active ceramic glazes

22. The use of uranium compounds to produce certain brightly colored pigmented glazes for ceramic-ware such as platters, pitchers, vases, water mugs and coffee cups was reported as early as 1906. For a set of tableware widely available in the United States, it is estimated that the beta-radiation dose to the hands, assuming a continuous contact with the tableware for 90 minutes per day, ranges from 2 to 10 rads per year (36).

f. Thoriated electrodes in welding rods

23. When thoriated tungsten electrodes are used to generate an arc, thorium is released from the arc and becomes airborne as a fume. The activity released is sufficiently diluted by normal convection currents for the concentration in the air breathed by the operator to be very low. Significant concentrations might result only if the equipment is used in a small, totally enclosed, space (5).

B. PRODUCTS THAT ARE NATURALLY RADIO-ACTIVE

1. Building materials

24. The relative content of natural radio-nuclides in building materials may lead to a significant difference between the external radiation dose rates received indoors and outdoors. The walls of buildings act as a shield against outside radiation but this effect is often offset by radiation resulting from the radio-activity of the building materials (annex A, paragraphs 132-136).

25. Increases in exposure occur when highly-radio-active construction materials are used. For instance, phosphate rocks often have a high content of radium (37). In the United States, the growth of the phosphate industry, linked to the use of the tailings as building material, has possibly led to a significant increase in the exposure of local populations (32). In a United Kingdom survey, gypsum which is also a waste product from fertilizer from imported phosphate rock was found to be at least twice as active (in terms of gamma-ray emission rate per gramme) as any other building material (14). In Sweden, light-weight concrete from uranium-rich shales has been reported to give indoor dose rates two to three times the normal outdoor dose rate (59).

26. A special situation arose in Grand Junction, Colorado, in the United States, where approximately 200,000 tonnes of uranium-mill tailings were used during the period 1952-1966 as fill material under streets, driveways, swimming pools, water pipes and sewer mains, but also in habitable structures where they resulted in potential exposures from external gamma radiation and inhalation of ^{222}Rn decay products. By August 1971, gamma levels had been assessed in approximately 10,600 structures out of 18,000. About 3,000 of these were actually found to have tailings under, or adjacent to, the building (11, 55). It is estimated that the total number of structures with tailings located under or against them in the Grand Junction area is about 3,600 (55).

27. Analyses of gamma maps of about 1,000 habitable structures, including residences, schools, business and public buildings, were completed by October 1971. Data for 670 residences show that, in 80 per cent of these, the average levels above background (taken as $9 \mu\text{R h}^{-1}$) are less than $10 \mu\text{R h}^{-1}$; in about 18 per cent they are in the range $10\text{--}50 \mu\text{R h}^{-1}$, and in only 0.3 per cent above $100 \mu\text{R h}^{-1}$ (11). Assuming that the average time spent indoors is 17 hours per day (paragraph 263 of annex A), doses to the gonads corresponding to levels of 10, 50 and $100 \mu\text{R h}^{-1}$ are approximately 50, 250 and 500 mrad y^{-1} , respectively.

28. The concentration of ^{222}Rn decay products in structures built with tailings are not readily correlated with the gamma levels. Preliminary measurements indicated levels of radon daughters ranging up to 0.4 WL^1 which is 100 times the background level (11).

¹ A working level (WL) is the term used in uranium mines to describe radon-daughter product activities in air. This term is defined as any combination of short-lived radon-daughter products in one litre of air that will result in the ultimate emission of $1.3 \cdot 10^5 \text{ MeV}$ of potential alpha energy. The numerical value of the working level is derived from the alpha energy released by the total decay through ^{214}Po of the short-lived radon decay products ^{218}Po , ^{214}Pb and ^{214}Bi at radio-active equilibrium with 100 pCi of ^{222}Rn per litre of air.

29. So far the area of Grand Junction is the only one where it has been determined that tailings have been used extensively in construction. However, some tailings have been found under structures in other cities in Colorado and surveys are being carried out in the United States to investigate the extent of use of tailings in all areas surrounding present and former mill operations (11). It is not known if similar situations occur in other countries.

30. By contrast it is clear that an appropriate choice of low radio-activity raw materials would cause a significant reduction in the population dose from external radiation, as several studies have shown that, on a national basis, the radio-activity of a building material varies considerably (30, 64).

