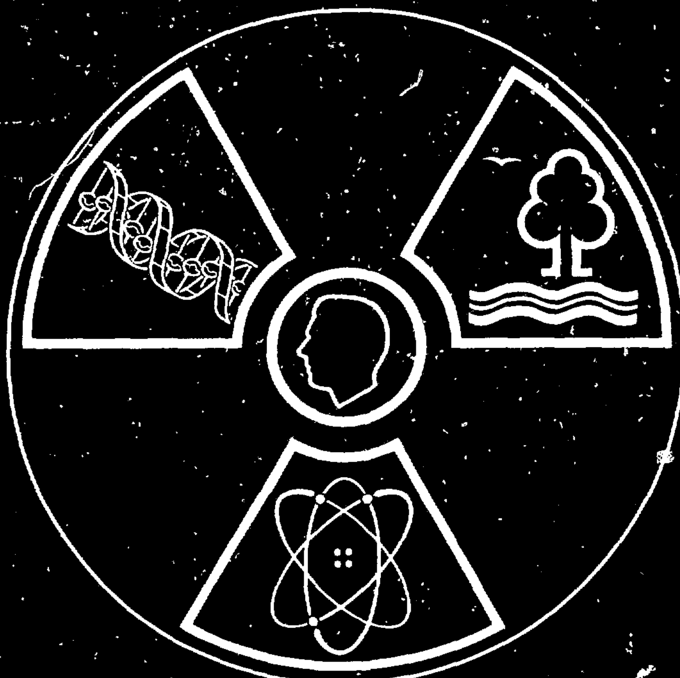

REFERENCE

ATOMIC ENERGY OF CANADA LIMITED

BIOLOGICAL EFFECTS OF IONIZING RADIATION

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J.A.L. Robertson and J.L. Weeks*

Chalk River Nuclear Laboratories
*Whiteshell Nuclear Research Establishment

Chalk River Nuclear Laboratories
Chalk River, Ontario KOJ 1J0
1981 May

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L'ENERGIE ATOMIQUE DU CANADA, LIMITEE

Effets biologiques des rayonnements ionisants

Edité par

A.M. Marko

Collaborateurs
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Laboratoires nucléaires de Chalk River
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Résumé

Dans ce document récapitulatif les rayonnements produits par l'industrie nucléaire sont comparés aux autres sources de rayonnement existant dans l'environnement terrestre. On y passe en revue les effets des rayonnements sur la santé des êtres humains, les normes dérivant de ces effets et les estimations des risques. On y évalue les implications de l'exposition des travailleurs et de la population en général aux rayonnements engendrés par les centrales nucléaires. On y passe également en revue les effets des rayonnements sur l'environnement. Finalement, on identifie les lacunes de nos connaissances en matière de rayonnements et on fait le point de la recherche actuelle sur les effets biologiques, sur les aspects environnementaux et sur la dosimétrie des rayonnements à l'EACL et au Canada.

Laboratoires nucléaires de Chalk River
Chalk River, Ontario KOJ 1JO
Mai 1981

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ABSTRACT

In this review radiation produced by the nuclear industry is placed into context with other sources of radiation in our world. Human health effects of radiation, derivation of standards and risk estimates are reviewed in this document. The implications of exposing the worker and the general population to radiation generated by nuclear power are assessed. Effects of radiation on the environment are also reviewed. Finally, gaps in our knowledge concerning radiation are identified and current research on biological effects, on environmental aspects, and on dosimetry of radiation within AECL and Canada is documented in this report.

Chalk River Nuclear Laboratories
Chalk River, Ontario KOJ 1J0
1981 May

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FOREWORD

The objective of radiation protection is to prevent acute effects of radiation and to minimize late effects of radiation in workers and the general population. Acute effects of radiation appear in a matter of weeks while delayed effects are only apparent after tens of years. Late effects, such as cancers and leukemia, which become manifest in the irradiated individual are called somatic and late effects affecting the descendants of the irradiated individual are known as hereditary or genetic. Defects in the development of the embryo or the fetus after irradiation are called teratogenic and may be regarded as specialized somatic effects.

Radiation protection is important because it is expected that the production of electricity by nuclear means in Canada, as well as the rest of the world, will increase appreciably over the next few decades, although the extent of these projected increases is still uncertain. Under these circumstances, it seemed appropriate to review the present state of our knowledge as well as the philosophy concerning radiation protection. It will be shown that high standards of safety are maintained in the nuclear power industry by the strict application of radiation protection regulations. These regulations are based on extensive consideration by international committees of the biological effects of radiation.

In this review radiation produced by the nuclear industry is placed into context with other sources of radiation in our world. Human health effects of radiation, derivation of standards and risk estimates are reviewed in this document. The implications of exposing the worker and the general population to radiation generated by nuclear power are assessed. Effects of radiation on the environment are also reviewed. Finally, gaps in our knowledge concerning radiation are identified and current research on biological effects, on environmental aspects, and on dosimetry of radiation within AECL and Canada is documented in this report.

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BIOLOGICAL EFFECTS OF IONIZING RADIATION

I. INTRODUCTION

A. Sources and Uses of Radiation

Ionizing radiation is present everywhere in the human environment. It is in fact almost impossible to find any material which does not naturally contain small amounts of radioactive materials. Over the past 40 years, we have learned how to measure small amounts of radiation very precisely and how to distinguish between different types of ionizing radiation from various sources. We know that all living organisms, including man, are exposed, and always have been exposed under natural conditions, to ionizing radiation from cosmic rays, from the earth and from the natural radioactive constituents of our body. We know too that many normal human activities which have been carried on for thousands of years may increase our natural exposures to radiation; the major increase for most persons results from the custom of living in houses (1).

Since X rays were discovered by Roentgen in 1895, radioactivity by Becquerel in 1896 and radium by the Curies in 1898, ionizing radiation has been utilized for many peaceful and constructive purposes in our society. The major uses, apart from the nuclear industry, are in the following areas:

(i) medical diagnosis and treatment

X rays are commonly used by medical doctors and dentists to assist them in their diagnoses. Radionuclides are increasingly used for similar diagnostic purposes, for example, scanning of the heart. Intense radiation beams are used by radiotherapists for the treatment of cancer.

(ii) industrial uses

X rays and gamma rays, the latter from radioactive sources, are used industrially by radiographers to gauge density and thickness of pipewalls, for example, or to examine welding and to locate leaks in a piping system.

(iii) <u>other uses</u>

X rays are currently employed to examine luggage in airports for security purposes. Radioactive materials, usually containing tritium, are used to produce luminous dials and signs. Other current applications include smoke detectors, sterilization of certain medical supplies, food preservation, plant breeding, insect control, and power for heart pacemakers, isolated weather-stations, satellites, and ships.

B. Protection Against Radiation and Other Cancer-Causing Agents

In the nuclear power industry, careful attention has been given to the potential risks as well as to the benefits of the uses of radioactive materials. Cancers produced by uncontrolled exposures to high doses of ionizing radiation (that is, X rays) were first reported in the early 1900's. Radiation is only one of many agents in our environment that can cause cancer. The fact, however, that exposure to large amounts of a combustion product, that is, chimney soot, could cause cancer was reported as early as 1775. The list of known or suspected cancer-causing agents (2) has now been extended to include more than 2,000 natural or man-made chemicals and other agents (for example, sunlight). Many of these cancer-causing agents are both natural and man-made. To quote three specific examples:

(i) Ionizing radiation is ubiquitous in the environment, as noted above, and is also produced in various human activities which are deemed useful to our society.

(ii) Benzo(a)pyrene and related polyaromatic hydrocarbons are natural products of combustion processes and can be found preserved over millions of years in ancient fossils (3); the concentrations of benzo(a)pyrene have, however, been increased appreciably in urban atmospheres as a result of increased combustion of organic fuels (4).

(iii) Dimethyl nitrosamine is a natural constituent of human blood in trace amounts (5); the same compound has in recent years been produced synthetically in large amounts as an intermediate in the production of rocket fuel (6).

In order to protect both workers and the general public against deleterious health effects of any of these agents, exposures should obviously be controlled. The degree of control achieved in the nuclear industry can be judged from one simple, but little known comparison: The risk of fatal cancers which might be caused by continuously breathing combustion products in the air of the average North American city is estimated to be 250-500 times greater than the risk of fatal cancers which might be caused from radiation by living continuously on the boundary of a 2,000 megawatt nuclear power station such as Pickering A near Toronto (7). This estimate is derived directly from the conclusions of several different scientific committees which have reviewed the cancer-causing potential of combustion products such as benzo(a)pyrene (4) and of ionizing radiation in its various forms (1). It is also useful to recognize that both of the risks involved, whether from combustion products or from radiation, do not represent more than a minute fraction of the total number of fatal cancers in our society.

Apart from uranium mining, the nuclear power industry in Canada has an outstanding history of continued safety. This safety record is due in large part to a persistent emphasis on the protection of humans against exposure to unnecessary radiation. In order to maintain a body of expertise on measuring radiation levels, on the biological effects of radiation, and on the environmental behaviour of radioactivity, research in these areas has been supported by Atomic Energy of Canada Limited at Chalk River since 1946 and at the Whiteshell Nuclear Research Establishment since 1963. These research personnel are paid by the Canadian taxpayer and are thus responsible to the Canadian taxpayer, not to any privately owned organization.

C. The Scientific Peer Review System

It may help the reader to have some appreciation of how the scientific community operates when it accepts or rejects certain facts, ideas or concepts. The following paragraphs describe briefly the peer review system and how scientists interact to arrive at either a consensus or a split in viewpoints.

Scientists usually communicate their findings to other scientists the world over by publishing papers in scientific journals. All reputable international and national scientific journals use a review system to select publications from the manuscripts or papers sent to them. In a typical instance the editors of the journal would send manuscripts to at least two scientists of internationally recognized reputation for review; if the two scientists and one of the editors of the journal agree independently on the value of the data in the manuscript, the paper would normally be accepted or rejected for publication on the basis of this initial review, frequently with a request for minor revisions. If, as frequently happens, the two scientific reviewers disagree on the merits of the manuscript, a third scientist is usually asked to review the paper. The comments of all of the reviewers are returned to the authors of the manuscript with a request to consider major revision of the paper. In general, the revised manuscript is required to go through the same review process again before it is accepted or rejected for publication in the journal. Throughout this process the identities of the reviewers are not revealed to the authors of the manuscript. Most journals carry letters to the editor which allow further discussion of controversial questions raised in published articles.

This is not the only mechanism for communications among scientists. Results are discussed at conferences and published proceedings normally give a report of what was said by each scientist. Various newsletters are also available in which short reports of new developments are given. These reports are not reviewed by other scientists before publication. However, the scientific journals with their "peer review" system continue to represent the reliable core of all scientific reporting. Research scientists from Atomic Energy of Canada Limited operate within this system as do all other reputable scientists. The purpose of the reports in these journals is to provide reliable scientific information and interpretation. In the field of protection against ionizing radiation this information is periodically assessed by the various national and international scientific committees (1 - 16) appointed for this purpose. The results of these assessments are described in greater detail in the remainder of this report.

The system of evaluation and publication of scientific results is by no means universal. Throughout this document reference will be made to AECL reports. These reports, although not subjected to external refereeing, are reviewed within AECL. Documentation via AECL reports is used when findings are preliminary, when existing scientific results are being re-assessed or when there is a specific need for AECL to produce a report such as this document, which was prepared as a contribution to public understanding of the biological effects of ionizing radiation.

Most reputable scientists will be prepared to offer an opinion only after they have examined documentation that has been through the peer review system; newspaper reports or transcripts of hearings are often inaccurate and normally do not report sufficient technical detail.

Not all scientists are in agreement on any topic; open discussion of the meaning of research results is in fact essential to the development of science. When the news media report apparent disagreement of knowledgeable scientists on a technical issue such as the biological effects of radiation the non-expert cannot decide who is right; indeed, there is no easy way to tell how 'expert' the expert is. The non-specialist is apt to conclude that the scientific community is split right down the middle on the matter. This impression is due to the interest in reporting controversies and is not accurate. To quote from a recent report (17) on the Three Mile Island accident: "It should be noted that there exist a few members of the scientific community who believe the risk factors may be as much as two to ten times greater than the estimate of the 1972 BEIR [Biological Effects of Ionizing Radiation] report. There also is a minority of the scientific community who believe that the estimates in the 1972 BEIR report are two to ten times larger than they should be for low doses of gamma and beta radiation". This quotation represents a more accurate assessment of the scientific situation; the majority of the scientific community is not in fact split down the middle on this question. The risk assessments used in the present document will be those on which the <u>majority of scientists on national and international committees have agreed</u> (see Appendix 1).

II. HUMAN HEALTH EFFECTS

A. Basic Concepts in Radiation Protection

As mentioned previously, ionizing radiation has always existed in nature in the form of radiations from naturally occurring radioactive materials and as cosmic radiation from outer space and from the sun. Following the discovery of X rays by Roentgen in 1895 (18), the potential for human exposure to large amounts of ionizing radiation increased tremendously.

Within weeks of the discovery of X radiation and the recognition and application of some of its properties, there appeared the first evidence of its damaging and destructive powers. Early workers with X rays discovered that the radiation could cause erythema (reddening) of the skin and if the exposure was large enough, complete destruction of tissue (19,20). The destructive capability of radiation was almost immediately applied to the treatment of malignant disease. It was also recognized that ionizing radiation could itself cause malignancies, the first case, reported in 1902, being that of skin cancer contracted by a factory technician who routinely checked the operation of X-ray sets by radiographing his hand.

However, for doses producing moderate radiation damage such as reddening of the skin, it was found that there was apparent recovery, and it was considered, in analogy with chemical poisons, that below a certain dose X rays could be 'tolerated' in the sense that no detectable harm would result. Accordingly, the first approach to radiation protection was to establish a tolerance dose chosen to be a small fraction of that known to yield skin reddening.

Unfortunately, the serious harm that could result from chronic exposures to radiation was at first not recognized, mainly because of the long latency periods involved, about 10 years for leukemia and about 25 years or more for other cancers, but also because no instruments were available to measure radiation levels accurately. Altogether, very little was known about the characteristics of radiations and their interaction with cells. In 1920 attention was drawn to a special kind of radiation hazard with the appearance of aplastic anemia (lack of production of blood cells) among those who had worked with military medical services but it was not until the next decade that delayed effects, as understood today, were appreciated (21).

Committees were established in several countries during the early 1920's to consider the problems and in 1928 two committees were formed under the sponsorship of the International Congress of Radiology, the International Committee on X-ray and Radium Protection, and the International X-Ray Unit Committee. The latter committee established the first internationally accepted unit for exposure, the roentgen (R), named after the discoverer of X rays. The protection committee began the task of making recommendations regarding the safe handling of X rays and radium, the only significant man-made sources of ionizing radiation at the time.

Both committees were reorganized in 1950; the Protection Committee is now known as the International Commission on Radiological Protection (ICRP) and the Units Committee as the International Commission on Radiation Units and Measurements (ICRU). Each commission has thirteen members who are scientists and physicians working in radiation therapy, radiology, radiation physics and biology; at the present time members of the two commissions come from twelve different countries. In addition, each commission operates a system of committees and task groups which prepare the material published by the ICRP and by the ICRU.

Because these commissions operate independently of national authorities, control their own programs of work and choose their members as individual experts from the international community of scientists and medical practitioners, their decisions and recommendations are held in extremely high regard and indeed have formed the basis of radiation protection practice throughout much of the world (see Appendix 1).

The first basis of radiation protection rested upon the concept of a tolerance dose, which implies that below a certain level of exposure there are no ill effects to those exposed. As knowledge accumulated, both from research into the effects of radiation upon small animals and other living species and from the observation of late effects of radiation in those who had not otherwise been injured in any recognizable manner, the position developed that there is probably no level of radiation exposure that is entirely without risk. As the amount of exposure decreases, the risk of injury decreases, probably in direct proportion. With the development of this viewpoint on radiation exposure, it was clearly improper to think in terms of tolerance to radiation or "tolerance doses" that could be received by workers and by the public at large from the activities of others.

The concept of "tolerance doses" was eventually abandoned in the 1950's and replaced by the present attitude which is that the use of radiation should be so ordered that the total benefits to the community outweigh the detriment. Not only must these net benefits be maintained, but in effect, the goal should be exceeded by as great a margin as the prosperity of the society can support. This second requirement is often referred to as the ALARA principle, the acronym ALARA being derived from the statement that "all exposures shall be kept <u>a</u>s <u>l</u>ow <u>a</u>s <u>r</u>easonably <u>a</u>chievable, economic and social factors being taken into account". To summarize, the main features of the ICRP system of dose limitation are as follows:

"a) no practice shall be adopted unless its introduction produces a positive net benefit;

b) all exposures shall be kept as low as reasonably achievable, economical and social factors being taken into account; and

c) the dose equivalent to individuals shall not exceed the limits recommended for the appropriate circumstances by the Commission" (22).

B. Types of Radiation

Ionizing radiation consists of either electromagnetic waves or swiftly moving particles.

In the former category belong X rays (produced artificially in high voltage apparatus) and gamma rays (emitted by most radioactive materials either of natural origin or produced artificially in nuclear reactors or charged particle accelerators such as cyclotrons). In the latter category, there are alpha particles, beta particles and neutrons. Alpha and beta particles are electrically charged particles emitted by radioactive materials; neutrons are neutral particles produced in various nuclear "reactions", notably those taking place in reactors and accelerators. Ionizing radiations are so called because they have the ability to separate neutral atoms into negatively charged free electrons and positively charged ions. This process of ionization may occur in a gas, a liquid or a solid providing a very important means for measurement of quantities of ionizing radiation. Ionizing radiation is detected and measured using devices that respond to the direct or indirect effects of the ionization that is produced in them. Various detectors are available that are capable of distinguishing between the different radiations, and their sensitivity is adequate for radiation protection purposes.

In regard to human health effects, the ionization occurring within the tissues of the body may cause the destruction or modification of individual cells. Cellular destruction may cause death if sufficiently widespread in the body or it may have no lasting effect; at a sufficient level in a local area of the body, it leaves behind evidence in the form of scars. Cell killing is exploited in cancer treatment where the objective is to get rid of abnormally growing tissue.

The ability of a given radiation dose to damage or modify cells is influenced by the type of ionizing radiation, in particular by the rate at which it loses energy in passing through tissue. Alpha particles, which are comparatively slowly moving helium nuclei, are heavily ionizing. Thus they lose energy very rapidly -- a sheet of paper stops them -- and they are described as a high linear energy transfer (LET) radiation. On the other hand beta rays (which are swiftly moving electrons) are absorbed much more slowly and may penetrate several millimetres of tissue; beta rays are lightly ionizing and have a low LET. Neutrons interact with tissue mostly by the production of heavily ionizing recoil protons having a high LET; gamma radiation transfers its energy to electrons having a low LET.

Amounts of ionizing radiation are measured in terms of the energy absorbed per unit mass of the tissue which has been exposed. The new unit of energy absorption in the International System (SI) of units is the joule per kilogram and this unit has been given (23) the special name gray (Gy). Before SI units were adopted by the Metric Commission, the unit of radiation dose was the rad; one gray equals one hundred rads. In the past where most exposures to people were from X-ray sets, the amount of radiation was measured in terms of the ionization produced in air at the surface of the tissue being exposed. The unit of radiation exposure was named the roentgen (R) and an exposure of one R of high energy X radiation resulted in a dose to the exposed tissue of about one rad (or 0.01 Gy).

In radiation protection, the quantity of interest is the biologically effective dose received by an exposed person. Biologically effective dose varies with the degree of ionization produced by a particular radiation exposure. Sources of radiation having a high LET (alpha particles and neutrons) are more effective than those with a low LET (X or gamma radiation). So that all radiation exposures, regardless of source, may be evaluated on a common scale the quantity known as "dose equivalent" was defined. The dose equivalent is the absorbed dose (in gray or rad) multiplied by a factor, characteristic of the radiation, known as the quality factor (QF). If the absorbed dose is expressed in SI units the dose equivalent equation is:

Gy x QF = sievert (Sv).

Using the rad unit the dose equivalent equation is:

rad x QF = rem.

As 1 Gy = 100 rad, it will be readily seen that 1 Sv = 100 rem.

For radiation protection purposes, quality factors have been defined for the different types of radiation. X rays, gamma rays and electrons (including beta particles) have a QF value of 1. Fast neutrons and protons have a quality factor of 10 and alpha particles have a quality factor of 20.

In occupational exposure to radiation, exposure may be received from a variety of sources of different types and energies. A dose of 1 rad of gamma radiation and 0.1 rad of fast neutrons would thus be evaluated as a dose equivalent of 1 + (10 x 0.1) = 2 rem.

Throughout the remainder of this text, doses will usually be expressed simply in rad or rem because these are the conventional units to which most persons are still accustomed. Another unit used in Section C will be the millirem, which is a thousandth part of the rem (1 rem = 1000 millirem).

The above units are applicable to radiation exposures of the whole body or of any given organ in the body, except in the case of radiation exposures resulting from the inhalation of radon daughters (radioactive decay products of radon) into the lungs. There is no direct method of measuring these latter exposures in rem or millirem, and there is as yet no general agreement on the methods by which doses could be theoretically calculated in rem. Pending agreement on appropriate conversion factors, radiation exposures resulting from the inhalation of radon daughters are therefore estimated in working level months or WLM. The working level (WL) is defined in terms of the concentration of radon daughters in the air; the working level month (WLM) is equivalent to inhalation for 170 hours by a working adult of air containing radon daughters in equilibrium with 3.7 becquerels of radon per litre. The risk of fatal cancer after exposure to one WLM is approximately equivalent to the risk of fatal cancer caused by exposure of the whole body to one to four rem (1000 to 4000 millirem) of X or gamma radiation. However, inhalation of radon daughters does not produce any appreciable numbers of non-fatal cancers or genetic defects, in contrast to whole body irradiation;the total health hazard of exposure to one WLM might therefore be more closely approximated to the total health hazard of about 0.4 to 1.6 rem of X or gamma radiation.

C. Sources of Radiation

1. Natural Radiation

In most tissues of the body, the average radiation exposure from natural sources is estimated to be about 100 millirem per year (100 millirem = 0.1 rem = 1 millisievert) in most inhabited parts of the world (Table 1). About 30% of this is due to cosmic radiation, about 30% to radiation from potassium, uranium daughters and thorium daughters in the soil, and about 40% to the natural radioactive constituents of the body (12).

An abbreviated list of these natural radioactive elements in the body is given in Table 2. About half the total of our normal radiation exposure from internal radionuclides derives from potassium-40, a primordial radionuclide which is concentrated in all living organisms since potassium is essential for the function of living cells. Smaller contributions derive from sodium-22, carbon-14 and tritium (Table 2), all of which are natural components of our body and are formed continuously in the biosphere as a result of cosmic radiation.

Our natural exposure to radiation varies considerably depending upon altitude and the amount of radioactivity in the soil in different areas of the world (1b,12). Although the average is about 100 millirem per year (Table 1), the exposure varies from about 85 to 250 millirem per year in different parts of North America. In certain localized areas in India, Brazil and other countries, several thousands of inhabitants are exposed to natural background radiation levels in excess of 1,000 millirem per year due to high levels of radioactivity in the soil (1c).

The values given in Table 2 refer specifically to the gonads, where radiation may produce genetic defects, and to bone marrow, where radiation may induce leukemia.

The lung (Table 1) is exposed to much higher radiation levels as a result of the inhalation of radon daughters from natural sources. Since most of the lung exposures are due to the custom of living in houses (1d), this topic will be considered in more detail in the next section.

Table 1

Summary of the major sources of radiation exposure for the average member of the general public in North America

Source of radiation exposure	Average radiation dose in millirem per year*	Potential harm to society: % of all fatal cancers that occur normally	Potential harm to society: % of all genetic defects that occur normally
Radon daughters in the air (primarily indoor exposures)	[0.165 WLM]**	1-3	~ 0.0
Background radiation			
- cosmic	30		
- terrestrial	30	0.5	0.5
- internal	40		
Medical diagnoses	100***	0.5	0.1
Fallout (1979 levels)	4***	0.02	0.005
Nuclear power			
- USA 1975	0.02	0.0001	0.001
- boundary of Pickering reactor	1	0.005	0.005
- future maximum	≤3	≤0.015	≤0.015
All other man-made sources	≤3	≤0.015	≤0.015

* All radiation exposures except those from radon daughters represent average whole body doses. Radiation exposures resulting from alpha-particles are multiplied by a quality factor of 20 to convert doses given in millirad per year (1a,1h) into millirem per year.

** Radiation exposures of bronchial epithelium of the lung only; inhalation of radon daughters has little influence on total radiation doses to other tissues of the body. Radon daughter exposures are expressed in WLM for reasons explained in the text (see p.11). Data are derived from reference (1h) and may not be directly applicable to Canada.

***The genetically significant component of the average radiation dose from medical X-rays is estimated to be about 20 millirem per year and from fallout is 1 millirem per year.

≤Signifies "less than or equal to".
~Signifies "approximately".

Table 2

Average radiation exposures from natural radioactive constituents of the body

Radionuclide	Half-life in years	Radiation dose in millirem per year*	
		Bone marrow	Gonads
Potassium-40 (primordial)	1.3×10^9	27	15
Uranium-238 and daughter products (primordial)	4.5×10^9	19	15
Thorium-232 and daughter products (primordial)	$14. \times 10^9$	7	1.4
Rubidium-87 (primordial)	$60. \times 10^9$	0.4	0.8
Carbon-14** (cosmogenic)	5700	2.2	0.5
Sodium-22 (cosmogenic)	2.6	0.002	0.02
Tritium** (cosmogenic)	12	0.001	0.001

* Radiation exposures from alpha particles are multiplied by a quality factor of 20 to convert doses in millirad per year (1a) into millirem per year.

**Concentrations of carbon-14 and tritium in the biosphere have been increased as a result of atmospheric bomb tests around 1960. Carbon-14 levels are currently increased about 30% while tritium concentrations are currently increased about tenfold.

2. Technological Enhancement of Natural Radiation Exposures

Many human activities result in increased exposure to radiation from natural sources. This effect is called the technological enhancement of radiation exposures to distinguish it from increased exposures resulting from the deliberate and planned use of man-made sources of ionizing radiation (1e).

In most cases, the mere fact of living in some brick or stone building constitutes a technological enhancement of radiation exposure (1e). On the average, absorbed dose rates from external radiation (i.e., cosmic plus terrestrial) are lower than those outdoors for persons in a wooden building and higher than those outdoors for persons in a brick or masonry building (1f). Moving from a wooden to a masonry building would on the average increase radiation exposures to the whole body by about 15 millirem per year (1g). (This is roughly the same increase that occurs as a result of the higher altitude if one moves from sea level to Calgary.) This value will of course vary considerably depending upon the radioactivity of the masonry used in the construction of the building.

The most important increment in radiation exposures resulting from living in houses is caused by the inhalation of radon and its daughter products into the lungs (Table 1). Radon-222 is a chemically inert gas that is part of the decay chain of natural uranium-238. Radon diffuses out of the ground and out of many building materials, and is therefore more abundant in the atmosphere than any of its precursors in the uranium decay chain (1d). The average radiation exposure to the bronchial epithelium of the lung is thought to be about 0.165 WLM per year in most western countries (Table 3); detailed studies on radon daughter exposures in Canada have not yet been completed* but it seems reasonable to expect that the average for

* Preliminary data has been published by R.G. McGregor, P. Vasudev, E.G. Lētourneau, R.S. McCullough, F.A. Prantl and H. Taniguchi (Health Physics, 39, pp. 285-289, 1980).

Table 3

Average radiation exposures of the bronchial epithelium

Source of radiation exposure	Average radiation dose in millirem per year*
Cosmic rays	31
Terrestrial	32
Inhalation of radon daughters	
- 5 hours per day outdoors	[0.005 WLM]
- 19 hours per day indoors	[0.16 WLM]
Potassium-40 and other internal radionuclides	25
Total	88 millirem plus 0.165 WLM

*Radiation exposures from alpha particles are multiplied by a quality factor of 20 to convert doses in millirad per year (1a,1h) into millirems per year. Radon daughter exposures are expressed in terms of WLM rather than millirem for reasons explained in the text.

persons living in wood-frame houses is somewhat less than 0.165 WLM per year. Nearly all of this radiation exposure of the bronchial epithelium results from inhalation of the radon daughters which accumulate inside enclosed spaces such as our houses and public buildings (Table 3).

The biological consequences of these technologically enhanced radiation exposures of the lungs are still imperfectly understood. If the risk estimates for uranium miners given in the 1977 report of the United Nations Scientific Committee (1i) can be applied to members of the general public, it would appear that as much as 1-3% of fatal cancers in North America at present might be due to inhalation of radon daughters (Table 1), as compared with a value of about 0.5% caused by the natural radiation exposures of all other tissues in our body (7,24).

Compared to the effects that result from living in houses, most of the technologically enhanced exposure to natural radiation is relatively small. Approximate estimates of the radiation doses resulting from various activities are listed in Table 4. The increases in exposure will, of course, vary considerably from one individual to another. However, the average increment in natural radiation dose to the population of North America that results from all of these other human activities (Table 4) is currently estimated to be a small fraction of the natural radiation levels to which we are all exposed.

3. <u>Man-Made Radiation</u>

For the average person in North America, the major increment in average radiation exposures resulting from the deliberate use of man-made sources is due to the application of X rays for medical and dental diagnoses (Table 5). Again, the increases in exposure will vary considerably from one individual to another, but the average increment due to this particular application of ionizing radiation (Table 1) was estimated to be about 100 millirem per year in the USA in 1970 (1j,12). Despite advances that have been made in reducing exposures for a particular type of diagnosis, there is no evidence

Table 4

Radiation exposures to average member of the general public in North America resulting from various human activities

Activity	Average radiation dose in millirem per year	Reference
One jet flight per year Washington to San Francisco return	3.	(1n)
Living within 500 km of a 1000 megawatt coal-fired power station	0.1	(1o)
Use of phosphate rock in U.S.A.		
- for fertilizer	0.0004	(1p)
- as phosphogypsum for building material	0.2	
Use of radioactive materials in luminous dials, signs, smoke detectors, ceramics, etc.	1.	(1)
Use of electronic devices such as television	1.	(1q)

Table 5

Average bone marrow doses resulting from various X-ray examinations for medical diagnoses (data for USA, 1970)

Type of examination	Radiation dose in _millirem_*
Barium enema	875
Pelvimetry	595
Barium meal	535*
Lumbar spine	347
Dorsal spine	247
Abdomen	147
Ribs and sternum	143
Head	78
Whole chest	10

*All values are taken directly from reference 1r. The values will of course vary somewhat from one clinic to another. Skin doses as high as 90,000 millirem have been observed recently in Canada for the barium meal X-ray examination when proper procedures for minimizing radiation exposures were not followed (30).

to indicate that the total average radiation exposure is decreasing. In fact, the use of radioactive pharmaceuticals in nuclear medicine is increasing rapidly and may add as much as 20 millirem per year average to the 100 millirem average from diagnostic X rays (12). Average medical diagnostic exposures in Canada are not known as yet but are believed to be similar to those in the USA. Values in Sweden are similar to those in the USA; average medical exposures in the UK are smaller and those in Japan are somewhat larger than in the USA (1j). Average medical exposures are of course much smaller in those countries that are less technologically developed.

The use of ionizing radiation for cancer therapy is not normally included under medical radiation exposures of the general public, because this procedure is restricted to a small percentage of the population and because it is so obviously of potential benefit to the particular individuals being treated who might not survive for long in the absence of treatment.

Fallout from atmospheric bomb tests carried out around 1960 has raised natural tritium levels in drinking water markedly (see footnote to Table 2) and has also resulted in measurable increases in carbon-14 as well as in certain unusual radionuclides in our environment (1k). The average radiation exposures resulting from these bomb tests reached values approaching 10 millirem per year (i.e., a 10% increase in natural radiation levels) in the early 1960's and are now estimated to have dropped to about 1-4 millirem per year (Table 1).

Other human activities which result in minor increases in exposure to radiation from man-made sources include the use of radioactive materials in luminous dials and signs (1ℓ) and the use of electronic devices such as colour television receivers (Table 4). Exposures from these sources have decreased over the past decade. The current increments in our radiation exposure from all of these particular sources taken together probably do not exceed 2 to 3 millirem per year or 3% of the average natural radiation levels (Table 1).

Average radiation exposures from the nuclear power program are also very low (Table 1) but will be considered in detail in section F.

4. Occupational Exposures

In countries such as Canada, France, Germany, Sweden, the UK and the USA, between 1.5 and 4 of every thousand persons in the country are involved in occupations which entail an increased exposure to ionizing radiation (1m). The number involved in each of the various categories listed in Table 6 varies from one country to another but medical workers consistently form the largest single group, roughly half of all occupationally exposed workers (1m). The average whole body radiation exposure of all the occupational groups in Table 6 is currently well below the maximum limit (5 rem or 5,000 mrem whole body radiation exposure per year) that has been recommended by the ICRP (22).

Because the number of people involved is small, the total potential harm to the health of the community as a whole is also relatively small. (For example, if 3 persons out of every thousand were occupationally exposed to an average increase of, let us say, 333 millirem per year, the potential harm to the whole population would only amount to that produced by an average exposure of 1 millirem per year.) However, the annual radiation exposures of the persons in these particular groups can be several times (Table 6) the normal exposures from natural radiation sources or from medical X rays (Table 1). Uranium miners (and indeed certain other underground miners) were for many years exposed to concentrations of radon daughters (26,27,29) well in excess of those recommended by the ICRP in 1959 (28). This particular situation has been improved in recent years, although uranium mining, like any other form of underground mining, is still a relatively hazardous occupation.

Table 6

Radiation exposures (additional to background) resulting from selected occupations

Occupation	Average radiation exposures per year (data for various western countries)	
	Whole body (millirem)	Bronchial epithelium only (WLM)
Uranium miners	1000	1-4
Underground miners (non-uranium miners)	(not available but low)	0.1-4
Nuclear reactor workers	600-1000	-
Tritium luminisers (dial painters)	400-1500	-
Nuclear research and development	100-750	-
Aircrew of jet aircraft	250-500	-
Industrial radiographers	40-600	-
Medical workers (radiology, therapy, nuclear medicine)	10-500	-

D. Effects of Radiation on Humans

1. Early and Acute Effects

Acute doses of radiation, that is, large doses delivered over a short period of time, produce well-defined clinical effects in animals and humans. These effects appear in a relatively short time, from 1 hour to 2 months (31). Acute effects are also characterized by having a threshold, that is, minimum doses are required to produce such effects. If the same large dose is administered chronically, that is, over a longer time period, the clinical effects are either greatly diminished or absent.

The prominent clinical features of acute effects have been observed as a result of therapeutic uses of X rays and radium as well as studies at Hiroshima and Nagasaki and are identical to those observed in laboratory studies of other mammals. Doses above 600 rad (in discussing acute effects dose is expressed in rad and not in rem) delivered to a large part of the body are lethal for humans as well as other mammals. Between 400-500 rad is believed to be the LD_{50} for humans; or in other words, in this dose range 50% of exposed humans would die. Radiation exposures in the range of 400 to 1000 rad result in the destruction of bone marrow cells and death results in 1 to 2 months. In the dose range of 1000 to 5000 rads the gastro-intestinal tract is damaged severely, with death occurring in about 2 weeks. Doses over 5000 rad damage the central nervous system and death occurs in 1 to 2 days (31).

Acute doses above 100 rad, but below the LD_{50}, need not be fatal but persons exposed in this dose range may suffer from acute radiation sickness (32). This syndrome can be related to a form of shock where after 2 to 5 hours the person has nausea, headache, loss of appetite, vomiting, diarrhea, and prostration. After the early phase of shock persons may show, within a week or two, a variety of effects depending on different organ damage. There may be changes in the amounts of different blood cells, emaciation, widespread hemorrhages, generalized infection and loss of hair. Gradual recovery will finally take place provided that the exposed person is protected from infectious diseases.

Exposure of skin to doses of 600 to 1000 rad causes reddening. Still higher doses result in burns.

Sterility can also be caused by high doses of radiation. In females, the impairment of fertility varies with age. At 40 years a dose of about 300 rad can cause permanent sterility, accompanied by a menopause. Such a dose in a younger woman would produce only temporary impairment of fertility. A dose of 25 rad to the male gonads can depress the sperm count, but more than 250 rad would be required to cause permanent sterility (22).

A variety of acute effects ranging from burns to deaths have of course occurred as a result of the atomic bombing of Hiroshima and Nagasaki. Since 1945 nuclear accidents associated with the USA military program have resulted in 8 radiation-caused deaths (33); all of these occurred before 1969. Acute exposures are usually avoided by strict adherence to safety procedures and no fatality from such an exposure has ever occurred in the Canadian nuclear industry. Since 1944 at Chalk River, there has occurred one serious burn of the fingers when a worker picked up a heavily irradiated capsule that had dropped from the reactor core. Two other workers were found to have reddening of a small area of their skin because of irradiation from tiny particles of radioactive materials. Skin burns of the fingers of two other workers resulted from overexposure of the skin to soft X rays. These two were exposed in a laboratory under conditions which were similar to those which have caused many similar injuries in non-nuclear programs.

2. Delayed and Chronic Effects

Delayed and chronic effects can occur years after the exposures have occurred (10 to 40 years later). These late effects are similar to effects that can occur spontaneously or from causes other than radiation. The probability of certain late effects appearing is conservatively taken to be proportional to the dose without a threshold. Because of this hypothesis, late effects are assumed to occur even at low doses. Effects that appear later in the irradiated individual are referred to as somatic while those occurring in the descendants of irradiated persons are termed hereditary or genetic. Examples of late somatic effects are cancers of all types including leukemia; hereditary damage also covers a wide spectrum of defects. Almost any organ in the body can be affected as a result of a hereditary defect. Some of these genetic changes may be less serious, such as colour blindness, while others are more serious and require medical attention at some time during the person's life. Hereditary diseases afflict about 10% of live-born children and the cause of these defects is usually unknown. For this reason these diseases are said to occur spontaneously. Some common examples of hereditary effects according to different organs are as follows:

skin	albinism, ichthyosis (fish skin)
bone	cleft palate, dwarfs
lips	harelip
heart	blue babies
brain	mental retardation, microcephaly (small head), Huntington chorea
blood	hemophilia (bleeder's disease)
ears	deaf-mutism, hereditary deafness in old age
eyes	cataract, myopia (nearsightedness)
fingers, toes	polydactylism (extra fingers or toes)
hair	hypertrichosis (excess hair on face)
gonads	hermaphrodite

Some of the above conditions, for example, cleft palate, harelip, blue babies, mental retardation, etc., have multiple causes with a strong environmental component, the hereditary aspect being small. In certain other conditions, for example, Down syndrome, more than one organ is affected.

It should be mentioned that some late somatic effects do not appear unless a threshold dose is exceeded. Examples of these kinds of effects are cataract of the lens, cell depletion in bone marrow, and vascular changes in connective tissue and blood vessels. Since connective tissue and blood vessels are widespread throughout the body, almost any organ can be thus affected at high doses above the threshhold (32).

Late somatic effects of radiation have been observed in the survivors from Hiroshima and Nagasaki; in patients who have received radiation treatment for disease of the spine (ankylosing spondylitis) and in patients who received repeated fluoroscopic examinations of the chest in the treatment of tuberculosis.

Genetic changes as a result of irradiation of the sperm or egg have not been observed in irradiated human populations. Some pregnant women exposed to high radiation doses at Hiroshima and Nagasaki delivered abnormal babies but this was caused by direct irradiation of the developing fetus which is regarded as a teratogenic (somatic) effect, not a true genetic defect. As a result, most of our information on hereditary defects and corresponding risk estimates comes from experimental work on mice irradiated at high doses; measurements are made of frequencies of changes in coat colours and of skeletal deformities in the resulting offspring.

All the international and national committees that have considered the hazards of exposure to ionizing radiation have agreed that the biological effects of exposures to doses of 5 rem (5000 millirem) per year or less are restricted to two categories:

a) induction of cancers (including leukemia) in the exposed person;
b) induction of genetic defects in the descendants of the exposed person.

It is also generally agreed that doses of 5 rem per year or less will not produce the following biological effects (which can be produced by exposure to much higher doses at a higher dose rate):

c) cataracts
d) vascular changes and tissue scarring
e) decreased resistance to infectious diseases
f) reddening of the skin and burns
g) nausea, headache, etc.
h) greying and/or loss of hair
i) temporary or permanent sterility
j) interference with normal development of the embryo or fetus.

The risk estimates which are of any concern at low levels of exposure (up to 5 rem per year) are therefore those for the induction of cancers in exposed persons and of genetic defects in their descendants. These risk estimates are considered in the next section.

There is no evidence for non-specific life shortening (11,12). Life shortening is accounted for by the cancers that terminate life prematurely. For this reason further discussion of this topic will not be undertaken.

Genetic defects with harmful effects upon the well-being of other kinds of organisms living under natural conditions are largely eliminated by the process of natural selection and become a problem only in human societies, where essentially all of the progeny are kept alive.

The statistical problems an investigator must deal with in determining late effects of radiation in experimental animals and humans are described in greater detail in Appendix 2.

E. Risk Estimates

Based on the studies of late effects observed in the survivors of Hiroshima and Nagasaki and in medically irradiated patients who have been irradiated at high doses and high dose rates, estimates have been made for the probability of these effects occurring at lower doses. To estimate the radiation risks it is considered prudent to assume that the likelihood of an induced cancer or hereditary defect varies in direct proportion with the dose, down to zero dose, and that where large numbers of individuals are exposed to low doses the numbers of possible casualties will be proportional to the sum of various individual doses. Current estimates of risk from exposures to radiation are in the vicinity of:

a) 1×10^{-4} fatal cancers per rem, for example, one fatal cancer induced if 10,000 persons are each exposed to 1 rem of whole-body radiation over the course of a lifetime,
b) a similar or perhaps somewhat larger number of non-fatal, curable cancers (for example, most thyroid cancers are not fatal), and
c) 2×10^{-4} cases per rem of serious hereditary disease in subsequent generations, resulting from exposures of the gonads prior to reproduction. The values given in Table 7 are obtained by correcting the figure of 2×10^{-4} for the average reproductive age of the general population.

The risk estimates given in three recent committee reports are summarized in Table 7. The reports of the two international committees all agree that their estimates of the risks of cancer induction are maximum values and that the actual risks at low levels of X or gamma radiation may well be considerably smaller. This potential safety factor is ignored in the subsequent calculations given below, as well as in Table 1. The most recent BEIR committee (12) report "used a linear-quadratic model that is felt to be consistent with epidemiological and radiobiological data, in preference to more extreme dose-response models, such as the linear and the pure quadratic." The implications of the linear-quadratic model are identical to those of the linear model at low doses and low dose rates of radiation, i.e., the radiation hazard is directly proportional to total accumulated dose (at least up to total doses of say 20 rads, above which deviations from linearity may be observed when the dose rate is high but not when the dose rate is low). This report (12) has thus provided a probable value for carcinogenic risks of low levels of radiation plus an "envelope" of values for risk estimates based on other models for dose-response relationships. The minimum predicted values approach zero in the case of X, gamma or beta rays while the maximum probable values are about two-fold higher than the most probable value (Table 7). The most probable values are in turn very similar to those proposed by the international committees.