2. Natural gas

31. Average ^{222}Rn levels in natural gas samples collected from different geological formations of the United States were found to range from 3 to 67 pCi l^{-1} , with a maximum observed value of 160 pCi l^{-1} (6). When natural gas is used, ^{222}Rn is released. Its maximum build-up is expected to occur in a closed area containing unvented gas appliances. In a typical dwelling, its concentration in air would be about 500 times less than its concentration in gas (24). Taking an average ^{222}Rn level in gas of 35 pCi l^{-1} , the concentration in air would be about 0.07 pCi l^{-1} , which, assuming average conditions of radio-active equilibrium between ^{222}Rn and its daughters, corresponds to a dose of about 20 mrad y^{-1} to the basal cell nuclei of the bronchial epithelium (annex A, paragraph 117). However, actual doses are expected to be much lower because most appliances are vented and also because any appreciable transmission time from well to consumer would decrease the ^{222}Rn content by radioactive decay.

C. ELECTRONIC PRODUCTS

32. Electronic products may be sources of ionizing radiation when electrons are accelerated at potentials in excess of about 10 kilovolts. Potential emitters of x rays are high-voltage rectifiers, radio-transmitter tubes, klystrons, electron microscopes, etc. A large variety of those devices are used for medical, industrial, or research purposes and are outside the scope of this annex. However, it may be recalled here that the problem of stray x rays around high-voltage tubes was exemplified in 1960 when two technicians exposed to pulsed x rays from an unshielded klystron tube were seriously injured in Lockport, USA (17).

33. Household colour television receivers are the most common electronic products with the potential of exposing the general public to x radiation.

1. Colour television receivers

34. Since the advent of commercial television broadcasting, it has been recognized that cathode-ray tubes of television receivers produce x rays, the output of which depends sharply on tube voltage and is directly proportional to tube current.² In monochrome sets, the x rays are produced in small amount and have a poor penetrating power, because of the relatively low accelerating voltage of about 20 kilovolts and the

small beam current of some 0.1 milliamperere. X-ray production in colour television sets is enhanced because of an increase of the accelerating voltage to 25 kilovolts or more and of the beam current to about one milliamperere resulting in a greater production of more penetrating radiation. High-voltage rectifiers and shunt regulator tubes are the other sources of x rays in a television receiver. Certain models are designed to operate without shunt regulator tube and some are fully transistorized. The trend towards solid-state circuitry is likely to continue and implies that the only vacuum device remaining in a television receiver within a few years will be the picture tube (7).

35. The public-health significance of the problem is potentially greatest in the United States, where 25 million colour sets were in use in January 1970 (53) and where it is estimated, from the present rate of increase of colour television sets, that approximately 70 per cent of all homes will have them by 1975 (16). In 1967, approximately 110,000 large-screen colour television receivers were modified by replacing the high-voltage shunt regulators which produced an excessive downward emission of x rays (47). A field survey conducted in the state of Florida in November 1967 on 148 sets showed that the modification programme had been effective but discovered that 43 sets had x-ray emissions from sources other than the shunt regulator tube in excess of the ICRP limit. These x rays originated from component sources that could be associated with the sets of all manufacturers, thus indicating a potential industry-wide problem (38). To obtain additional information, a home survey was conducted in the Washington (D.C.) metropolitan area in December 1967 and January 1968. It was found that 76 per cent of the 1,124 colour television receivers examined did not emit any measurable levels of x rays but that 6 per cent exhibited exposure rates above the ICRP limit, in most cases because of excessively-high voltage (39). X rays were detected regardless of the age of the sets but there was evidence of a downward trend for receivers sold from 1964 to 1967.

36. Table 3 presents the estimates of the average annual doses for both children and adults, based on average viewing habits and on the average front face exposure rate of 43 $\mu\text{R h}^{-1}$ at five centimetres that were observed in the Washington survey. The average dose to the gonads of male children is estimated at 1.5 mrad y^{-1} but the distribution of x-ray emission would suggest that about 1 per cent of the viewing population might receive doses larger than those presented in table 3 by a factor of about 60 (40). The annual genetically-significant dose to the United States population was estimated to be 0.5 millirad based on the assumptions that, over the country, the distribution of x rays from television sets and the viewing habits of the population are similar to those observed in the Washington metropolitan area (66). However, it was pointed out that the energy dependence of the detectors used in the Florida and Washington surveys led to overestimates of up to a factor of three of the exposure rate of cathode-ray tube and rectifier tube emissions (66).