The risks of fatal and non-fatal cancers given by United Nations Committee on the Effects of Atomic Radiation (UNSCEAR) and ICRP (Table 7) were calculated using an "absolute risk" model. The National Academy Sciences Committee on the Biological Effects of Ionizing Radiation (BEIR) used both the "absolute risk" model and the "relative risk" model in its 1972 and 1980 reports (Table 7); as noted above, the most probable values calculated by BEIR Committee (12) agree closely with those given by UNSCEAR and ICRP. The absolute risk model assumes that exposure of a given number of persons to a given radiation dose will eventually produce a definite number of cancers on the average, regardless of the country or the natural incidence of cancer in that country. The relative risk model assumes that radiation will produce a certain percentage increase in the normal cancer incidence, which can vary appreciably from one country to another. The relative risk model predicts relatively fewer cancers early in life and relatively more cancers late in life; the actual loss of life expectancy in days is essentially identical with both models (7,34).

The estimates of risk of fatal lung cancers caused by inhalation of radon daughters are still under discussion in the scientific literature. Risk estimates vary from about 0.5×10^{-4} to 12×10^{-4} fatal cancers per WLM (29,35,36). The 1972 BEIR report did not estimate these risks directly, although a value of 1×10^{-4} to 4.5×10^{-4} fatal cancers per WLM can be derived from this

Table 7

Recent estimates of the *maximum* probable health effects resulting from exposure of the general public to low level radiation

Source of Estimate	Probable effects of exposing 10,000 persons to 1 rem each			
	Number of fatal cancers induced	Number of non-fatal cancers induced	Number of genetic defects in first generation*	Number of genetic defects in all generations**
UNSCEAR 1977 (1)	1	1	0.24	0.74
ICRP 1977 (22)	1.25	1.25	-	0.8
BEIR 1980 (12)	0.8 (0.1-1.7) <u>or</u> 2.3 (0.3-5.0)***	similar to values for fatal cancers	0.02-0.3	0.24-4.4

* These particular values are corrected for genetically significant doses. For the general public it is assumed that 40% of the population is less than age 30, the average age of humans at the time of reproduction. The values for radiation workers who commence work at age 18 would, on the average, be about one-half or about 25%.

** The number of genetic defects gives the total harm expressed in all generations resulting from a single dose of one rem. If the population is exposed to a repeated dose of one rem per year or per generation, then equilibrium will be established and the number of genetic defects will be the resulting harm per year or per generation respectively.

***Values based on the relative risk model; all other values for cancer induction are based on the absolute risk model as described in the text.

report (11). The 1977 UNSCEAR report (1) suggests a value of 2×10^{-4} to 4.5×10^{-4} fatal cancers per WLM for uranium miners, of whom a majority are cigarette smokers: in the past it has been assumed that lower values would apply for non-smokers but this is not certain. Pending further scientific resolution on the current discussion, the best risk estimates for radon daughters can be taken to be approximately $1\text{-}4\times10^{-4}$ fatal cancers per WLM.

The inhalation of radon daughters does not result in any appreciable increase in the radiation exposures of tissues other than the bronchial epithelium of the lung. Thus, the risk of non-fatal cancers or genetic defects resulting from this source can be taken as very close to zero. Excess lung cancers have been reported in uranium miners in Czechoslovakia, in USA and in Canada, who were exposed to radon daughter concentrations much above those presently allowed (1). The risk estimates for inhalation of radon daughters are based on these studies.

For the remainder of the nuclear fuel cyle there is no good evidence that late somatic effects are occurring in occupationally exposed workers; the doses received by these workers, at or below the maximum permissible limits, are such that the predicted risks are low, and the epidemiological investigations to date are not sensitive enough to detect these small effects. There is still some controversy about the Hanford, Windscale and Portsmouth studies (7,37-40). It would appear that the conclusions on the Portsmouth workers (38) have been premature* and the methodology used by Najarian and Colton has been criticized (41). Most scientists are agreed that the data of the Hanford and Windscale workers do not show an excess of total fatal cancers or leukemias when compared to the expected incidence in control population matched for age and sex. Indeed, comparisons of these groups indicate that radiation workers show a lower incidence from all causes of death, including cancers, than the general population (Figures 1 and 2). Thus radiation workers are healthier than the general public and this observation is often referred to as the "healthy worker" effect. This latter effect is thought to be due to the selection of relatively healthy persons at the time of employment and to the enforcement of safety programs.

* Robert A. Rinsky et al, Lancet, 1, pp. 231-235, 1981 did not find an excess due to leukemia or any other cause.

FIGURE 1

RELATIVE INCIDENCE OF DEATHS FROM ALL CAUSES FOR EMPLOYEES AT NUCLEAR FACILITIES

(ACTUAL NUMBERS OF DEATHS ARE INDICATED IN EACH RECTANGLE)

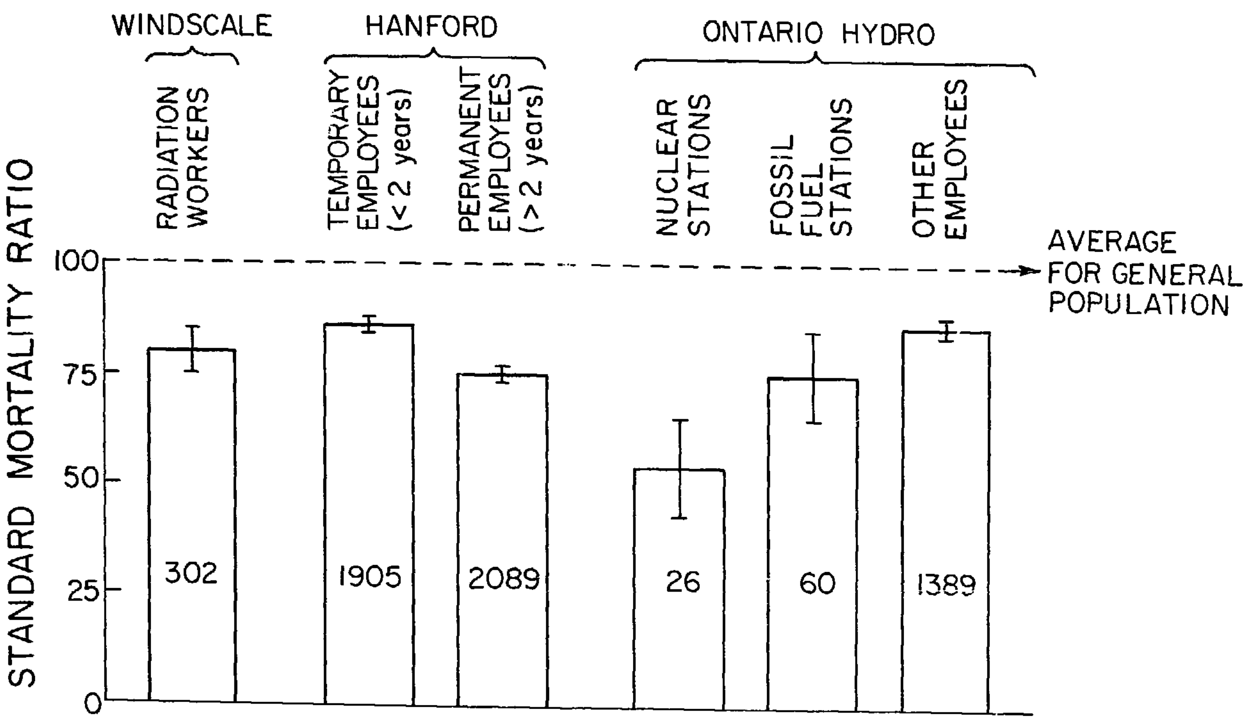
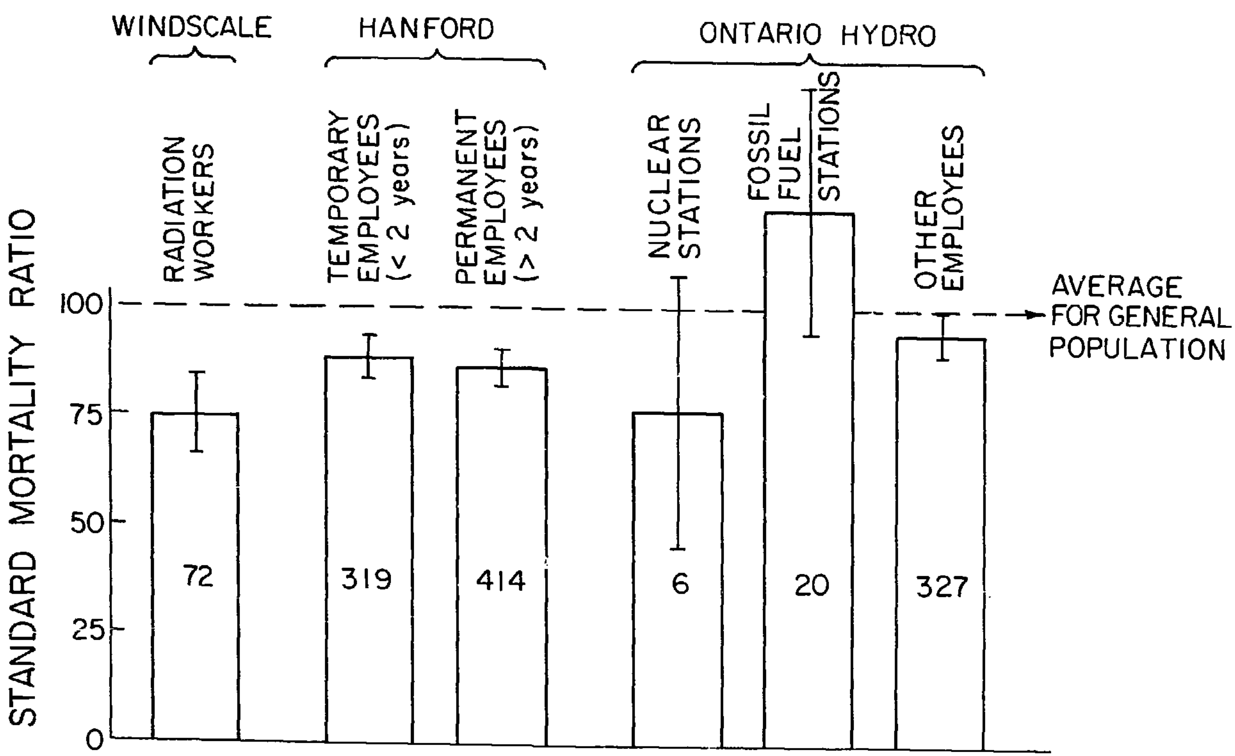


FIGURE 2

RELATIVE INCIDENCE OF DEATHS FROM CANCER FOR EMPLOYEES AT NUCLEAR FACILITIES

(ACTUAL NUMBERS OF DEATHS ARE INDICATED IN EACH RECTANGLE)



Preliminary studies of Ontario Hydro workers (Figures 1 and 2) also indicate the healthy worker effects (42). Atomic Energy of Canada Limited, the Department of National Health and Welfare, Statistics Canada and the National Cancer Institute of Canada are preparing proposals to carry out other epidemiological studies of radiation workers (43).

F. Exposures of People During Nuclear Power Production

1. Methods of Estimating and Measuring Doses to People

Radiation exposures resulting from nuclear power production include those received by the workers in mines, fuel production plants, power reactors, reprocessing plants, and waste handling facilities and also those received by the population at large who may live in the immediate vicinity or at considerable distances from the various operating parts of the industry. The summation of all exposures from all parts of the nuclear fuel cycle to both the workers and to the public is known as the collective dose. Since the doses from a given unit of present electrical production may extend over a period of time into the future, the summation of these doses over all time is referred to as the collective dose commitment (22).

For routine operations, population doses resulting from the release of radioactivity into the air and water of our environment are too small to be amenable to direct measurement for the case of each individual member. Consequently they are estimated from the knowledge of the quantities of material released, the patterns of dispersion in air and water, and the distribution pattern of population around nuclear facilities. Part of the intake of the released radioactivity may be by way of food which is cultivated on ground upon which airborne radioactivity has deposited. Knowledge of origin of food supplies is needed to assess the radiation exposure by this route. A particular case is that of the intake of radioactive iodine in milk from local dairy herds which may graze in the vicinity of nuclear power plants. Estimates of population dose made in this way are entirely adequate for the assessment of the risk associated with the nuclear industry. Actual doses to individuals in the population in normal operations are so small that the risk of harm to any individual is very small. Of greater interest is the statistical estimate of harm to a very large population whose collective dose may be enough to suggest the possibility of a few cases of delayed effects per generation.

The doses received by workers in the nuclear industry can be substantially larger than those received by the general population and are determined directly on an individual basis. Thus workers carry small dosimeter badges which are responsive to radiations from sources in and around their work place. In addition, if there is a likelihood of ingestion, inhalation, or absorption of radioactivity, measurements will be made at appropriate intervals of the activity in the body. The doses due to the incorporation of radioactive substances can be found in this manner. Individual determinations of workers' doses are made, first because it is technically feasible and second because it is required by law to limit the maximum exposure received by individuals and there must be evidence to show that compliance is being maintained (44).

Radiation sources external to the body may, depending upon their penetrating ability, expose only the skin or tissues at varying depths. The most common type of exposure in the nuclear industry is from sources of beta and gamma radiation. The dose received is measured by the effects of these radiations upon small crystals of lithium fluoride carried in the dosimeter badge (45). Lithium fluoride has the property of storing the radiation energy it absorbs; the amount stored can be found by heating the crystal to release the energy in the form of visible light. The amount of light released is proportional to the radiation dose received by the crystal and therefore to the amount received by its wearer. Generally the badge will contain two crystals

- one is covered by an aluminum filter so that its dose is representative of the dose received through the whole body of the wearer; the other crystal is covered only by a thin plastic film so that its dose is the same as that received by the skin of the body. Doses from sources of neutrons are generally measured by the radioactivity they induce in special substances which are contained in the dosimeter badge. Thus the production of radioactive phosphorus in a tablet of sulfur provides one measure of the magnitude of an exposure to high energy neutrons.

When radioactive material has been ingested or inhaled by a worker it may be detected by measuring the concentration in body fluids, most simply by counting the radioactivity in a urine sample. In some cases, however, the ingested material may be insoluble and will not be eliminated from the body into urine. In such cases, the amount of activity may be found by analysis of the feces or by direct measurement, with very sensitive detectors, of the radiation emitted from the body of the exposed person. To achieve adequate sensitivity such a counter must be well shielded from radiations from natural radioactivity in the normal environment and any other man-made radiation sources in the vicinity. These conditions are achieved in "whole-body counters" (46). Workers enter heavily shielded rooms containing sensitive detectors and in this way the amount and type of radioactivity in their bodies can be determined. Potassium-40, a radionuclide that emits gamma radiation, is present in all of us naturally. Therefore, a whole-body count of any person would reveal radioactivity from this nuclide very prominently.

If workers are exposed to radioactive nuclides of iodine in the atmosphere, about a third of the iodine which they breathe will be incorporated in the thyroid, and in this case, a small detector placed directly on the neck of the worker, close to the thyroid, provides a convenient means of estimating the amount of radioactivity inhaled.

In the operation of heavy water reactors, a significant part of the total radiation exposure of the workers is due to the inhalation and absorption through the skin of tritium (a radioactive isotope of hydrogen) in the chemical form of water vapour. This radionuclide emits only beta radiation which is entirely absorbed within the body so that external detectors such as whole body counters cannot be used. Tritium intake is therefore measured by urinalysis.

The estimation of intakes of activity by urinalysis has an advantage over whole body or thyroid counting in that the sample can be processed without the attendance of the individual and many samples can be counted very simply in automatic apparatus (47). In this case the metabolism of the radionuclide must be known in order to calculate the dose, since the activity eliminated from the body rather than the amount it contains is being measured. On the other hand, whole body counting provides an estimate of the actual amount of radioactivity contained within the body and the calculation of the corresponding dose is more direct.

A particular case of radiation monitoring which is different from the others is that of the monitoring of miners for exposure to radon. Because of the short half-lives that are involved, any air containing radon will also contain its immediate radioactive daughter products which are solids and when breathed along with the radon will be retained on the tissue surfaces in the lung. These daughter products have very short lives of less than an hour so that it is not possible to estimate the extent of the exposure by whole-body counting even on a daily basis, nor is urinalysis of any use. It is therefore possible to make estimates of the radioactivity of radon and its daughter products absorbed by workers only by measuring the levels of activity in the air they breathe and making certain assumptions about breathing rates. Simple and adequate means of providing each worker with a small air monitoring device have yet to be developed (experimental devices can always be tested on a few selected workers). Sufficient sampling must be done to ensure that the assessment is realistic and typical of the actual working conditions. Thus the radiation exposure of all workers in a particular location will be estimated from measurements of activity in the ambient air. The same is true for estimations of the exposure of members of the general public to radon daughters, a related topic which was mentioned earlier in Section C-2 of this chapter.

Records of radiation workers' doses are obtained and accumulated so that exposure beyond permissible limits can be prevented. The accumulated exposure records for large numbers of workers may eventually be useful in showing statistical relationships between radiation exposure and the actual incidence of adverse health effects. Such a relationship was demonstrated for uranium miners (refer to Section E). Further details of the measurement of low radiation exposures is given in Appendix 3.

2. Overall Assessment of Harm from Nuclear Power Production

The production of electrical power, by virtually any means, is associated with some degree of risk; in the case of nuclear power, the risks are associated in part with exposures to radiation and in part with conventional accidents.

From the whole nuclear industry, the collective dose commitment (that is, exposure of the workers and of the public) from the various steps in the fuel cycle has been estimated (1,48,49,50) to be between 2 and 7 man-rem per megawatt-year (MW-year) of electrical power production for current practice (see Table 8). Roughly half of this total is received by workers and roughly half by the general public. Because of the age distribution of those exposed, only about one-third of these doses is of genetic significance (1).

Harm commitments may be derived from these whole body dose commitments, and it is convenient to express them in terms of the numbers of serious casualties per 1000 MW-years of electrical power production (see Table 9) which may be visualized as the amount of electrical power required to provide an average of one kilowatt continuously to each person in a city of a million people for a period of one year. Using risk estimates given in Section E, Table 7, a dose commitment of 6000 man-rem (for example) associated with this amount of product might thus be associated with a harm commitment of 0.6 cancer deaths, plus a similar or slightly larger number of non-fatal cancers, and about 0.4 serious genetic defects in later generations. The total is thus in the vicinity of one serious delayed radiation casualty per 1000 MW-years of electrical production. Other estimates do not vary greatly from this (48-50).

Table 8

Dose allocation by steps in the fuel cycle (man-rem per MW-year)

<table>
<tr><th></th><th colspan="2">GESMO (49)</th><th colspan="2">Pochin (48)</th><th colspan="2">WHO (50)</th><th colspan="2">UNSCEAR 1977 (1)</th></tr>
<tr><th></th><th>Env.</th><th>Occ.</th><th>Env.</th><th>Occ.</th><th>Env.</th><th>Occ.</th><th>Env.</th><th>Occ.</th></tr>
<tr><td>Mining</td><td>0.5</td><td>0.2</td><td>-</td><td>0.1</td><td>-</td><td>0.05</td><td colspan="2" rowspan="2">0.3</td></tr>
<tr><td>Milling</td><td>0.1</td><td>0.1</td><td>-</td><td>0.1</td><td>-</td><td>0.1</td></tr>
<tr><td>Reactor Op.</td><td>0.1</td><td>0.6</td><td>0.1</td><td>2.0</td><td>0.4</td><td>1.0</td><td>0.4</td><td>1.0</td></tr>
<tr><td>Reprocessing</td><td>0.4</td><td>0.03</td><td>1.3</td><td>2.0</td><td>0.3</td><td>1.0</td><td>3.9</td><td>1.2</td></tr>
<tr><td>Disposal of Fuel</td><td colspan="2">Minute*</td><td colspan="2">"Minimal"</td><td colspan="2">"Minimal"</td><td colspan="2">No estimate</td></tr>
<tr><td>TOTAL</td><td>1.1</td><td>0.9</td><td>1.5</td><td>4.2</td><td>0.7</td><td>2.2</td><td>4.3</td><td>2.5</td></tr>
<tr><td></td><td colspan="2">2</td><td colspan="2">6</td><td colspan="2">3</td><td colspan="2">7</td></tr>
</table>

* Actual values are given as 0.000002 for environmental exposure and 0.0003 for occupational.

The estimated contributions from the major steps in the nuclear fuel cycle, to the integrated dose commitments and harm commitments, are given in Tables 8 and 9. These exclude the relatively minor contributions from fuel fabrication and transportation (see UNSCEAR 1977, ref. 1, p. 212). They also exclude the very long-term contributions from mill tailings and from the disposal of spent fuel and its product, i.e., as integrated over hundreds of thousands, or millions, of years. The component of harm from deaths due to conventional accidents is included in the estimates given by Pochin (48), and so also are the dose commitments and harm commitments

Table 9

Radiation induced cancer deaths by steps in the fuel cycle (per 1000 MW-year).

	GESMO (49)	Pochin (48)	WHO (50)	UNSCEAR 1977 (1)
Mining	0.07	0.01	0.01	0.03
Milling	0.02	0.01	0.01	
Reactor Op.	0.07	0.21	0.14	0.14
Reprocessing	0.04	0.33	0.13	0.51
Disposal of Fuel	0	"Minimal"	"Minimal"	No estimate
TOTAL	0.2	0.6	0.3	0.7

associated with accidents of varying degrees of severity involving releases of radioactivity. The dose commitments from accident releases are generally believed to represent only a small proportion of the total (48,49), and the UNSCEAR 1977 document (1) places this at 0.25 man-rem per MW-year of electrical production, that is, about 5 per cent of the total.

Conventional fatal accidents, e.g., in the mines and while transporting the fuel, may add somewhat less than one additional serious casualty per 1000 MW-years (49,51,52,53).

As a basis for choosing between various energy options, the above estimates of harm commitment per unit of product are of value only when compared with corresponding estimates for the other options. This comparison is important to arrive at a rational decision concerning energy options.

The dose commitments and harm commitments described above include the contributions to the exposures of both workers and the public, from the various steps in the fuel cycle, summed over a hundred years. When a similar summation is carried out over hundreds of thousands to millions of years, a few radionuclides, notably, uranium, radon, carbon-14 and iodine-129 yield large dose commitments, especially to particular organs (e.g., lung, bone marrow and bone lining, and the thyroid--see UNSCEAR 1977, ref. 1, p. 212). The additional harm commitment from these sources has not been estimated in the UNSCEAR report, partly because the above-mentioned radionuclides are associated with exceedingly low individual doses, partly because of the need for caution when extrapolating so far into the future, and partly because of the continued improvements in technology and regulatory control (1). Although the individual doses received beyond the hundred year period will undoubtedly be minute in comparison with natural radiation exposures, and with natural variations in these round the world, it is nevertheless considered that the total societal impact over all time, of any current practice, ought to be kept as low as possible. This emphasis on long-term consequences should apply to other energy sources as well. Comparisons with the all-time impacts on society of other options will be important for the purpose of future decision making, but such comparisons, where they are possible at all, are still exceedingly crude. Since the risks to any one individual will be almost infinitesimal, the problem is clearly societal rather than personal.

Estimates of the very long-term population dose commitments from the two ends of the fuel cycle will necessarily depend on the manner of treatment of the respective wastes. Radon is always present in the air because it diffuses from the soil everywhere; the land mass of the USA emanates about a hundred million curies (1 curie = 37 giga becquerels = 3.7×10^{10} disintegrations per second) of radon into the air each year. Uncovered tailings, for example, from the mining and milling of the uranium needed for the US nuclear industry to the year 2000 would be expected to raise the concentration of radon normally present in the air by about one part in one thousand (54). By way of comparison it might be noted that the use of natural gas for cooking is thought to increase radon concentrations in the home by about five parts in one thousand (1), while decreased ventilation rates may have relatively large effects on radon concentrations in the home. Major reductions in radon releases are possible, however: a) covering the tailings with six metres of earth could effect something like a 10-fold reduction; b) extraction of large part of the radium-226 and thorium-230 appears possible and might result in a further 5-fold reduction; and c) extensive use of breeder reactors and final reprocessing to lessen the requirement for uranium mining could perhaps result in as much as a 50-fold reduction in some future period. Similarly, the number of barriers placed around vitrified wastes from the back end of the fuel cycle (for example, barriers of glass, metal, synthetic rock, ceramic and clay, and of sealants such as magnesium oxide to keep out water) could presumably be increased so as to delay leaching to virtually any degree desired. There is thus no reason in principle why the very long -term dose commitment and harm commitment from a repository for this kind of waste could not be reduced below that for the original ore body. Furthermore, deep underground waste repositories would be less susceptible to disturbance by glaciation than many of the shallower ore bodies. Useful estimates of the very long-term impact of the wastes from the two ends of the nuclear fuel will thus depend much on the specifics of the management procedures.

3. Practical Implications for Radiation Workers

Potential radiation hazards to occupationally exposed workers are summarized in Table 10. The values are calculated for persons exposed to maximum permissible levels of radiation every year for 35 years commencing at age 20. The biological effects of smaller exposures each year (Table 6) would be in direct proportion to the size of the doses involved. Exposures past 55 years of age have not been included in the calculations of Table 10 since there is normally an appreciable latent period between exposure and death due to induced cancers and it is doubtful whether exposures after age 55 would appreciably alter the numbers given in Table 10.

For radiation workers, the degree of safety associated with the annual limit of 5 rem has been re-evaluated recently by the ICRP (22). Given that the group average dose to radiation workers is generally two to ten times less than this individual maximum, the radiation risks will be two to ten times less than the values given in Table 10. When the risks from conventional accidents are added in, the total may then be compared with the risks associated with other occupations that are generally viewed as having high safety standards (Fig. 3). Comparisons of this kind have been refined (55) and it would appear that the present annual limit of 5 rem to an individual achieves the required comparability, provided that there is no systematic attempt to expose all workers to doses approaching the maximum for an individual. The above statement does not apply to underground uranium mining because of non-radiation hazards associated with mining.

TABLE 10

Potential radiation hazards to occupational workers exposed to maximum permissible limits (cases per 10,000 persons)

Type of Hazard	Normal Incidence	Increase in occupational workers exposed for 35 years commencing at age 20*	
		5 rem whole body per year	4 WLM to lungs per year
Leukemia	80	35	0
Lung cancers	380 (males 600, females 100)	35	140-560
Other fatal cancers	1540	150	0
Total fatal cancers	2000	220	140-560
Non-fatal cancers	2000	220	0
Genetic defects after repeated exposures over many generations	1050	100	0

*Data are calculated from ICRP risk estimates for whole body radiation and assuming a risk of 1×10^{-4} to 4×10^{-4} lung cancers per WLM for uranium miners. The values given in Fig. 3 used the same risk estimate for the effects of whole-body radiation but allowed for the fact that the average time between radiation exposure and death is about 10 years in the case of leukemia and about 25 years for other types of cancer. The numbers given above are therefore slightly higher than those given in Fig. 3.

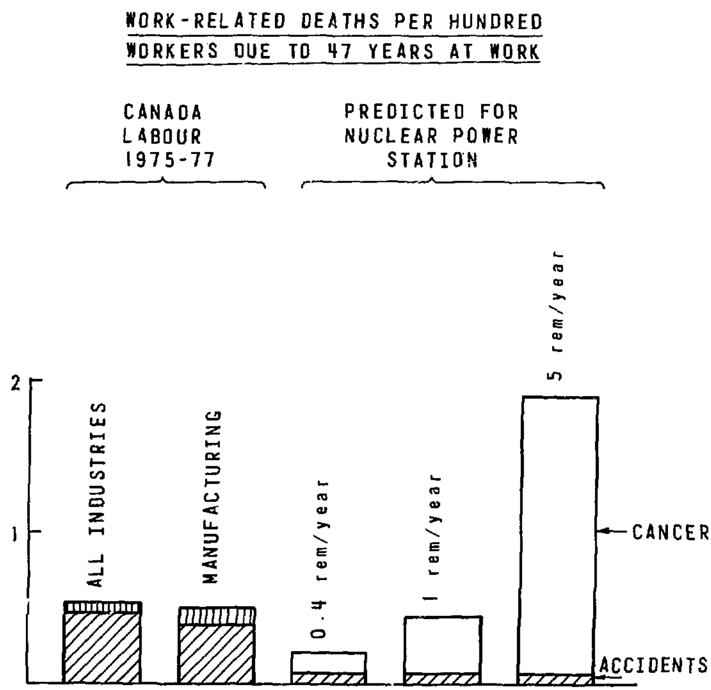

WORK-RELATED DEATHS PER HUNDRED
WORKERS DUE TO 47 YEARS AT WORK
CANADA
LABOUR
1975-77
PREDICTED FOR
NUCLEAR POWER
STATION
2
1
ALL INDUSTRIES
MANUFACTURING
0.4 rem/year
1 rem/year
5 rem/year
CANCER
ACCIDENTS

FIGURE 3

A group average dose of 1 rem per year may be viewed as resulting in an average risk of delayed cancer death of about 1 in 10,000 per man-year of work. The risks from the hereditary changes induced by the radiation, and from conventional accidents with fatal outcomes, are considerably smaller than this. In general, occupations with fatality rates of one per 10,000 man-years of work, or less, are viewed as having high safety standards. In making the comparison with radiation workers, it must be remembered that deaths from conventional accidents tend to occur much earlier in life than those from delayed cancers (55), the average losses of life expectancy among the affected individuals being about 30 and 12 years respectively. On the other hand, the worry caused by incipient cancer has suggested to others (56) that a death from cancer should be weighted more heavily than an accidental death.

4. Practical Implications for the Public

For the dose to an individual member of the public living on the boundary of a nuclear generating plant, there is a legal limit of 0.5 rem per year in Canada. But guidelines exist which reduce this limit by a factor of 100, and in practice the actual exposures are roughly 5 millirem or 0.005 rem per year.

These dose limits are often referred to as primary standards. Using models for dispersion of radioactivity into air, water, milk, food and the resulting intake of radioactivity by humans, these primary standards can be used to calculate secondary standards, also known as Derived Release Limits (DRL)*. The DRL of a radionuclide is expressed as concentration per unit volume of air or milk and per unit mass of food. When commonly occurring radionuclides are released at 1% of the DRL levels, the total of all such releases would not exceed the whole-body dose of 5 millirem per year to the hypothetical individual living 24 hours per day at the boundary of the exclusion area of a nuclear

* DRL's have been published for Chalk River and Whiteshell: (1) J.F. Palmer, AECL-7243, 1981,"Derived Release Limits (DRL's) for Airborne and Liquid Effluents from Chalk River Nuclear Laboratories During Normal Operations." and (2) W.E. Dunford and D.M. Wuscke, AECL-6312, 1981, "Calculation of Derived release Limits for Radionuclides in Airborne and Aqueous Effluents for Whiteshell Nuclear Research Establishment."

station; this hypothetical individual breathes the local air, drinks the station effluent and consumes locally grown food. Thus the personal risk of developing a cancer from this exposure is well below one in a million per year of residence in proximity to a nuclear reactor. For the general populations the integrated dose commitment is estimated to be less than that for the radiation workers except for mining or fuel reprocessing (see Table 8). In other words, not only is the personal risk much lower, but the total number of radiation casualties per year from nuclear energy production is lower in the general population than it is in the group of radiation workers.

For members of the public* living in the vicinity of uranium mining and mill tailings, the main hazard is due to radon daughters. The exposure to radon daughters will be mainly indoors and will vary with the distance of their houses from the tailings piles and with the amount of earth covering the piles. (Radon in the outdoor air will have had little time to produce radioactive daughter products locally before being dispersed.) The risk indoors has been estimated for uncovered tailings piles of average size to increase the risk of lung cancer by 70 percent at a distance of 50 metres, by 3 percent for houses at 1 kilometre, and by 1 percent for houses at 2.2 kilometres (page 109 of ref. 54). At distances above 1 kilometre, the predicted increase in cancer incidence is not zero, but of course, predicted increases of only a few percent would be very difficult to detect statistically.

There should be no problem with radium in drinking water, if drinking water standards (secondary standards) are observed (57).

* R.D. Evans, J.H. Havley, W. Jacobi, A.S. McLean, W.A. Mills and C.G. Stewart, Nature 290, pp. 98-100, 1981 give an upper estimate for the lifetime risk of 1×10^{-4} lung cancers per WLM for members of the general population.

5. Risks to Society Per Unit of Product

For the purpose of deciding between various energy options, comparisons of risks must be based on producing the same amount of energy. The relevant measure is thus the number of serious casualties per unit of energy produced. It is convenient, for example, to estimate the numbers of immediate plus delayed casualties per 1000 MW-years of electricity produced, and to do so for each form of electrical power production being compared (7). The resulting comparisons fall outside the scope of this paper and the reader is referred to previous reviews (7,24,50-53) and a document by R.S. Dixon (58) on the safety aspects of alternative energy sources.

Past estimates of these sorts have indicated that nuclear fuels and natural gas rank high on the scale of safety, and that coal ranks low (7,24,50-53). It is thought that combustion of coal results in about ten times as many deaths as does nuclear power per unit of energy produced (7), although a review by the American Medical Association Council on Scientific Affairs (52) suggests that this ratio could be as high as 100. The comparisons are, of course, dependent on the time scale over which the nuclear casualties are totaled, on the manner of disposal of the very long-lived radionuclides from the front and back ends of the nuclear fuel cycle, on the extent to which fuel reprocessing is employed to reduce the amount of uranium mining, and on the population densities in the areas exposed to air and water carrying minutely increased quantities of the long-lived radionuclides.

Unfortunately, such comparisons, and especially those involving coal, suffer from a limited understanding of the risks of the energy options other than nuclear. For example, in the case of coal, only partial risk estimates are possible because of a lack of quantitative information on the effects of such products of combustion as the polycyclic hydrocarbons, the oxides of nitrogen, the heavy metals contained in the fly ash that escapes removal, and in the seepage from repositories in which the rest of the ash is stored.

6. Decommissioning

The problem of decommissioning CANDU reactors is dealt with in detail in another AECL publication (59). Radiation exposures to personnel during the dismantling of a 600 MW CANDU reactor, after 30 years of service, are estimated to total 600 man-rem, or roughly 0.04 rem per MW-year of power production assuming a lifetime capacity of about 80%. This may be equated with a risk of delayed cancer of 0.004 per 1000 MW-years of electrical production and can be compared with 0.6 cancer deaths per 1000 MW-years for the whole industry. The radionuclides of greatest importance for disposal in active waste repositories are given as cobalt-60 with a half-life of 5.3 years, and nickel-63 with a half-life of 92 years. It is concluded that "the environmental impact of decommissioning will be no greater than that of any large construction project" (59).

7. Reactor Accidents

Considerable effort has been devoted to estimating the likely frequencies of reactor accidents of various degrees of severity, and the collective impact of these per unit of electricity produced. Almost universally, the severity and the frequency of accidents tend to be inversely correlated: that is to say, the more severe accidents occur less frequently. This appears to be applicable for example in coal mining as well as in other areas. The most frequently quoted study predicting the frequencies and consequences of accidents to nuclear reactors is the U.S. report designated as WASH-1400 (60). This report has been reviewed for the U.S. Nuclear Regulatory Commission by

H.W. Lewis and colleagues (61); the review group concluded that they were unable to define whether the overall probability of a core melt given in WASH-1400 (60) was high or low, but they were certain that the error bands were underestimated. In other words, the suggested values are subject to considerable uncertainty and might be either too small or too large. A similar criticism was applied to the estimates in WASH-1400 of health effects due to accidents; although the values are generally regarded as reasonable, they could be in error by as much as 5-fold or possibly even 10-fold (61).

Other recent views concerning this study have been summarized in the Ford-Mitre report of 1977 (62) and the UNSCEAR report of the same year (1). The WASH-1400 report (60) estimates, as a consequence of reactor accidents, an average of 0.02 fatalities per 1000 MW-years of electrical production. The Ford-Mitre report (62) considers the possibility that the number could be as much as 500 times greater and concludes that "even in this extremely unlikely situation, the average fatalities would not exceed the pessimistic end of the range of the estimated fatalities caused by coal". (The estimated fatalities caused by coal include, in this particular case, fatalities due to mining, transportation and burning of coal but exclude fatal cancers that might be caused by effluents from a coal-burning power station.) The UNSCEAR report (1) estimates an average dose commitment from reactor accidents of 0.25 man-rem per MW-year, or about five percent of the estimated total dose commitment. Thus, reactor accidents are generally regarded as unlikely to have a major impact on the average risk.

An independent study of reactor accident risks has recently been carried out in West Germany. The findings have been described (63) as follows: "In general, the estimated numbers of early fatalities in the German study are lower by a small factor than those in WASH-1400, whereas the estimated number of fatal cancers are slightly higher. However, the differences are within the bounds of uncertainty of both studies and are not, therefore, statistically significant."

III. EFFECTS OF IONIZING RADIATION ON THE ENVIRONMENT

A. Effects of Ionizing Radiation on the Aquatic Environment

Several surveys of the published literature dealing with radiation effects on aquatic organisms have been published recently. The most recent of these have been those by Ophel et al. (64) and Blaylock and Trabalka (65). The majority of papers reviewed deal with the results of exposure of organisms to acute doses of ionizing radiation. In this review we will mostly refer to those that studied the effects of chronic, low-level exposure, since these are more relevant to the dose rates found in the environment due to controlled releases from nuclear generating stations and to the disposal of radioactive wastes from nuclear power reactors (66-68).

1. Comparative Radiosensitivity of Aquatic Organisms

Generally speaking, most aquatic organisms are relatively resistant to ionizing radiation. Exceptions to this general rule are the eggs of some fishes and the early stages of life of some invertebrates and fishes which suffer damage and lethal effects at the same levels that produce acute effects in mammals. Acute radiation doses in the range 20-200 rad when given at these early critical stages of life may produce significant damage to some individuals.

There is an extensive literature dealing with the effects of single massive doses of radiation on the survival of aquatic organisms. Comparative radiosensitivity has been discussed by Bacq and Alexander (69) and in other reviews (70,71). In general, it is found that radiosensitivity increases with increasing biological complexity, that is, as organisms occupy successively higher positions on the phylogenetic tree. For example, the lethal dose for some species of primitive algae may exceed one million rad whereas the lethal dose for one species of fish has been measured at about one thousand rad.

A recent compilation (64) of lethal radiation doses for adult organisms in various phylogenetic groups is given in Table 11.

Table 11

Ranges of Acute Lethal Radiation (64) for Adults of Various Groups of Aquatic Organisms (Expressed in thousands of rad)

Bacteria	5 - 2000
Blue-green algae	400 - 1200
Other algae	3 - 120
Protozoa	100 - 600
Molluscs	20 - 110
Crustaceans	2 - 60
Fish	1 - 6
(Mammals)	0.2 - 2

Radiation damage to aquatic organisms is greatly reduced when massive doses are fractionated or delivered over a longer period of time, just as with humans or other terrestrial animals. Splitting the dose gives more time for various repair processes to reduce the damage.

2. Effects of Chronic Exposure

When organisms are irradiated continuously there is an increase in the total dose necessary to cause death (or some other injury) as compared with a single radiation dose. At very low dose rates, repair processes and cell division may keep pace with radiation damage and no acute detrimental effects appear.

Continuous (chronic) exposure can be produced by radiation sources outside the body of the exposed aquatic organism (either from a fixed source or from radionuclides in the water) or from radionuclides taken up by the organism from food and water and incorporated into its tissues. (The same is of course true for other living organisms such as human beings.)

(a) Studies in Contaminated Waters

Most studies on contaminated aquatic ecosystems have examined the distribution and pathways of the contaminating radionuclides and have neglected the different question of possible radiation effects on the aquatic biota. Difficulties in detecting radiation effects arise because, even in what are considered to be highly contaminated environments, the dose rates are relatively small. Dose rates to aquatic organisms in the vicinity of a nuclear reactor are measured in fractions of a rad per year. However, a recent study (70) estimates that dose rates to certain aquatic organisms in the vicinity of discharges from nuclear reprocessing facilities could be as high as 30 rad per year. It would be very difficult to detect deleterious health effects in aquatic organisms even at dose rates as high as 30 rad per year.

Measurements in Perch Lake, a very lightly contaminated body of water within the controlled area of the Chalk River Nuclear Laboratories, have shown that many aquatic organisms receive lower doses than those received by terrestrial organisms in nearby uncontaminated areas (71). This is because the lake water is acting as a shield which reduces the radiation dose due to cosmic and terrestrial background radiation to a low figure that is hardly increased by the low radionuclide content of the water.

A number of field studies have been made at Oak Ridge National Laboratory in a small water-body called White Oak Lake, which is actually a radioactive waste settling basin. It does, however, contain some naturally reproducing populations of aquatic organisms. Dose rates in this ecosystem exceed 200 rad per year for benthic invertebrates and over 3500 rad per year for some fish species. Fish populations in White Oak Lake were studied over a three-year period and no changes were found that could be positively associated with radiation exposure (72). Later studies of fish and aquatic snails were made in the same body of water. Some slight changes in numbers of offspring (fecundity) were observed. However, due to compensating mechanisms operating within the population, these did not result in any visible population changes (65).

The long-term hazards of chronic irradiation are not due to effects on fecundity or mortality but to genetic changes in the DNA of organisms that survive. Mutations (many of them not serious) occur normally with a fairly high frequency in natural populations; no excess has been detected with radiation exposures of a few rad.

(b) Laboratory Studies

Many experimental studies of radiation effects in laboratory-maintained populations of aquatic organisms in radionuclide solutions have been carried out (64,65). The organisms used include algae, protozoa, molluscs, crustaceans, insects and fish.

It is difficult to assess and summarize the significance of the above experiments because of the difficulty in relating concentration of radionuclides in the aqueous phase to a tissue dose to the organism. However, no deleterious effects were observed until radionuclide concentrations in water or tissues were at least one million times greater than those presently found in environmental waters (see Table 12) in Canada (64).

(c) Effects of Incorporated Radionuclides on Developing Fish Eggs

Beginning with the crude experiments of Polikarpov and his colleagues in the USSR, there have been many studies of hatching fish eggs in water containing radionuclides in solution. This work was reviewed

Table 12

Concentrations of Radionuclides in Environmental Waters in Canada

Maximum concentrations in environmental waters Bq/L(pCi/L)

Location	^{3}H	^{90}Sr	^{137}Cs
Ottawa River	23.7 (640)	0.04 (1.1)	0.01 (0.3)
Lake Ontario	92.6 (2500)	0.03 (0.8)	0.002 (0.05)
Lake Huron	63.0 (1700)	0.03 (0.8)	0.01 (0.3)
Winnipeg River	-	0.06 (1.6)	0.01 (0.3)

in a 1966 book by Polikarpov (73). The Russian experiments were interpreted by Polikarpov as indicating that developing fish eggs were sensitive to minute traces of radioactivity in the water and that doses of a few millirads were affecting hatching and causing the appearance of abnormal larvae. Other workers in the US, UK, as well as in the USSR have not been able to duplicate these results.