37. Other home surveys were more recently conducted in the United States in order to check if the x-ray emissions complied with the guidelines. In Pennsylvania and in Puerto Rico, less than 10 per cent of the colour televisions surveyed were found to emit radiation in excess of the ICRP limit and none exceeded

² The ICRP recommends that the x-ray exposure rate 5 cm from the surface of any television set should not exceed 0.5 mR h^{-1} , which is equivalent to an air dose rate of 0.435 mrad h^{-1} (20).

3.0 mR h⁻¹ (9, 28). In Suffolk County, New York, over 6,000 sets were inspected in 1968-1969; about 16 per cent emitted radiation in excess of 0.5 mR h⁻¹, the maximum observed being 150 mR h⁻¹ (1). The outstanding causes of x-ray emissions were improper adjustment of the high-voltage control and faulty shunt-regulator tubes. A follow-up of this survey showed that approximately 11 per cent of the sets that were re-surveyed were emitting x rays above the ICRP limit because of improper servicing (2).

38. The first phase of the United States performance standard for television receivers became effective for sets manufactured after 15 January 1970, and the final and most stringent aspect was effective after June 1971. Television receivers must meet the 0.5 mR h⁻¹ limit under conditions of extreme misadjustment and with the component and/or circuit failure that maximizes emission (44). This means that under typical operating conditions, the emission from recently-built colour television receivers is expected to be indistinguishable from background (54).

39. Smaller-scale surveys have been conducted outside the United States. In the United Kingdom, the only source of x rays in currently-produced sets is the picture tube and the maximum dose rate occurs at the front screen. A survey completed by April 1970 concluded that the average male-gonad dose from normal viewing of receivers whose picture tube is set at a typical high voltage is about 0.8 μ rad y⁻¹ (41). Allowing for high voltage regulation, variability of x-ray output and the effect of line voltage fluctuations, the dose rate in air five centimetres from any receiver leaving a factory is unlikely to exceed 15 μ rad h⁻¹, corresponding to an average male-gonad dose of about 0.2 mrad y⁻¹. It was observed that under test conditions of service misadjustment or circuit failure tending to maximize x-ray emission or both conditions combined, some manufacturers' receivers could be made to exceed slightly the ICRP limit (42).

40. In Canada, in contrast to the other surveys, the front face of the sets was not monitored as it was assumed that the glass safety plate of the picture tube provided an effective shielding. About 11 per cent of the receivers tested gave dose rates above the ICRP limit but the proportion was found to decline in successive years since 1966 (10).

41. The foregoing surveys, as well as the results reported from other countries (23), tend to show that, under conditions of normal operation and proper servicing, the x-ray emission from recently-built colour television receivers is negligible.

2. *Electronic products used for educational purposes*

42. Many schools in their science class demonstrations use equipment which produces ionizing radiation. During April 1969, a survey was performed in 181 high schools throughout the United States to determine the magnitude of possible radiation hazards from demonstration devices designed to emit x rays or which may emit x rays as a result of their intended use (61).

43. Survey findings showed that three types of cold cathode gas discharge tubes produced outside the tube significant levels of x rays which were not essential to the effect demonstrated. An estimate of 15,000 to 30,000 of those tubes, which were used to demonstrate

the heat effect, the magnetic effect, and the fluorescence effect of cathode rays, had been distributed by the United States producer from about 1910 to 1968. The x-ray exposure rate at a distance of 30 centimetres was greater than 0.1 R h⁻¹ for 25 per cent of the 175 tubes tested, and greater than 1 R h⁻¹ in the proportion of 6 per cent. The number of students who might have been exposed and the average exposure were not determined. As a consequence of the survey, the company currently manufacturing the tubes in the United States ceased the production of the faulty tubes and redesigned them. The fluorescence-effect and the magnetic-effect tubes were then found to meet the newly-promulgated requirements of 10 mR h⁻¹ at 30 centimetres from any surface or enclosure of the tube, and were allowed to be sold. The heat-effect tube failed to meet requirements and its production was terminated (62).

44. In the same survey, 103 x-ray tubes were found, of which 97 were unshielded and many were reported as not in use. Measurements were made on 21 of the unshielded tubes. Eleven emitted at rates of roentgens per hour 60 centimetres from the anode, the maximum calculated value being 108 R h⁻¹. Some of the tubes could emit x rays in all directions at rates many times the recommended maximum. Under the new regulation, the divergence of the x-ray exit beam should not exceed π steradians and the enclosure must be equipped with a beam-blocking device (46).