Blaylock and Trabalka (65) have carefully reviewed all of these early experiments and a number of carefully executed recent research studies. They conclude that none of these later experiments supports the conclusion that developing fish eggs are abnormally sensitive to radiation from incorporated radionuclides.

(d) Effects of External Radiation on Developing Fish Eggs

Scientists at the University of Washington have taken advantage of the migratory habit of salmon to make a continuing long-term study of exposure to relatively low and high levels of radiation. Large numbers of eggs were irradiated by a cobalt-60 source during development and the young fish were marked and then allowed to migrate to sea in a normal manner. Adult fish returned several years later when they could be examined and their eggs used for further studies.

These experiments indicate that irradiation at rates of 0.5 rad per day and which resulted in total doses of up to 355 rad, produced no damage to the salmon populations sufficient to reduce the reproductive capability over a period of several generations. Although abnormalities in young fish increased, the number of adults returning was not affected. On the contrary, the low-dose irradiated fish returned in greater numbers and produced a greater total of viable eggs than the non-irradiated control fish. At dose rates of 10 rad per day and above, radiation damage was evident and the growth rate of these fish was significantly less than the controls.

Canadian scientists Newcombe and McGregor have studied embryonic malformations in fish (rainbow trout) due to radiation-induced chromosomal changes in laboratory irradiated sperm and eggs (74,75) and examined the shape of the dose-response curve for such malformations

(76). The dose response curve for eye malformations in rainbow trout embryos over a range of doses from 25 to 400 rad was found to be a straight line. The dose at 25 rad produced 12 malformations per thousand embryos, while 400 rad caused 43 malformations per thousand; about 6 malformations per thousand were observed in the unirradiated controls.

(e) Summary

Aquatic organisms used in radiation effects studies come from all the important plant and animal phyla and range from bacteria and algae to amphibia and fish. Effects recorded, or looked for, include mortality, histological damage, physiological and biochemical changes, effects on fertility and fecundity, as well as direct and indirect genetic effects.

The most sensitive aquatic organisms are the eggs and young of fish, although the results of a number of early experiments indicating exceptional sensitivity of the eggs of some species are now known to be wrong, due to poor experimental techniques.

As a general statement, it can be said that the radiosensitivity of fish is of about the same order as that of mammals, including man. Some effects on mortality of fish might be caused by acute radiation doses in excess of 100 rad. It has been found that chronic dose rates of about 1 rad per day can be tolerated before minor physiological or biochemical effects appear. These dose rates are much higher than those found in even the most contaminated environmental waters.

B. Effects of Ionizing Radiation on the Terrestrial Environment

1. Effects on Insects and Other Invertebrates

Unlike aquatic organisms, terrestrial invertebrates are constantly confronted with problems of dehydration, temperature variation and temperature extremes, all of which influence their response to ionizing radiation.

Table 13

Comparative radiosensitivity of three groups of organisms to acute doses of X or gamma radiation (81)

Group	Dose range to cause severe reproductive inhibition or mortality (expressed in thousands of rad)
Mammals	0.2 - 2
Invertebrates	2 - 100
Bacteria	5 - 2000

Table 14

Variation in radiosensitivity of insects (82)

Species of Insect	Acute dose of X or gamma radiation necessary for 100% sterilization (expressed in thousands of rad)
Screw-worm fly (Callitroga)	5
Wasp (Habrabyacon)	7.5
Fruit fly (Drosophila)	16
Powder post beetle (Lyctus)	32

Invertebrates are intermediate in radiosensitivity between mammals and simple life forms such as bacteria (Table 13). Severe effects on reproduction in the more radiosensitive invertebrates can be caused by 5000 rad while some resistant species require one million rad to cause 50% mortality. In addition to variation in radiosensitivity between invertebrate species (Table 14), significant variation with the stage of the life cycle is also present (Table 15).

The physiological, genetic and somatic effects of radiation on insects are the subjects of a number of recent reviews (77-80). There are no reports of the induction of even partial sterility (one of the most radiosensitive physiological effects) in experimental populations exposed to doses less than 500 rad. This observation is supported by work (85) at Whiteshell Nuclear Research Establishment (WNRE).

Table 15

Age variation in the radiosensitivity of the fruit fly (Drosophila sp.) (83,84)

Stage of life cycle	Acute LD_{50} dose of X rays (expressed in thousands of rad)
Egg before cleavage	0.29
Egg during cleavage (1.5 hours)	0.16
Embryo, 3 hours old	0.2
Embryo, 4 hours old	0.5
Embryo, 5.5 hours old	1
Young larva	1.3
Pupa	2.8
Adult	85 - 100

Irradiation has been observed to cause changes, not all deleterious, in population parameters such as behaviour, chromosomal aberrations, fecundity, inter-species competition, growth rate, survival, and ecological fitness. These changes are conditioned by interaction among ambient temperature, dose rate and total dose, but no detrimental effect to the population has been observed following chronic exposure to dose rates less than 10 rad per day, that is, about 3000 rad per year. Long-term studies of the effects of chronic irradiation have been made on invertebrate communities living under various ecological conditions, such as Mediterranean, temperate deciduous, tropical montane, boreal forests, deserts, and grasslands. Changes brought about by radiation in numbers of different species of invertebrates and change of the community of organisms to simpler types have been suggested but, in general, the naturally occurring fluctuations in community dynamics have obscured any effects that might be attributed to radiation. Where changes in the distribution of invertebrate species have been observed, they were the result of radiation induced modifications of the association of plants in the ecosystem, indicating that chronic dose rates greater than 13 rad per day are required to change the structure of invertebrate communities (82).

Laboratory experiments with Drosophila indicated little difference between control populations exposed to normal background radiation levels of 0.00001 rad per hour and populations exposed to 0.9 rad per hour (350 rad per generation) for 125 generations (see Fig. 4). Appreciable genetic differences were observed only when the dose rate was increased to 5.1 rad per hour or 2000 rad per generation (87); even at this latter level, the Drosophila continued to survive and to propagate for more than 125 generations.

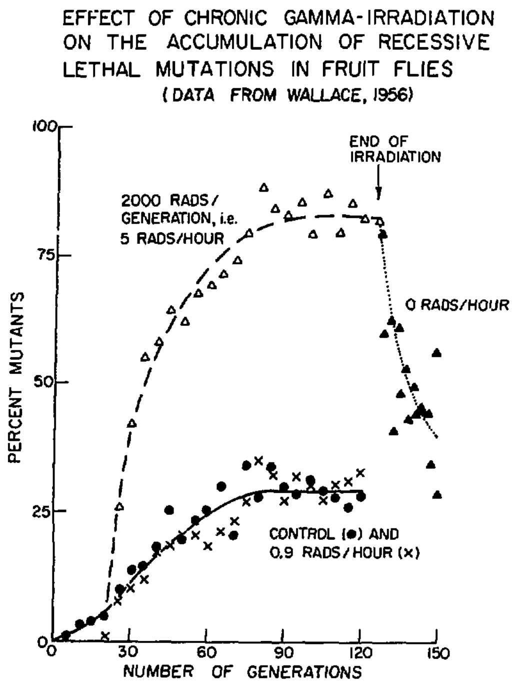

EFFECT OF CHRONIC GAMMA-IRRADIATION
ON THE ACCUMULATION OF RECESSIVE
LETHAL MUTATIONS IN FRUIT FLIES
(DATA FROM WALLACE, 1956)
END OF IRRADIATION
2000 RADS/ GENERATION, i.e. 5 RADS/HOUR
0 RADS/HOUR
CONTROL (●) AND 0.9 RADS/HOUR (×)
PERCENT MUTANTS
NUMBER OF GENERATIONS
0
25
50
75
100
30
60
90
120
150

Figure 4

2. Effects on Mammals

Studies of radiation effects on mammals were initially concentrated on the acute irradiation of individuals in the laboratory. Later work used either acutely irradiated animals released into natural or semi-natural habitats, or animals chronically irradiated in their natural environment. These studies showed that wild animals acutely irradiated, then returned to the wild, were generally more sensitive than those held in the laboratory. In addition, animals exposed to the same total dose over a long period had lower mortality rates than those given a single acute dose. (The same is true for humans and for aquatic organisms, as noted earlier.)

Several years later, work was begun on the radiation effects on populations living in areas of high natural radioactivity, populations receiving increased exposure from industrial operations as well as populations irradiated by artificial sources. Generally, dose rates in studies of high background areas are low compared to those in the other two types. Additionally, internal radiation via inhalation and/or ingestion is a factor in high background or waste disposal studies, whereas only external emitters (normally gamma) are involved in artificial radiation source studies. Effects on reproduction and survival, and to a lesser extent, behaviour have been the primary interest in these studies. It should, however, be noted that there were no significant differences in genetic characteristics (skeletal traits, pre-natal mortality) of natural populations of Indian black rats living in areas which differed 7.5-fold in background radiation levels (88). In laboratory experiments, parental male mice were repeatedly exposed to relatively high radiation doses (for example, 900 rad for each of eight generations, 300 rad for 15 generations, or 200 rad for 35 generations), so that the cumulative radiation exposure to the males of all of the combined generations approached 7,000 rad. Despite these high exposures, no change in the general health or fitness of the offspring could be detected in any of the generations (89). It is possible that these negative results could be ascribed to the relatively small size of the experiments and their inability to detect "small genetic variability" (89). However, these experiments provide good reason to believe that even large radiation exposures over many generations would not have any dramatic effect on the health and fitness of most mammalian populations.

Ecologists have generally not concerned themselves with the genetic effects of radiation, since natural selection would tend to counteract any radiation-imposed genetic alterations. Important reviews of the animal radioecology literature are those of Schultz and Whicker (90) and Turner (91).

A classic study of a free-ranging population of mammals was carried out on desert pocket mice in Nevada, continuously irradiated for several years (92). It found that a long-term exposure to about 365 rad per year (the dose was administered as 1 rad per day but the doses are converted to rad per year for easier comparison to other annual doses presented in this document; similar conversions can be found in this section) led to reduced survival, particularly in young animals, and suggested that, in years of adverse natural conditions, the population would be markedly reduced in numbers due to fewer young reproductive animals present. Exposure to long-term doses as low as 730 rad per year has been shown to reduce the number of offspring in deer mice, and increase the death rate. The only study showing effects at lower exposures were those in high background areas in the USSR, in which 35-70 rad per year led to reproductive sterility and decreases in population density of voles.

Current research at WNRE is being undertaken on the effects of long-term irradiation on a natural vole population. The initial experiment is being conducted at 3650 rad per year but later experiments will look for changes at lower levels (93).

3. Effects on Reptiles and Amphibians

Radiation effect studies of these vertebrate groups are very limited. An acute 1500 rad dose of a native toad population at spring emergence resulted in reduced survival by the following spring (94). An acute dose of 450 rad reduced natality in a lizard population and led to a decrease in population size (95). At the Nevada site, mentioned above, exposure of four lizard species to chronic doses of less than 365-1825 rad per year led to decreased populations due to female sterility. The only population that survived well was of the shortest lived species, which naturally reproduces at the earliest age.

4. Effects on Birds

Although radiation effects on birds have generated several reviews (96-98), the literature is too fragmentary to justify detailed synthesis and evaluation.

Radionuclide concentrations in birds have been studied on weapon, nuclear power and waste disposal sites and in relation to world-wide fallout and natural radioactivity. A general finding of these studies has been that birds accumulate a variety of radionuclides. Habitat selection, food habits and food web relationships are the major determinants of radionuclide loads. Usually, radionuclide concentrations are too low to cause gross radiation damage.

Experimental studies using acute gamma-radiation exposures have revealed that the LD_{50} for adult birds ranges from about 400 to over 3000 rad. Eggs and nestlings are usually more sensitive than adults. Radiation effects include loss of motor activity, disorientation, plumage changes, loss of fertility and reduced growth rate and are linked to tissue destruction. The limited data on chronic exposure indicate that doses of 400-500 rad during the breeding season can have disruptive effects by causing hatching failure and nestling fatalities.

5. Effects on Plants and Plant Communities

Plants of economic importance have been used in a variety of laboratory and greenhouse studies using incorporated radionuclides as tracers to determine processes and cycling of certain biologically important compounds. However, such studies have rarely included assessment of the effect of the radionuclide on the organism being studied.

Acute radiation has been used in horticulture, agriculture, and forestry for the improvement of economically important plants. Generally these studies involve the irradiation of seeds (or occasionally seedlings) with gamma or X rays followed by an analysis of the germination, survival, biomass, reproduction and perhaps mutant selection. These studies (reviewed in 99-101) usually include only one or two years of growth post-irradiation. Generally the studies of effects of acute radiation, especially on seeds, do not accurately predict the results of the long-term effects on plants in nature. This is because the seeds are dormant and thus radiation resistant.

Studies of ionizing radiation on terrestrial plant communities published before 1974 have been reviewed (99,102). Three major studies have been conducted since that time: Field Irradiator - Gamma (FIG) in Manitoba (1969-present) (103-106), Enterprise in Wisconsin (1970-1974) (107), and Mediterranean forest (1969-1972) (108). The studies particularly relevant to Canadian conditions are: FIG, Enterprise, Brookhaven (102) and the Colorado grassland studies (102).

A difficulty in generalizing about the effects of radiation on terrestrial plants and plant associations is the disparity of the data between different studies. Dose rates, total dose, measurements employed, species present, environmental conditions, and the length of time over which the measurements are continued are often different. Although many exceptions exist, the following general conclusions emerge from these studies:

(1) Plant associations characteristic of harsh environments and climatic extremes tend to be comparatively resistant to ionizing radiation.

(2) Early successional communities tend to be more resistant than succeeding communities.

(3) Within the plant kingdom the order of radiation sensitivity is roughly as follows (from most to least sensitive): trees>shrubs>herbs>thallophytes>microflora.

(4) Within the flowering plants there is a tendency for the phylogenetically primitive plants to be more sensitive than the phylogenetically advanced plants.

(5) Nuclear and chromosome variables, including polyploidy, play an important role in determining sensitivity.

(6) Photosynthetic capacity, relationship to respiration, protection of sensitive tissues, and environmental variables are also important factors in determining radiosensitivity.

A community being irradiated becomes progressively dissimilar to its original structure. Changes occur in species numbers and number of individuals due to both primary and secondary radiation effects. Herbaceous amd weedy plants often become dominant during and after a long-term radiation exposure. Productivity also generally decreases with increasing radiation dose. However, this response varies and may even be reversed depending upon the species and dose rates. Some effects of irradiation (for example stimulation of productivity) have been seen at dose rates as low as 14 rad per year (2 millirad per hour) after several years of irradiation. Detrimental effects can only be seen at higher dose rates.

IV. GAPS IN KNOWLEDGE

In 1977, Dr. H.B. Newcombe, Head of Population Research Branch of the Chalk River Nuclear Laboratories (CRNL), outlined in his report (109) gaps in knowledge on future radiation doses, on cancer and on hereditary risks as well as the direction of these uncertainties. His discussion is still valid today and is reproduced in the following pages. Further references and tables are to be found in the quoted document.

"GAPS IN KNOWLEDGE - FUTURE RADIATION DOSES

Attempts to estimate future radiation dose tend to be based on current practices, current trends in these practices, and new practices envisaged for the future. For example, although the frequency of diagnostic radiography may increase in the future there has been a substantial downward trend in the extent of the body dose from various radiographic examinations. Also of interest in the present context are the trends in exposures arising from the production of nuclear power.

Occupational exposures from the operation of nuclear reactors have been taken in the Nuclear Energy Agency (NEA) document as in the region of 2 man-rem per megawatt year of electrical power produced. There are a number of reasons to believe that this may be too high a value, and perhaps especially so in Canada.

One relevant trend is towards the use of larger reactors, and these are known to produce more electrical power per unit of occupational exposure. For a list of twenty nuclear power stations given in a United Nations report these exposures declined by about five-fold with increasing reactor size, i.e. being 2.6 ± 0.7, 2.1 ± 0.3 and 0.6 ± 0.3 man-rem/MW-year respectively for stations in the ranges 70-90, 150-300 and 500-1080 MW capacity.

For Canada, it is believed that an occupational exposure of 0.3 man-rem/MW-year is a reasonable objective for future power stations of 1200 MW capacity, or some seven-fold lower than the value of 2.0 used in the NEA document. Currently the figure for the larger Canadian reactors stands at about 0.6 man-rem/MW-year, i.e. about three-fold lower than the NEA figure. There are economic incentives to develop technologies which would further reduce the exposure below the predicted future level. These incentives arise because the total man-rem doses to the staff of a power station will sometimes determine the numbers that have to be employed to ensure that no one is exposed beyond the legal limit. Currently envisaged are such innovations as remote inspection methods, routine decontamination washes of the cooling system etc.

The typical integrated exposure to populations in the vicinity of nuclear generating stations and beyond (mainly from radioactive gases) has been taken in the NEA document as 0.1 man-rem/MW-year, and so is less important than the occupational exposure. The releases, however, are lower for pressurized water reactors than for boiling water reactors, by a factor of as much as 100 fold , although the two are similar with respect to occupational exposures. Since Canadian reactors resemble more closely the pressurized water reactors, the above estimate for the integrated dose to the population at large, as distinct from the occupational exposure, may likewise be unduly high for present purposes.

The other major component in the average population dose from nuclear power production as estimated in the NEA document, comes from the reprocessing of spent fuel. Because Canadian reactors currently burn natural uranium fuel, the need for extensive reprocessing can be substantially delayed in this country.

Occupational exposures in reprocessing plants will be mainly to external radiation, and are currently estimated to be similar to those in nuclear power stations. It is not possible to predict what the state of the art will be in the future when this kind of activity is undertaken on a substantial scale in Canada. However, a strong financial incentive will exist, as in the operation of reactors, to reduce as much as possible the numbers of radiation workers who have to be maintained on the payroll, and therefore the integrated man-rem dose for a given installation since this may determine the minimum number of radiation workers. Hopefully the current estimate, which is based on practice today, may prove to be an overestimate as applied to that future time. However, the circumstances will differ. Much of the past experience is presumably based on the processing of relatively-lightly irradiated fuel for the production of weapons-grade plutonium. For the future, the handling of heavily irradiated fuel from power reactors may involve additional problems. Over against this, it is expected that the larger reprocessing plants of the future, like the larger nuclear generating stations of today, will be more efficient in terms of their unit production per man-rem of exposure. Thus the reliability of current estimates of doses associated with fuel reprocessing is still limited. Because of Canada's use of natural uranium, experience in this matter will presumably come first from other countries.

GAPS IN KNOWLEDGE - CANCER RISKS

Although cancer induction by radiation has been studied in great detail in small laboratory animals such as mice, the results from these experiments are of limited use for the purpose of obtaining quantitative estimates of radiation risks in man. Much reliance has therefore had to be placed on the limited information obtained from observations carried out on the available irradiated human populations.

Since about one fifth of all people die of cancers that are not attributed to radiation, it becomes particularly difficult to detect a carcinogenic effect of the radiation in groups exposed to low doses. Moreover, for the same reason it is virtually impossible to determine by direct observation whether there is any safe level of exposure below which no cancers at all are produced by the radiation. Because of this it is regarded as prudent to assume for purposes of radiation protection that the risk of radiation-induced cancer varies in direct proportion to dose, down to the lowest doses. The possibility exists, of course, that the efficiency of the radiation in causing cancers might even be greater at the lower doses. But most of the available data at doses that can be studied indicate a probable mixture of "1-hit" and "2-hit" effects; i.e. the effect increases with the dose at a rate greater than the dose but less than the square of the dose. Only occasionally has a different relationship been demonstrated at the lower doses. Thus, if the assumption of linearity is wrong it is generally considered that the true risk will have been over-estimated rather than under-estimated as a result.

The irradiated human populations most suitable for study have, furthermore, been exposed either to a single large dose as in Hiroshima and Nagasaki, or to a limited number of individually substantial doses as in patients irradiated for ankylosing spondylitis (arthritis of the spine). Data from other populations have so far been less useful. Thus it is quite possible that the same total doses would have been less hazardous if delivered in smaller amounts over longer periods of time, as suggested by studies with animals. For purposes of radiation protection, however, it is customary to assume that the risk is independent of the rate at which a total dose is delivered.

Recently it has seemed more probable that only a part of the induced cancers varies in direct proportion with the radiation dose, and that another part varies as the square of the dose. Also it seems likely that protraction of a radiation exposure in time would reduce the frequency of this second part of the response. If this view is correct, and there is some evidence that it may be, the estimates presented here could be higher than the true risks, perhaps by as much as a factor of three.

GAPS IN KNOWLEDGE - HEREDITARY DISEASE

Failure to observe directly any increase in the frequency of hereditary diseases among offspring from irradiated humans has imposed a limitation on those who attempt to estimate the genetic risks of radiation exposure. Similarly, studies with laboratory mammals have provided only limited evidence of actual harm in offspring from irradiated parents. Indeed, experiments with populations of small mammals, heavily irradiated over many generations, have yielded so little indication of any increased disease, or lack of well-being, that this type of experiment has largely ceased to be of interest to those geneticists who study hereditary changes. Thus, an indirect approach to the problem of hereditary harm has had to be employed.

The estimates of genetic risks presented here assume that all of the known, serious, dominantly-inherited diseases of man would increase over the generations to a new level, in direct proportion to any sustained elevation of the mutation rate such as would occur with exposure to any environmental mutagen, including radiation. They also assume, with much less assurance, that some substantial fraction of the irregularly inherited diseases and congenital anomalies would do likewise.

The first of these assumptions may well be correct, but the combined frequency most often quoted for the severe dominant diseases is based on a survey which included common conditions that are no longer regarded as dominantly inherited. Until a revised estimate for the frequency of severe dominant disease becomes available, and is generally accepted, it would seem likely that there has been an over-estimation of this part of the risk, by perhaps something like three-fold.

The second of the two assumptions, i.e. that many of the severe irregularly inherited diseases of man would also increase similarly in frequency, is open to considerable doubt. Although testable in lower animals, no evidence has been produced in its support. If the assumption is wrong, two thirds of the original estimate is removed; and considering the two assumptions together, the true risk might be lower than that estimated here by perhaps as much as ten-fold. Alternatively, theoretical arguments are occasionally put forward to the effect that the estimated risk neglects some forms of genetic injury too subtle to be detected and measured by current methods in either man or laboratory mammal. No strong reasons have been advanced, however, to support this view in the absence of direct evidence.

THE DIRECTION OF THE UNCERTAINTIES

It might seem from the foregoing discussion that all of the uncertainties with respect to the radiation risk estimates fall in the one direction. This is, of course, not true. It could be argued (a) that radiation exposures will be higher in the future than has been estimated, (b) that low doses are relatively more efficient in causing cancer than are higher doses, and (c) that non-specific forms of hereditary lack of fitness may be induced by radiation and that these will be of greater importance than the known genetic diseases. Each of these possibilities is in fact suggested from time to time. However, no proponent of any one of these views has yet presented a reasoned case that has convinced his colleagues.

Most of those who have been involved in the estimation of radiation risks tend to feel that it would be more serious to underestimate the hazards now, when practices and standards are becoming established, than it would be to overestimate them. Also, scientists are unlikely to overlook possible effects which they believe to be real and feel can be demonstrated to be true. It is presumably for this combination of reasons that uncertainties in the risk estimates appear to be mainly in the one direction.

If one accepts that the risk estimates given here may overestimate the true risk, it is still reasonable that they be used as a basis for setting safety standards. Only when these safety standards are unduly restrictive will serious problems arise. In such circumstances, re-assessment of both the biological risks and the associated social benefits, in relation to each other, would be needed in order to arrive at a better balance between the two."

A. <u>Need for Research in Radiation Biology</u>

A summary for the needs for research in radiation biology is given below:

1. It is likely that future radiation exposures will increase as a result of an expanding nuclear industry and of an increasing use of diagnostic radiology, especially of radionuclides in nuclear medicine. Different reactor types will give different distributions of occupational and population exposures but the application of the ALARA principle (22) should result in keeping both categories of exposure to a minimum, that is, far below the maximum permissible dose.

2. It appears that risks of cancer induction from radiation based on a linear dose-response model have been overestimated by a factor of two to three for small amounts of low LET radiation. Research is needed to define more precisely the quality factors for high LET radiation. Although radiobiological theory does not support the concept that low doses are more efficient than high doses of radiation for the induction of delayed effects, experiments should be designed to furnish evidence for this view. Epidemiological studies of radiation workers will not answer the problem of the effectiveness of low doses but will reassure that the present day risks of radiation exposure have not been grossly underestimated.

It also appears that the risk of hereditary disease induced by radiation has been overestimated, however, the results of long-term animal experiments and of research on different categories of human hereditary diseases should be kept under review for future implications of these risk estimates.

4. Finally, research on the production of delayed effects by chemical agents [illegible] have meaningful input into the mechanism of radiation induced cancer and genetic defects and should be pursued vigorously.

B. Need for Environmental Research

The following recommendations for future research in the aquatic environment are taken from a draft document (110) prepared by the National Research Council of Canada Panel on Radioactivity in the Aquatic Environment under the Chairmanship of I.L. Ophel. Similar recommendations are applicable for future research in the terrestrial environment.

"1. There is a need for more information on natural radionuclides and background radiation levels in aquatic ecosystems in Canada. Consideration of the raw data already available (consisting mostly of gross gamma and beta measurements) would be useful, but of limited value, for unless quantitative measurements of individual radionuclides are made assessment of impact on the aquatic environment is not possible. Data on geochemistry of natural radionuclides is sparse for all of Canada, but particularly so for Arctic areas, glaciers and the Canadian west coast.

2. Some method of coordination between Canadian research groups should be devised to overcome present deficiencies in data presentation. Data from different sources are often unusable because the parameters are either unknown or disparate. Uniformity of models, consistency in radionuclide analysis and counting methods could best be achieved through inter-laboratory calibration studies.

3. Further consideration should be given to those natural radionuclides dispersed as a result of industrial processes (technological enhancement). Areas that clearly need more study are radionuclide releases from uranium mining and milling, coal-fired power stations, and phosphate fertilizer plants (including by-products). Here knowledge of the amounts of particular radionuclides released, and their subsequent environmental behaviour would be essential.

Monitoring programs near Canadian uranium mining operations often measure only one radionuclide (Radium-226). We suggest that such programs should routinely include determinations of radon and radon progeny (Lead-210, Polonium-210) as well as uranium and thorium. Data compilation of effluent flow rates to the environment is an essential first step for assessments of environmental impact.

4. Almost all the available information on radionuclides in the marine environment is from non-Canadian sources: there having been few measurements made of radionuclide concentrations in Canadian coastal waters. Radionuclide mobility caused, for example, by surface water transportation due to deforestation, or discharges to the sea from drainage basins, that might be specific to the Canadian environment, needs investigation. Atmospheric transport and precipitation of the radionuclide content of the marine environment needs further research.

5. Radionuclide concentrations in fresh water communities at each trophic level should be studied with particular reference to oligotrophic lakes and rivers, such as those found on the Canadian Shield. These low-nutrient waters result in high concentration factors for trace elements (including radionuclides) in aquatic organisms, due to lower concentration of competing stable ions in these waters.

6. Long-term effects of chronic low-level radiation on aquatic populations accumulating radionuclides under natural conditions are of interest. Concentration factors for most chemical elements and/or their radioisotopes are needed in both Canadian fresh water and marine communities, particularly for fish, but concentration factors for edible seaweeds, crustacea and mollusca are also of interest. Other factors also need to be examined, such as accumulated sediment contamination levels, chemical forms of specific elements and/or radionuclides and nutrient

levels that have direct effects on the radionuclide accumulation process in aquatic biota need examination.

7. There are few studies of radiation-induced somatic and genetic changes in populations of aquatic organisms. Although in terms of population mortality chronic radiation doses at environmental levels appear to be insignificant, this may not be true so far as mutation and reproductive rates are concerned. Possible interaction of other environmental factors with chronic low-level radiation doses is not well understood. Methods should be developed to enable recognition of somatic radiation effects, for example, cancer in individual biota as well as studies in whole populations and communities. Research on the effects of chronic low-level radiation might well prove non-productive so far as mortality, mutation rate, carcinogenesis and other somatic changes are concerned, but negative results (that is, no effects) are as important as positive results for the establishment of environmental criteria."

V. CURRENT RESEARCH ON THE BIOLOGICAL EFFECTS OF RADIATION

A. Research in Atomic Energy of Canada Limited Research Company (AECL-RC)

Because of the gaps in knowledge and the uncertainties outlined previously, many countries support research on the biological effects of radiation in their national laboratories and academic institutions. As has been mentioned before, international organizations such as UNSCEAR and ICRP examine the published results of these national organizations in order to assess the overall hazard of exposing man and the environment to radiation. Other international organizations carrying out related work are: International Atomic Energy Agency, United Nations Environment Program, World Health Organization, Nuclear Energy Agency, and International Labour Organization. To share in this international activity and to solve some of the problems concerning radiation effects it is important for AECL-RC to have people actively working in these subject areas, otherwise access to this body of international information would be difficult to achieve. AECL-RC has groups at both Chalk River (CRNL) and Whiteshell (WNRE) carrying out fundamental and applied research in radiation biology, environmental studies, and radiation protection. It is obviously impossible to cover every aspect of research needed to assess the biological effects of radiation and for this reason the two groups have selected particular areas of research which might yield the greatest returns for their efforts. Again the two groups, although not large (50 professionals plus double the number of supporting staff), have to maintain excellence in these areas in order to have credibility with their colleagues and peers. They must be aware of the world literature, as well as contributing to it, and be in a position to respond not only to deficiencies but to new discoveries and adapt their research programs accordingly.

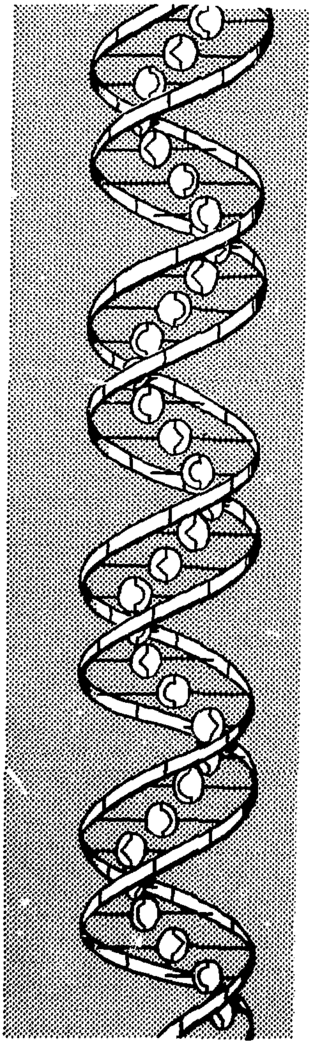
1. Research in Radiation Biology at CRNL and WNRE

Before describing the radiation biology research programs of CRNL and of WNRE it is necessary to describe in a general way what DNA is and the sequence of events following irradiation of a living organism.

About 25 years ago biologists established that the information for all life processes is contained in deoxyribonucleic acid (DNA) - a long threadlike molecule. The DNA molecule is the blueprint for the construction and function of living things; it stores all the genetic information that is passed from one generation to the next and in this manner ensures that the major characteristics of living things remain constant over many generations.

Both cancers and hereditary defects are believed to be caused by changes in the DNA coding. Numerous changes do occur spontaneously because DNA is not completely stable and is subject to slow breakdown. Current data suggest that up to 50 changes per minute (or several million a year) may occur spontaneously in the DNA of each living cell in the human body. Changes in DNA structures may also be brought about by radiation, ultraviolet light, viruses, and many chemical agents. In these circumstances, life as we know it would be impossible if the organism did not contain built-in mechanisms which repair the DNA molecule. The instructions for the repair mechanisms are also included in the DNA as part of the information necessary for life processes.

These repair systems identify and correct changes in DNA, whether these changes arise spontaneously or as a result of other agents. In fact, almost all changes in DNA are corrected unless the exposure to radiation or chemical agents becomes so high that the system is unable to cope with the amount of change that has been produced. Cancers and hereditary defects which occur naturally are believed to be the result of a small number of errors which are overlooked and therefore not repaired, or are repaired incorrectly. The DNA structure and function is summarized in Figure 5 (111).



DNA - The Genetic Material

DNA carries the hereditary information for all life processes

*

Approximately 100,000 separate instructions are encoded *in the DNA of each human cell.*

*

Errors *in* these instructions can lead to cancers and hereditary changes.

*

Errors *are* introduced into the DNA by spontaneous events, by environmental chemicals, by certain *viruses, by sunlight (skin only) and by* ionizing radiations such as X-rays.

*

Natural radiation levels are responsible for less than 1% of the errors which result in cancers or hereditary diseases in human populations.

FIGURE 5

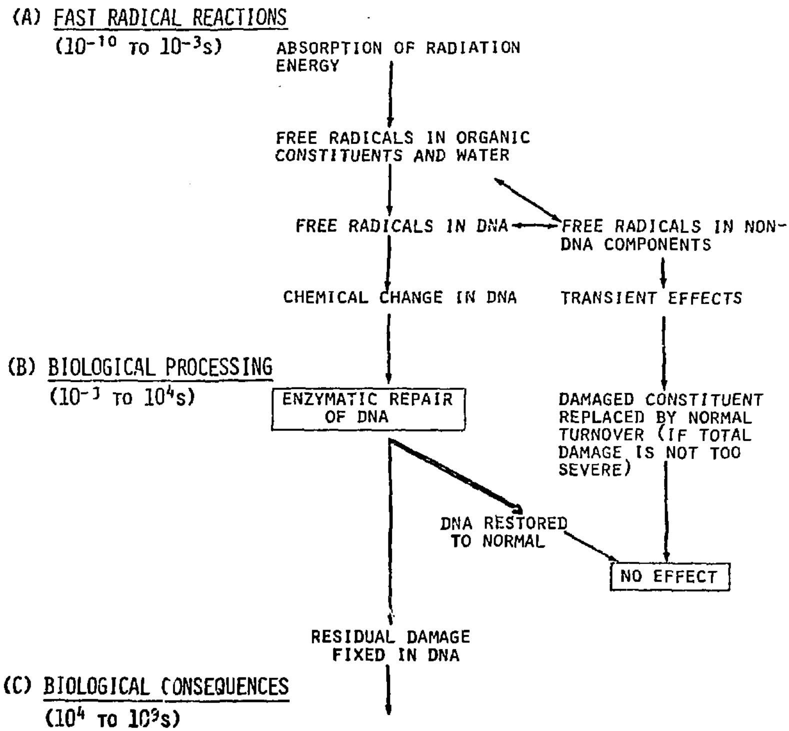
When radiation is deposited in tissues or cells a series of extremely rapid reactions occur. The physical energy is transferred to form a variety of highly reactive free radicals that react with many cellular constituents. These important cellular constituents become damaged. If the amount of energy deposited is very large (that is, at high doses or high dose rates) the damage is so overwhelming that the cell is killed. At lower doses and lower dose rates repair processes can predominate and if the repair is complete, there could be total recovery of the cell and it would be restored to a normal condition. In some instances, if repair of the damage in DNA is not carried out correctly, then the mis-repair results in delayed changes after a latent period, expressed as somatic or genetic effects. These processes are all illustrated in Fig. 6 (112).

(a) Radiation Biology Research at CRNL

The objectives of this research have been outlined in a previous document (112); the basic purpose is to provide a better understanding of the reasons why radiation causes various harmful effects in living organisms and to continue to ensure that radiation standards for health protection are in fact safely derived. Radiation effects are studied with a wide variety of living organisms using advanced techniques in molecular biology, in order to be certain that we understand the effects upon other living organisms in our environment as well as the effects upon humans.

Studies with microorganisms have provided increased understanding of the influence of hereditary deficiencies in DNA repair systems on radiation effects (112-114). Research programs in this area are in progress at CRNL. In recent years, it has also been discovered that a small fraction of human populations suffer from rare hereditary

SEQUENCE OF EVENTS FOLLOWING IRRADIATION OF A LIVING ORGANISM



1. GENETIC EFFECTS IN SUBSEQUENT GENERATIONS
   (A) POINT MUTATIONS
   (B) GROSS CHANGES IN DNA SEQUENCES
2. SOMATIC EFFECTS IN IRRADIATED INDIVIDUAL
   (A) DUE TO DNA DAMAGE IN SURVIVING CELLS
      (a) CANCER INDUCTION
      (b) PREMATURE AGING
   (B) DUE TO CELL DEATH AT HIGH DOSES
      (a) ABNORMALITIES IN FOETAL DEVELOPMENT
      (b) STERILITY
      (c) CATARACTS, LOSS AND GREYING OF HAIR, SKIN ULCERATION AND DEGENERATION, ETC.
      (d) SUPPRESSION OF IMMUNE RESPONSES
      (e) PROMOTION OF CANCER INDUCTION
      (f) DEATH OF WHOLE ANIMAL DUE TO BONE MARROW (C. 500 RADS OR 5 GY) AND INTESTINAL MUCOSAL (C. 1000 RADS OR 10 GY) DEATH

FIGURE 6

diseases which are associated with deficiencies in DNA repair systems (115-117). The individuals with these hereditary deficiencies are more prone to develop cancer than are most persons in the population. Cells from these individuals are frequently somewhat more sensitive than normal to the effects of radiation and of certain carcinogenic chemical agents (116,117). This research program has attracted considerable attention and is currently being supported at CRNL by funds from the U.S. National Cancer Institute as well as by AECL.

Other research programs are concerned with the biological interactions between ionizing radiations and environmental agents such as ultraviolet light, cigarette smoke condensate, nitrites, caffeine, urethane, etc. Research in this area using microorganisms is concentrated on an understanding of the basic mechanisms of these interactions and the influence of DNA repair processes (113,118). The accompanying studies with animals (114,119-121) are concerned with the effect of environmental agents on the shape and magnitude of the dose-effect curves for induction of cancer by ionizing radiation. The carcinogenic hazards of radiation in humans are estimated from known effects in human populations exposed to high radiation doses in the past (1) and who were presumably also exposed to all the normal environmental agents to which other humans have been exposed over the past 30 years. The research program described above is designed to improve our understanding of potential radiation hazards in particular working environments as well as in generally changing environments in the future.

An understanding of the shape of dose-effect curves is of crucial importance in extrapolation from known radiation effects at high radiation doses down to predicted effects at low levels of radiation where effects, if they exist, are much too small to be measured. A considerable portion of the research at CRNL is therefore devoted to an understanding of the effects of DNA repair processes on the shape of dose-effect curves (112,114,122). In general, the dose-effect curves for sparsely ionizing radiations such as X or gamma radiation tend to be curvilinear at high dose rates and linear at low dose rates, while the dose-effect relationships for densely ionizing particles such as neutrons tend to be linear at all dose rates (122). Currently, increased attention is being devoted both at CRNL and at WNRE to a comparison of dose-response relationships for the effects of gamma radiation and of tritium beta-radiation (122-124).

b. Radiation Biology Research at WNRE

The long-term goals of research at WNRE are naturally similar to those described for CRNL but the emphasis of effort is different. WNRE has concentrated its research on the very early events in cells following the deposition of energy. The aim is to understand the role of free radicals, activated oxygen species and their scavengers, and to characterize the initiating lesions in biochemical constituents of cells. The role of naturally occurring enzymes such as superoxide dismutase and peroxidases is being studied to learn how these enzymes can protect DNA or membranes from being damaged by the highly reactive free radicals (124-128).

The WNRE group has concentrated on another area, membrane research (124). Cellular and nuclear membranes have the important function of controlling exit and entry of essential metabolites, minerals and water while at the same time retaining macromolecules such as DNA, RNA and proteins. Damage to membranes may play a role in mediation of delayed effects. For example, free radicals captured in the membrane could be propagated to DNA, or damaged membrane could allow harmful constituents such as carcinogens to enter and interact with important cellular constituents, resulting again in ultimate expression as somatic or genetic effects. Model membranes prepared from phospholipids have been used to study effects of low doses and low dose rates (126), an the relative biological effectiveness of tritiated water to cause membrane damage (124). It is not known to what extent the results on model membranes carry over to membranes of living cells.

At CRNL, research is concentrated on DNA damage as the initiating event for delayed effects. An appreciable part of the research at WNRE is concerned with the alternative suggestion that the initiating event is not damage to DNA itself, but damage to substances produced from DNA and its derivatives. The genetic message of DNA is normally translated into a messenger-ribonucleic acid (m-RNA) and then m-RNA determines the detailed structure of proteins which either form the structure of the cell or catalyse various chemical reactions in the cell. The normal sequence of gene expression is thus DNA→ m-RNA→protein. Thus it is conceivable that damage subsequent to DNA, either in the RNA or in proteins, could also be a cause of delayed effects such as cancers, including leukemia. (However, damage subsequent to DNA cannot explain genetic defects as only damage to DNA can be transmitted from one generation to succeeding ones.) Research projects in this area include studies of the activation of viruses by radiation and of the mechanisms by which normal mammalian cells in tissue culture can be transformed into potentially cancerous cells by radiation and other agents (129).

2. Detection of Harmful Effects in Man

Appropriate safety standards must be based to a large degree on knowledge of the risks to man at various exposure levels. This is true not only for radiation but more generally for chemical agents that cause cancer or other harmful effects. For this reason, investigators at CRNL have taken a special interest in the potential value of existing routine health records (e.g., death registrations, hospital discharge summaries, and registers of special diseases) which contain diagnoses of cancers and of hereditary conditions (130). These records exist in the form of magnetic tape, which can be used to determine whether or not members of an "exposed" group suffer delayed harm from their exposure. Computer methods developed by CRNL staff

(130,131) enable the records of populations exposed to various working environments, or to medical X rays, to be searched for medical information concerning subsequent harm. All names are converted into code and strict precautions are taken so that personal identification is impossible and no breach of privacy occurs. Currently our computer methods are being used by the National Cancer Institute of Canada, in collaboration with Statistics Canada, to follow up large populations of employees in various Canadian industries, and large numbers of persons who received repeated fluoroscopic examinations some decades ago in the course of treatment for tuberculosis (132,133).

By using these computer methods to reduce the costs and increase the sizes of the populations that can be followed up, it is expected that much better human risk data can be obtained on which future safety standards in many industries may be based. Thus, an emphasis on radiation safety has led to methods for obtaining information on the hazards of less well-understood industrial chemicals.

As noted previously, data from other establishments in the UK, the USA and Canada have indicated that the health of radiation workers in these establishments is at least as good as that of workers in other safe industries and is better than the health of the average person of the same age and sex in the general population (Figs. 1 and 2). Similar follow-up studies of Atomic Energy of Canada Limited (AECL) have not yet been carried out, however, WNRE and CRNL are cooperating very closely to monitor the health of <u>all</u> Atomic Energy of Canada Limited employees, with special emphasis on setting up a prospective follow-up study on the health of <u>radiation workers</u> in AECL (134,135). Close cooperation with provincial registrars, Statistics Canada, Health and Welfare Canada and agencies such as the National Cancer Institute of Canada will be needed to execute these studies properly.