45. In a preliminary survey conducted in Kansas schools in 1968, measurable exposure rates were recorded in the vicinity of the x-ray tubes and of some cold-cathode gas discharge tubes (57). The maximum exposure which resulted from the use of hand fluoroscopes was to the hands of 10 high school students over a school year and amounted to about 700 millirads. Other exposure rates were lower by at least an order of magnitude. Most of the x-ray-producing devices available in the schools were not in use. Subsequently, discontinuance of hand fluoroscopy was recommended.

3. *Shoe-fitting fluoroscopes*

46. In its 1962 report, the Committee referred to the irradiation of individuals by shoe-fitting fluoroscopes. Information available to the Committee indicates that those devices are much less frequently used than formerly. When in use, they will cause exposure rates to the feet of about 5 rads per minute or more.

III. Conclusion

47. The widespread use of self-luminous wrist watches activated by ²²⁶Ra led to a genetically-significant dose of about 2 mrad y⁻¹ around 1960. As a consequence of international recommendations and national regulations in some countries, the use of ²²⁶Ra is being gradually discontinued and is being replaced by ³H and, to a lesser extent, ¹⁴⁷Pm, which give rise to much lower doses to the users. There is no recent estimate of the present contribution of self-luminous wrist watches to the genetically-significant dose but it is expected to be considerably reduced from the 1960 value. However, significant individual doses are likely to be received in case of accidental ingestion of the radio-luminous paint.

48. The radiation exposure from colour television receivers seems to follow the same trend. In the United

States, the genetically-significant dose from that source was estimated to be 0.5 mrad y^{-1} in 1967. Since then, federal performance standards for television receivers have gone into effect so that the genetically-significant dose should now be very small. In the other countries, because the proportion of colour television sets is much lower than in the United States, the genetically-significant dose is also certainly very small.

49. The external radiation is influenced to a large extent by the radio-active content of the building ma-

terials. Analysis of table 18 of annex A indicates that the average external dose rate indoors may be lower or higher than the outside dose rate depending upon local circumstances such as geology, choice and origin of building material, etc. It is evident that the influence of the building material on the external dose rate is very high, and that the choice of material therefore should be given proper attention. Building materials with unusually high radio-active contents should be avoided.

TABLE 1. PRODUCTS CURRENTLY AVAILABLE CONTAINING RADIO-NUCLIDES (13)

<i>Products</i>	<i>Nuclide</i>	<i>Activity or mass per product (range of approximate values)</i>
A. Radio-luminous products		
(a) <i>Paints and plastics</i>		
1. Timepieces	^3H ^{147}Pm ^{226}Ra	5 to 25 mCi 65 to 200 μCi 0.1 to 3 μCi
2. Aircraft instruments	^3H ^{147}Pm ^{226}Ra	up to 10 Ci up to 0.3 Ci up to 20 μCi
3. Compasses	^3H ^{147}Pm	5 to 50 mCi 10 μCi
4. Instrument dials and markers	^3H	25 mCi
5. Instruments, signs and indicators	^{147}Pm	0.75 Ci
6. Thermostat dials and pointers	^3H	25 mCi
7. Automobile lock illuminators	^3H ^{147}Pm	2 to 15 mCi 2 mCi
8. Automobile shift quadrants	^3H	25 mCi
9. Bell pushes	^3H	0.3 mCi
10. Speedometers	^{147}Pm	0.1 mCi
11. Rims for underwater watches	^3H	0.3 mCi
12. Fishing lights	^{14}C	3 to 4 mCi
13. Spirit levels	^3H	5 to 25 mCi
(b) <i>Sealed tubes</i>		
1. Marine compasses	^3H	0.2 to 2 Ci
2. Marine navigational instruments	^3H	0.25 Ci
3. Markers	^3H ^{85}Kr	4 Ci 0.3 Ci
4. Instruments, signs and indicators	^3H ^{85}Kr	2 Ci 0.25 Ci
5. Exit signs for commercial buildings	^3H	15 Ci
6. Large signs	^3H	30 Ci
7. Small exit signs	^3H	2 Ci
8. Step markers	^3H	2 Ci
9. Mooring buoys and lights	^3H	2 Ci
10. Public telephone dials	^3H	0.5 Ci
11. Light switch markers	^3H	0.2 Ci
12. Bell pushes	^3H	10 mCi
13. Miniature light sources	^3H	20 mCi
B. Electronic and electrical devices		
1. Electronic tubes	^3H ^{63}Ni ^{147}Pm ^{85}Kr ^{60}Co ^{226}Ra ^{137}Cs	1 to $10^4 \mu\text{Ci}$ 1 to 5 μCi 1 μCi 1 to 5 μCi 0.15 to 5 μCi 0.1 μCi 5 μCi