3. Environmental Research at CRNL

Evaluation of the capacity of ecosystems to receive radionuclides without creating a potential hazard requires a thorough knowledge of environmental behaviour. Radionuclides in the environment behave in the same way as their stable counterparts, that is, they are dispersed in air, soil, and water and some are subject to biological concentration in plants and animals (136). This means that there are a large number of potential environmental pathways available to radionuclides for transport through the ecosystems.

On CRNL property there is a wide range of fresh water and forest habitats suitable for environmental field-research. One such habitat is Perch Lake, a small dystrophic-eutrophic lake within CRNL boundaries. Because Perch Lake has contained small amounts of radionuclides for many years it has provided the opportunity to study radionuclide behaviour in a natural fresh water ecosystem. A typical biological food chain for a lake is shown in Fig. 7. Research at CRNL on cobalt-60 and strontium-90 transfer through the food chain has shown a progressive decline in concentrations of both these radionuclides and their stable counterparts as they move to higher trophic levels. This means that top predators, such as large carnivorous fish, accumulate less radioactive cobalt-60 and strontium-90 per unit body weight than do plants and smaller fish (137,138).

For a substance to be an environmental hazard it must not only be potentially toxic but also environmentally mobile. This fundamental concept has prompted considerable research at CRNL to assess the geochemical controls in radionuclide migration in the Perch Lake basin (see Fig. 8).

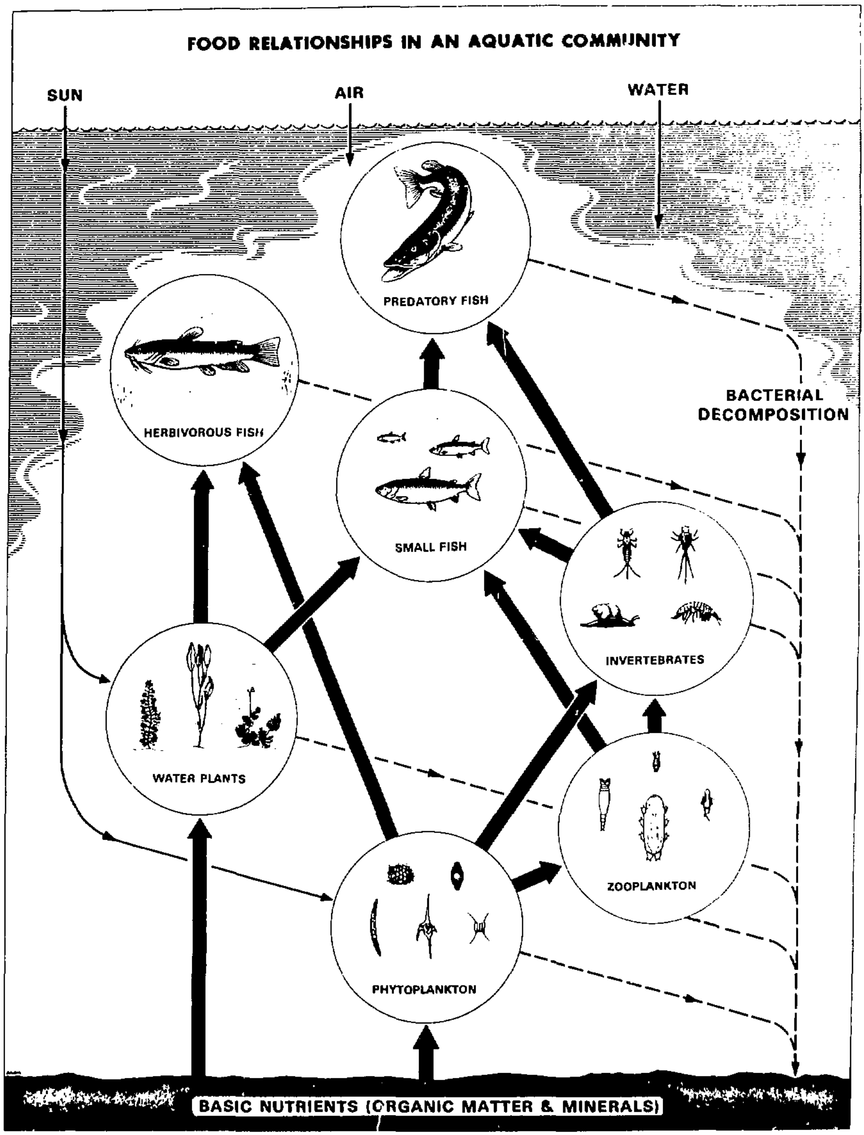


Fig. 7. Food chain in a Lake

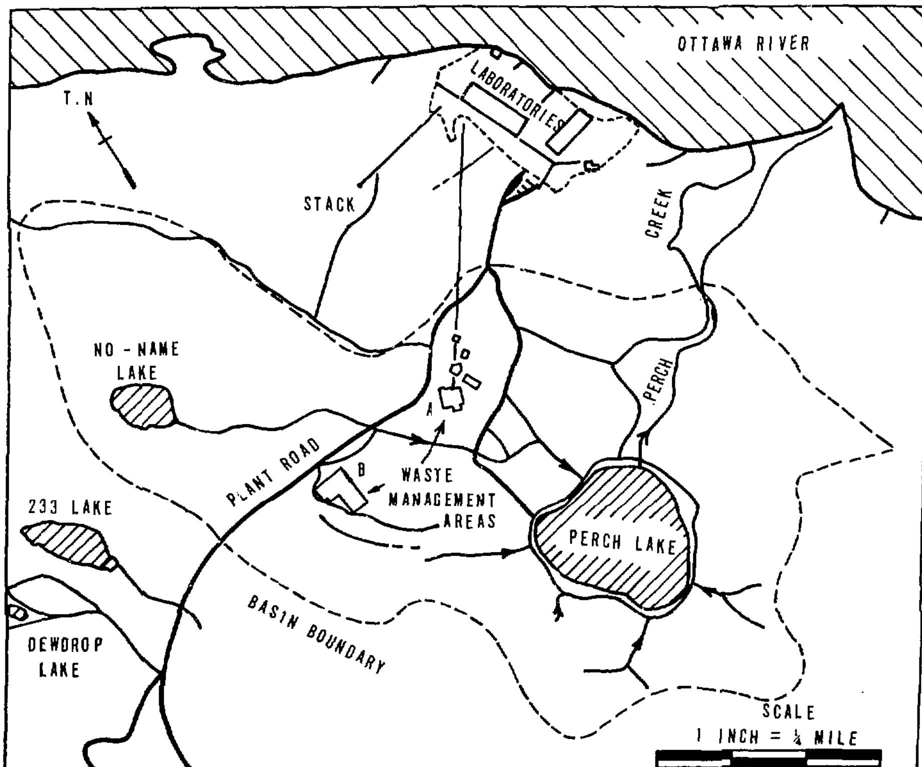


Fig. 8. The Perch Lake Basin

During 1954 and 1955 approximately 60 m^3 of medium-level liquid radioactive wastes, containing several hundred curies each of strontium-90 and cesium-137, were released into experimental waste disposal pits at CRNL. Beginning in 1960 (139) and until the present time the movement of these wastes has been carefully studied and documented (140). Strontium-90 and cesium-137 are chromatographically separated as they pass through the sandy aquifer and move at characteristic velocities that are specific to the radionuclide and much less than the velocity of the transporting groundwater. For strontium-90 the characteristic velocity is 3% of that of groundwaters; for cesium-137 it is 0.3% (141).

Various geochemical processes influence the mobility of radionuclides in groundwater systems. For this reason the geochemistry of the Perch Lake basin has been studied. Oxidation-reduction (redox) characteristics, microbial catalysis, precipitation, complex-ion formation, acid-base buffering and interaction between different valence states are factors affecting ion mobility that are the subject of a series of investigations at CRNL (142,143).

Since early in the 1950's it was recognized that a method was needed for the permanent disposal of radioactive wastes from nuclear fuel cycles. Studies conducted at CRNL prior to 1955 demonstrated that radioactive fission products could be incorporated in nepheline syenite glass blocks. In 1959-60, high-level wastes incorporated in this highly durable glass were buried beneath the groundwater table at CRNL (Fig. 9). Since then, and up to the present time, the leaching of radionuclides from the blocks has been monitored (144). Although approximately 39 L/day of groundwater has flowed past the blocks for nearly 20 years the amounts of radionuclides released to the environment are small (about 0.0003%).

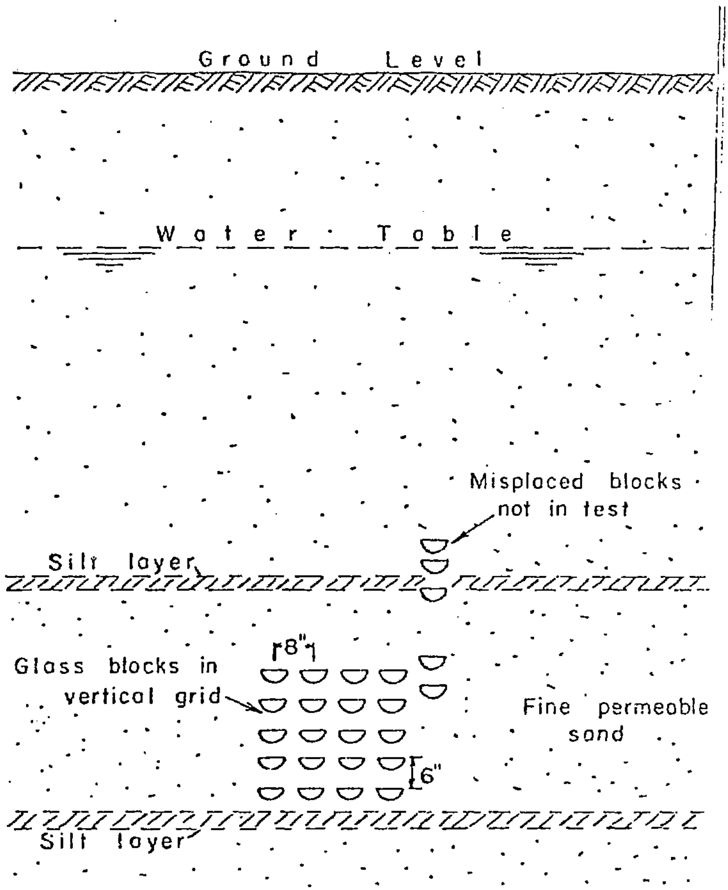


Fig. 9. Grid of glass blocks in soil.

The development of procedures for radiochemical monitoring, particularly for the determination of actinides in environmental samples, is being studied as part of the ongoing research into the improvement of environmental monitoring methods. A radiochemical survey of vegetation indicates the presence of beta (tritium, strontium-90) and gamma (cesium-137, cobalt-60 and potassium-40) emitters in samples of twigs, buds, and tree sap from trees growing in the vicinity of CRNL waste management areas (145). The objective is to determine the distribution of radionuclides taken up by vegetation surrounding waste management areas. Some details of environmental monitoring at CRNL is given in Appendix 4.

The uptake of cobalt-60 by edible plants (that is, tomatoes, potatoes, beans, root crops and cereals) grown in contaminated soils has been investigated under a variety of experimental conditions (146). This work has shown that cobalt-60 is readily taken up by these crops with uptake ratios (= ^{60}Co sample/^{60}Co soil) of from 0.08 to 0.55 on a dry weight basis.

Since 1975, groups of scientists from several Canadian universities and government departments have been studying the hydrological, geochemical and geological properties of the Perch Lake basin (147). The Perch Lake basin (Fig. 8) has become recognized as a national environmental facility for numerous cooperative studies by Canadian scientists. The object of these studies is to develop simulation models to describe the time-dependent mass flow rates of water and dissolved and suspended substances through the basin. These models can be used to predict the future behaviour of radioactivity in the environment. The results of these studies are important for the Waste Management Program (148) mentioned in the next section.

4. Environmental Research at WNRE

Research on the movement of radionuclides through the terrestrial environment is the main interest at WNRE; the CRNL program is mainly concerned with research on the aquatic environment. To an increasing extent the research at both establishments has been related to work undertaken in support of the Waste Management Program (148), that is, the disposal of high level wastes, either as irradiated fuel or separated fission products, in a deep rock repository in the Canadian Shield. Pathways analysis (see Appendix 4) is being undertaken for the migration of radionuclides from the rock repository to the biosphere with emphasis by WNRE on the terrestrial component and by CRNL on the aquatic pathways. Good progress has been made in developing models for the movement of radionuclides through the food chains to man in the context of Canadian conditions (149).

Effects of radiation on plants and animals in the environment have emphasized the need for studies at the community and species level. Plant species and associations are being studied before and after irradiation in a project termed FIG (Field Irradiator Gamma)(103). The animal counterpart is a study called ZEUS (Zoological Environment Under Stress)(93) and this project will be used to determine the long-term effects of low-level radiation exposure of a population of field voles (see Fig. 10 and 11).

A goal of the FIG project is to detect and characterize any ecological changes in plant associations (including trees) being irradiated at approximately 100 times that of background. Since March of 1973, when long-term radiation study began, observations have been continuously compiled (150,151). Radiation effects at progressively lower levels of exposure have been found as the experiment has continued. The specific radiation effects have been followed by secondary effects on species composition and numbers affected by changes in the canopy.

Irradiation of the area surrounding FIG will continue until an equilibrium is established as follows:

a. No increase in the area of plants killed by radiation,
b. No major unpredicted ecological change at any dose rate,
c. Return to stability following outbreaks of forest tent caterpillars, spruce budworms, or other disruptions.

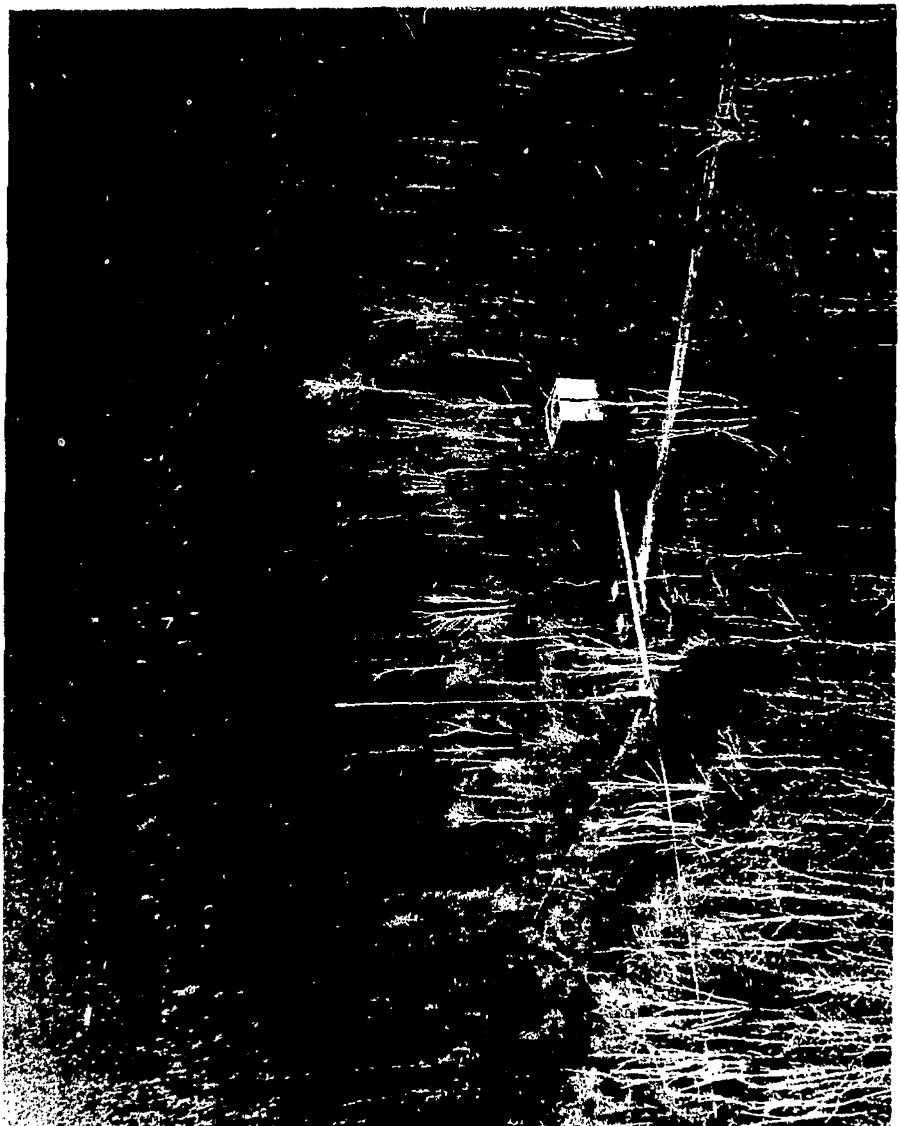


Fig. 10. Aerial View of FIG.

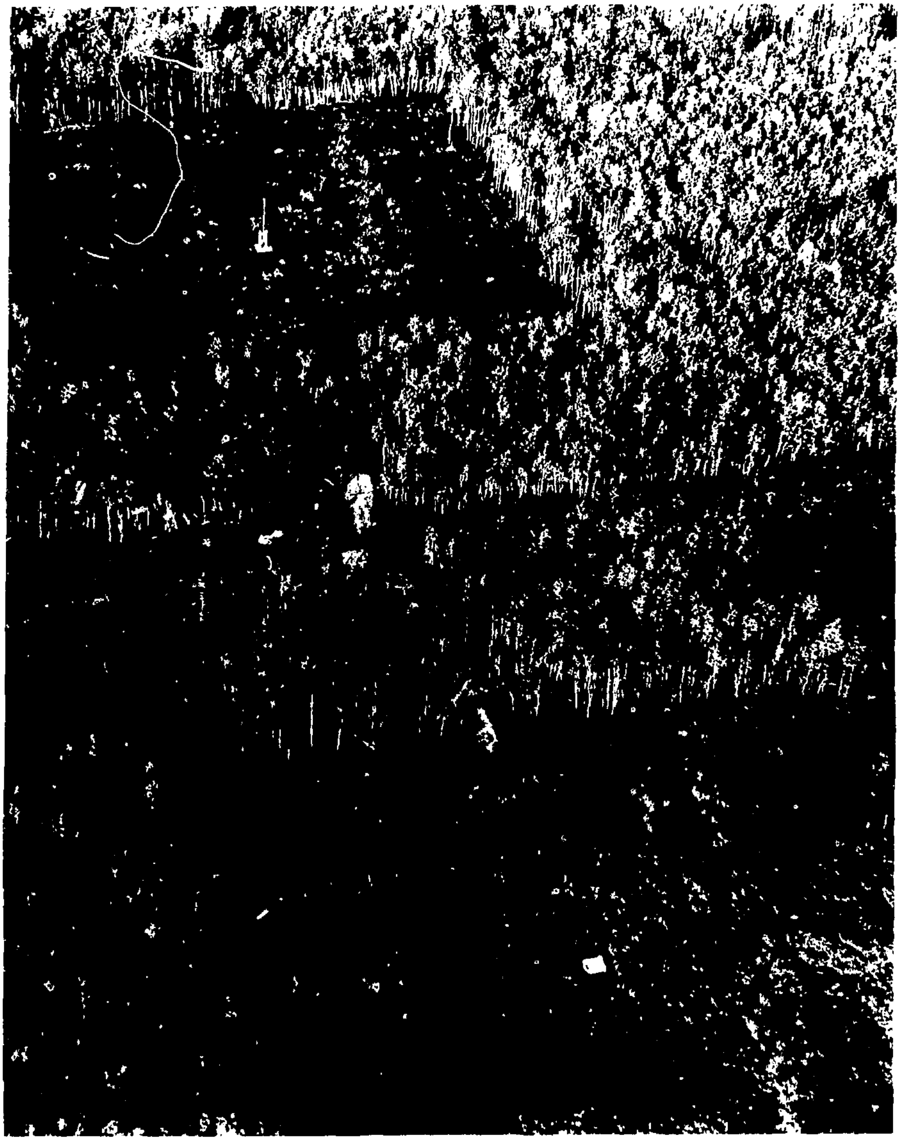


Fig. 11. Aerial View of ZEUS

After these criteria have been fulfilled irradiation will cease and study of the recovery phase will begin. The duration of this phase will be determined by similar criteria to those listed above. The same measurements and observations will be made during recovery.

Final preparations have been made for the startup of the ZEUS experiment which now only awaits some modification to the shielding of the irradiator by which defined dose rates are achieved in the irradiated area. Project ZEUS (93) will be used to identify the lowest level of chronic exposure to ionizing radiation at which there occur demonstrable effects on the population. It involves irradiation of a free-living population of meadow voles (152). The design of the irradiation facility and the development of the experimental sites, "island meadows", are almost complete. The irradiation facility will provide a uniform radiation field over an island meadow, a grassland area surrounded by forest. The intensity of the facility's radiation field can be reduced from a maximum of 10 rad per day to background by the addition of extra shielding. The irradiation facility is transportable. Hence, results obtained from one population can be replicated using another population inhabiting another island meadow.

5. Radiation Dosimetry Research at CRNL

Research is in progress at CRNL on those problems of radiation dosimetry that are of particular concern in the Canadian nuclear program. Those classified as external dosimetry problems are:

(i) neutron dosimetry

(ii) the measurement of tritium and noble gases in air and tritium in water

(iii) the measurement of natural and long-lived alpha emitters in air

(iv) the estimation of beta and gamma doses and dose rates.

The work on internal dosimetry comprises:

(v) radiochemical analysis

(vi) *in vivo* monitoring

(vii) metabolic modelling

These topics are discussed further below.