TABLE 1. PRODUCTS CURRENTLY AVAILABLE CONTAINING RADIO-NUCLIDES (13) (continued)

Products	Nuclide	Activity or mass per product (range of approximate values)
2. Glow discharge tubes	^{85}Kr	0.01 to 10 μCi
3. Voltage discharge tubes	^{147}Pm	3 μCi
4. Cold cathode tubes	^3H	90 μCi
5. Fluorescent lamp starters	^{226}Ra	1 μCi
6. Gas discharge lamps (high pressure mercury-vapour lamps)	Natural thorium	6 10^{-3} μCi
7. Vacuum tubes	Natural thorium	0.8 to 1.2 per cent by weight
8. Electric lamps	Natural thorium	50 mg
9. Germicidal lamps, sun lamps, lamps for outdoor and industrial lighting	Natural thorium	2 g
10. Glow lamps	^3H	0.01 mCi
11. Spark gap tubes	^{147}Pm	30 μCi
	^{60}Co	5 μCi
	^{63}Ni	5 μCi
	^{137}Cs	5 μCi
12. High voltage protection devices	^{147}Pm	3 μCi
13. Low voltage fuses	^{147}Pm	3 μCi
C. Antistatic devices		
1. Lightning rods	^{228}Ra	0.2 to 1 mCi
	^{241}Am	0.06 to 0.7 mCi
2. Antistatic devices contained in instruments	^{228}Ra	10 μCi
3. Antistatic brushes	^{210}Po	0.05 to 0.5 mCi
	^{241}Am	2 to 25 μCi
4. Antistatic devices contained in precision balances	^3H	1 mCi
D. Gas and aerosol (smoke) detectors		
1. Smoke and fire detectors	^{241}Am	0.06 to 0.1 mCi
	^{226}Ra	0.01 to 15 μCi
	^{85}Kr	7 mCi
	Natural or depleted uranium	7.5 mg
E. Ceramic, glassware, alloys, etc. containing uranium or thorium		
1. Chinaware	Natural uranium	10^{-2} $\mu\text{Ci cm}^{-2}$ surface
2. Ceramic tableware glaze	Natural thorium	20 per cent by weight (glaze)
	Natural or depleted uranium	20 per cent by weight (glaze)
3. Glassware, glass enamel, glass enamel frit	Natural thorium	10 per cent by weight
	Natural or depleted uranium	10 per cent by weight
4. Optical lenses	Natural thorium	Up to 30 per cent by weight
5. Incandescent gas mantles	Natural thorium	Up to 0.5 g
6. Magnesium-thorium alloys	Natural thorium	Up to 4 per cent by weight
7. Products containing rare earths i.e.: arc carbons, lighter flints, metallurgical additives, precision lenses, television tubes, electronic ceramics, microwave devices, etc.	Natural thorium	0.25 per cent by weight
	Natural or depleted uranium	0.25 per cent by weight
	Natural thorium	1 to 2 per cent by weight
8. Welding rods		
F. Other devices, including scientific instruments		
1. Gas chromatographs	^3H	250 mCi
	^{63}Ni	12 mCi
2. Static meters	^{241}Am	0.5 to 50 μCi
3. Vending machine coins	^{14}C	2 μCi
4. Bank cheques	^{14}C	0.01 μCi

TABLE 2. ESTIMATED ANNUAL GENETICALLY-SIGNIFICANT DOSES (GSD) FROM RADIUM IN SELF-LUMINOUS WATCHES

<i>Country</i>	<i>Year</i>	<i>Estimated annual GSD (mrad)</i>	<i>Reference</i>
Denmark	1961	1.2	34
Switzerland	1960	3.3	25
Federal Republic of Germany	1959	2.6	51
Federal Republic of Germany	1961	1.5	52
United Kingdom	1960	0.5-1.0	35
Sweden	1960	1-3	31

TABLE 3. ESTIMATED AVERAGE ANNUAL DOSE FROM COLOUR TELEVISION SETS, BASED UPON THE WASHINGTON, D.C., SURVEY (40)

<i>Organ</i>	<i>Children less than 15 years of age (mrad)</i>	<i>People 15 years of age and older (mrad)</i>
Skin	3.6	1.6
Thyroid	2.6	0.9
Male gonads	1.5	0.7
Female gonads	0.4	0.2
Lens of eye	3.0	1.3

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