(a) External Dosimetry

In order to keep the radiation exposure of workers below the statutory limits each worker wears a dosimeter which records his accumulated exposure. The dosimetry system designed at CRNL and used throughout Canada for measurement of beta- and gamma-radiation exposure (Fig. 12) is undergoing further development to improve its capabilities (153). In particular, the calibration constants of each dosimeter in use are stored in a computer file so that as each dosimeter is processed the correct exposure estimate may be made. The result is then retained automatically in the radiation history of the wearer and also printed out for the information of both the individual worker and his supervisor. The individual calibration procedure replaces the earlier arrangement of using a batch calibration factor for a large number of dosimeters and thereby results in improved accuracy of dose estimates. Sensitivity of the dosimeters may be enhanced by special annealing procedures prior to use and these will allow not only the measurement of lower levels of occupational exposure but will permit this basically simple monitoring procedure to be used for measurement of low radiation levels in the environment both from natural radiation sources and nuclear facilities such as power stations. This dosimetry system is not intended for the detection of neutron exposure. Neutron exposure can occur either when there is an accidental assembly of an unshielded critical mass fissile material - a criticality accident - or during the routine operation of accelerators and in fuel fabrication facilities.

In the event of a criticality accident the objective is the determination with the least delay of the neutron doses which have been received. The measurement of neutron dose is not at all simple and requires both a knowledge of the response functions of the detectors used and the nature of the energy spectrum of the neutron source. With both of these data a dose estimate may be made. However, in an accident situation the energy spectrum, which depends strongly upon the structure and composition of the neutron-emitting assembly, will not be known. To deal with this problem, calculations (154-156) of neutron spectra from a credible variety of likely neutron sources have been

THE AECL PERSONAL DOSIMETER

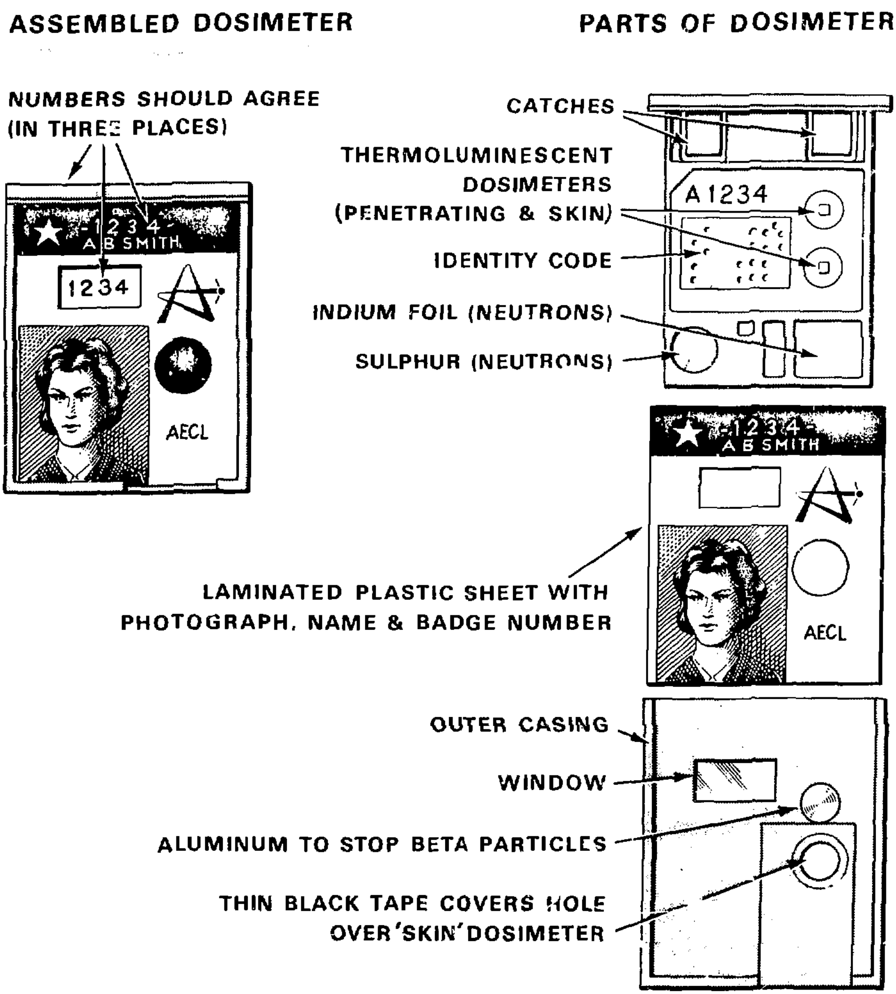


Fig. 12 The AECL Personal Dosimeter

made and some of these are being verified experimentally using a specially designed neutron spectrometer. While the chance of a criticality accident occurring is very small, it has been necessary to undertake these extensive investigations so that if ever needed the means will be available to arrive at reasonably accurate estimates of the large doses which might be expected, since this knowledge will be of considerable help to the medical service which is looking after the exposed workers.

Much lower neutron exposures may be received in the operation of research equipment and in the development of reactor fuel containing plutonium isotopes. To meet these monitoring requirements low level neutron dosimeters have been designed and these are also capable of recording high level accidental exposures.

Some of the techniques and analytical methods developed in the study of neutron accident dosimetry are directly applicable to neutron radiation therapy both in the determination of patient doses and in the design of shielding and neutron beam collimators.

Tritium, a radioactive isotope of hydrogen is produced in CANDU reactor coolants and moderators and tritiated water is easily absorbed in the body through the skin and by breathing. Methods have been developed (157,158) for the detection of tritium in air and water and instruments to perform this task automatically have been designed. Since most detectors suitable for tritium detection are sensitive to gamma radiation special arrangements have been devised to minimize this unwanted response. Tritium may also be present simultaneously both in its elemental form and also combined in water. Since the risk of tritium ingestion is grossly different depending upon its chemical form, selectively permeable membranes are being used to separate tritium gas in air from tritiated water in air so that the concentrations of each form may be determined.

When radioactive elements are present in the atmosphere the risk to exposed workers depends strongly upon the extent to which the particular substance is retained in the body. Thus at one extreme inhaled tritiated water is taken up in the body whereas radioactive noble gases such as xenon and krypton are to a large extent promptly exhaled. Radioactive iodines are retained and accumulated in the thyroid of an exposed person. Since in practical situations many kinds of radioactive isotopes may escape simultaneously from a nuclear facility much use is made of radiation spectrometers to identify particular nuclides by the energies of the radiations they emit. The method is particularly useful in the detection of radio-xenons and radio-iodines which may be identified by their gamma radiation energies (159).

It is also employed in the detection of airborne plutonium where frequently other less hazardous and naturally occurring alpha activity may be present because radon and thoron emanates from the earth's surface and many building materials. In this instance, thin semiconductor detectors permit the recognition of different alpha emitters by their energies. The natural alpha activity is less hazardous to man because its residence time in the body is very short.

Radiation spectrometry using very complex and often bulky equipment has long played a major role in nuclear physics research but the continuing task in radiation protection is the development of simplified and, wherever possible, portable versions of this type of apparatus capable of meeting the specialized needs of radiation protection.

In some locations in Canada, either because of natural causes or through the actions of man, natural radiation levels from radon are uncommonly high and very variable. To enable the assessment of this widespread but low level risk apparatus was designed (160) to measure radon concentrations in buildings over extended periods.

Monitoring instruments are designed for the assessment of exposure hazards in the work place. In this continuing program innovations are made (161) to make best use of new techniques and to respond to new operational requirements in order to meet the basic objective of radiation protection - that all exposures to radiation shall be kept as low as reasonably achievable...(22).

(b) Internal Dosimetry

Research in internal dosimetry at CRNL is concerned with improving methods of estimating doses to individuals following an intake of a radioactive substance, and is in three general areas; radiochemical analysis, in vivo monitoring and metabolic modelling.

Radiochemical analysis of excreta (bioassay), particularly of urine, is one of the most sensitive and useful methods of screening employees to insure that they have not had an intake (ingestion or inhalation) of radioactivity (162). It can also be used to estimate the actual amount of a radionuclide inside an individual if an intake does occur, provided that the metabolic model that describes the retention in and excretion from humans of the radionuclide being considered is known with sufficient accuracy (163-165). In order to use bioassay to its full potential, reliable and sensitive methods of extracting radioactive substances from biological samples are required. These methods often differ from methods commonly used for extraction because the concentration of the element being extracted is usually many orders of magnitude below that of other elements in the sample and these other elements interfere with the extraction. Current research is directed towards improving extraction techniques for actinide elements, in particular, thorium, uranium, plutonium, neptunium, and curium (166).

In vivo monitoring is the measurement of radionuclides in organs and tissues of individuals by measuring externally the number and energies of the photons that escape. It is required to complement bioassay monitoring; in some situations, bioassay monitoring is more sensitive, in others, in vivo monitoring is. In vivo monitoring requires efficient photon detectors with good energy resolution and low background count rates. Developmental work at CRNL is directed toward reducing the background count rate and toward improving the calibration techniques used. Backgrounds can be reduced by improving the amount and type of shielding used around the detectors, by carefully selecting construction materials used in the building housing the monitoring facility, and by sophisticated electronic techniques. CRNL has built a special facility out of selected materials, with several large, well-shielded rooms that have very low background levels (167). Work on reducing the background count rate by electronic techniques is continuing at CRNL (168,169). Calibration of the detectors requires a realistic phantom into which can be put known amounts of radionuclides, with a known distribution in the various organs and tissues. Several different types of phantoms are available at CRNL, and work is directed towards determining which type is most suitable (being able to duplicate the important features of humans) for given radionuclides and organs.

Metabolic modelling, as it relates to internal dosimetry, is the construction of a mathematical model which describes the uptake of a radionuclide and its retention by organs and tissues. Recently a major review of existing models and model parameters was undertaken at CRNL (170). The purpose of the review is to provide "up-to-date" values for radiation doses following any postulated intake of any of the many radionuclides that might be encountered in nuclear energy, nuclear medicine, or nuclear research in Canada, and to identify elements for which current models are inadequate or model parameters not well enough known. Current research is directed towards improving the metabolic models for the alkaline earth and actinide elements.

Once the amount of radioactivity in the organs and tissues of an individual is known from bioassay and/or in vivo monitoring, or is postulated from a metabolic model, the resulting radiation dose can be calculated. Knowing the intensities and energies of different radiations emitted during radioactive decay, doses to the tissues containing radioactivity, and to surrounding tissue and organs, can be calculated. These calculations are straightforward in most instances. Exceptions are the walls of the gastro-intestinal tract, the surfaces of bone, and the bronchial epithelium, where the major fraction of dose comes from activity in surrounding media, which in itself is not considered to be radiosensitive. Dose calculations for these tissues are extremely sensitive to the assumed spatial relationship between them and the media containing the radioactivity. Work to improve these calculations is not currently being done at CRNL but developments elsewhere are being kept under review.

B. Research on the Biological Effects of Ionizing Radiation in Canada

A.M. Marko recently has summarized (171) the research program in Canada in this area and placed the research of the AECL-RC in the context of the overall Canadian scene. AECL-RC supports one-third of the total funds allotted to research in Canada on the biological effects of ionizing radiation. Further references are to be found in the original report (171).

> "It can be seen that almost half the support in Canada is devoted to biological radiation research involving long term effects of the nuclear industry on workers and on populations. In this area there is an interest in defining quantitatively the biological effects of radiation especially at low doses and low dose rates. For this reason epidemiological studies on humans have been initiated to assess the risks to atomic radiation workers and uranium miners. Mechanisms of radiation-induced damage of DNA and its subsequent repair, as well as mechanisms of interaction of radiation with other important biological constituents, are studied to gain understanding, in fundamental terms, of the effects of radiation on living systems. With this body of knowledge it is expected that one could acquire better understanding of the adequacy of current radiation protection standards as proposed by the International Commission on Radiological Protection. This type of research is often called mission-oriented.
>
> The next area of interest, as seen from the amount of support (32.4%), concerns cancer research. In this survey only cancer research involving radiation or radiomimetic chemicals has been included. Therefore projects concerning cancer mechanisms and treatment methods have been included only on a restricted

basis and represent just a fraction of total cancer research undertaken in Canada. The interest in radiation effects and cancer therapy usually involves high doses and high dose rates in contrast to the interests described above particularly in the nuclear industry. Emphasis is usually given to the modification of radiation effects by oxygen, hyperthermia and radiosensitizers with the objective of improving treatment of cancers. Some studies are concerned with the mechanism of cancer induction, and DNA alterations which are in turn believed to play an important role in the initiation of malignant changes. This latter type of work overlaps significantly with the kind of research carried out by those interested in the delayed effects of radiation. Although cancer research is obviously mission-oriented, it is largely carried out in academic institutions and is usually fairly basic in nature.

HISTORY OF RADIATION BIOLOGY IN CANADA

In 1968, A.M. Marko, in a submission to what was then known as the Science Secretariat of Canada Radiation Biology Task Force, reviewed the extent of radiation biology and radiation protection in Canada. That report contains a chronological review of actions taken by various agencies from 1944 to 1968. Events leading up to 1961 resulted in a justifiable case for the expansion of radiation biology in Canada. Based on these events a new Division of Radiation Biology of the National Research Council was established in Ottawa with G.C. Butler as the Director. For a number of reasons this Division lost its separate identity when it was incorporated with the Division of Biosciences to finally form the Division of Biological Sciences. In a reply from C.T. Bishop, the present Director, he states that they currently do not have any projects on the biological effects of ionizing radiation.

From 1962 to 1968 the National Research Council Associate Committee on Radiation Biology attempted to foster research in Canadian universities. It appeared that support to universities in the form of grants levelled off at $600,000-$800,000 per year. From 1968 to the present time no follow-up has been carried out to evaluate the support for radiation biology in Canada. In 1976, D.K. Myers, Head of Radiation Biology Branch, Chalk River Nuclear Laboratories concluded that the major granting agencies in Canada supported mainly individuals who were concerned primarily with cancer therapy, and few if any who were conducting studies related to the practical assessment of hazards of low levels of ionizing radiation. For this reason, the interest of the two radiation biology groups within Atomic Energy of Canada Limited (at the Chalk River Nuclear Laboratories and Whiteshell Nuclear Research Establishment) tend to diverge from those of most other groups of investigators concerned with biological radiation research in Canada. The same conclusion was reached in this survey.

DISCUSSION AND CONCLUSIONS

Public awareness of nuclear power is often focussed on the biological hazards of radiation. In view of the projected increase in electrical power to be generated by nuclear means and the present-day public concerns over nuclear power, the funding for research on the biological effects of radiation can be considered to be inadequate in Canada. It would seem unreasonable that there has been no increase in total effort since 1962-63. In fact, although the support in constant dollars appears to have been unchanged during this time, the effective support for some particularly relevant projects has been reduced. For example, greater emphasis on the need for data involving low doses and low dose rates has served to direct special attention to experimental projects that are more costly because of the longer irradiation times and the larger sample sizes to yield valid statistical observations, pertaining to smaller effect, with corresponding increase in man-power effort.

In Canada, in both government laboratories and academic institutions, there is considerable interest in studies at the molecular level, notably studies on DNA. This observation may not be too surprising since research work with DNA currently lies on the forefront of molecular biology, and good scientists understandably prefer to undertake research in meaningful and exciting areas. This research is much more sophisticated and expensive than the simpler experiments in radiation biology that were carried out 20 years ago.

Large scale animal experiments on toxicity of radionuclides, such as plutonium or other transuranics, are completely lacking in Canada because these types of experiments are extremely expensive. Similarly large scale animal experimentation to observe genetic effects produced by radiation have been largely avoided in Canada. Thousands of animals and their offspring have to be observed to score the frequency of genetic defects induced by radiation; because of this the experiments are time-consuming and costly. One experiment on the genetic effects of radiation in mice is currently in progress at Chalk River Nuclear Laboratories (CRNL) but this study is being conducted on a very modest scale because of financial constraints. (The same constraints also limit severely the size of current experiments on cancer induction in animals at CRNL.) However, genetic studies using microorganisms can be carried out cheaply and effectively as has been done at CRNL. Advantage is taken of the fact that, although millions of microorganisms are used in the test system, only the relatively small number of radiation-induced, genetically altered organisms need to be scored. This amplification is achieved with relative ease by manipulation of the metabolic medium in which the organisms are grown.

Because of (i) the manner in which vital statistics and associated registries are organized in Canada, (ii) the federal-provincial arrangements concerning the use of such information, and (iii) the early pioneering work on medical record linkage by Newcombe, Canada is well ahead of the United States in its ability to carry out computerized medical record linkages and epidemiological studies on atomic radiation workers and uranium miners as well as other groups of people who are known to have been exposed to high doses of medical X rays. The advantages of computerized over manual studies are lower cost and higher reliability. Studies of this type are currently in progress.

Because of the increasing awareness of the hazards of the inhalation of radon daughter products, greater emphasis has been placed recently by federal and provincial agencies on studies of the hazards arising from uranium mining, milling, and the resulting tailings. It seems probable that more research of this kind will be undertaken by government organizations, or with their backing, in the near future.

As pointed out by the U.S. Interagency Task Force studies on massive populations exposed to low levels of radiation are unlikely to answer definitively questions concerning the hazards of exposures to low levels of radiation and hence the adequacy of radiation protection standards. This is basically because the effects due to radiation will be small, and it will be impossible to assemble a "control group" who will accurately duplicate all the important non-radiation effects.

Current radiation biology theory cannot rule out absolutely the suggestion that low doses and low dose rates may be more efficient per unit dose than corresponding higher ones, although this does seem highly improbable on the basis of our current understanding of the mechanisms involved. It is generally agreed among Canadian radiobiologists that the most promising way to improve the theory with current financial limitations is to pursue fundamental studies of the biological effects of radiation in an attempt to obtain more insight on which to base more realistic models for the shape of the dose-effect curve, especially over the low dose range. As a check, populations exposed to low levels should be studied empirically to ensure that effects at low doses have not been grossly underestimated by current theory. However, it should be realized that if the cancer risks have not been underestimated, then not too much in the way of positive findings should be expected even from the most elegantly designed epidemiological studies of populations exposed to low levels of radiation. Similar ideas have been expressed recently by A.S. McLean, Director of the United Kingdom National Radiological Protection Board. Because virtually no directly relevant research on the biological effects of radiation of interest to the nuclear industry is undertaken in academic institutions and because previous attempts to foster this research both in universities and in other government laboratories have not been successful in Canada, the brunt of the burden of dealing with problems of low-level radiation from most of the nuclear fuel cycle is left by default to AECL. (It is recognized that other government agencies are supporting work on radon and radon-daughter products.) Leaving aside the question of whether the extra funding should go to AECL laboratories, or to other government laboratories or to academic institutions, it would not be surprising if AECL continued to provide more funding for research in this area. It is possible that the Atomic Energy Control Board would decide they had responsibility to improve the reliability of the scientific basis for their regulations and therefore could provide more funding. Also, because of the benefits derived by the industry in the production of electricity by nuclear means, manufacturers and utilities might likewise decide to fund research of immediate interest to them. For example, the utilities might be expected to support studies on the relative biological effectiveness of tritium. It would be a very healthy sign indeed if all of the interested parties in Canada were to contribute more in the future to improve the state of knowledge of biological radiation effects."

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   k) p. 152-154, para. 159-165
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APPENDIX 1
WORK OF INTERNATIONAL COMMITTEES

The two most authoritative assessments of radiation risks are those produced by the following two international committees:

(1) The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) was established in 1955 and has been issuing reviews concerning levels and effects of ionizing radiation at about 4-year intervals since 1958. The recent UNSCEAR report (1977) cites 1212 scientific articles pertaining to radiation exposure levels, 929 relating to cancer risks, 637 relating to genetic risks and 373 relating to embryonic risks. These articles are selected from a total of roughly 3000 articles concerning ionizing radiation that are published each year in international journals. In general, UNSCEAR is concerned with an accurate assessment of radiation exposures and effects; this committee does make recommendations for future research, but does not make recommendations on maximum permissible radiation exposures.

(2) The International Commission on Radiological Protection (ICRP) "has been functioning since 1928, when it was established under the name of the International X-Ray and Radium Protection Committee, by the Second International Congress of Radiology held in Stockholm, Sweden. It assumed its present name and organizational form in 1950 in order to cover more effectively the rapidly expanding field of radiation protection" (ICRP No. 2, p. ix). The membership of the Main Committee and its committees is international; individual members are selected for their expertise "in the fields of medical radiology, radiation protection, physics, health physics, biology, genetics, biochemistry and biophysics" (ICRP No. 26, p. 45). Those who served in the period of 1973-1977 came from seventeen different countries.

Background studies of questions bearing on radiation protection are prepared from time to time by task groups appointed by the ICRP, and use is made also of official reports and reviews from such organizations as the United Nations Scientific Committee on the Effects of Atomic Radiation, the U.S. National Academy of Sciences, the Nuclear Energy Agency, the International Atomic Energy Agency and the U.S. National Council on Radiation Protection and Measurements. In the period 1959-1979, the ICRP produced 30 numbered publications relating to protection, of which thirteen are major reviews of the scientific bases on which the recommended standards are set. These thirteen reviews have extensive bibliographies, and all together some 1900 scientific publications are referred to in these reports.

In addition to the reviews by ICRP and UNSCEAR, the hazards of low-level radiation have been reviewed from time to time on an ad hoc basis by various other committees associated with, for example, the American Medical Association, the British Medical Research Council, the Nuclear Energy Agency, the U.S. National Academy of Sciences, the U.S. National Council on Radiation Protection and Measurements, the U.S. National Cancer Institute and the World Health Organization. By and large, the conclusions reached in these various reviews agree with the conclusions also reached by ICRP and UNSCEAR.

Assessment of radiation hazards to man depends primarily upon measured effects in human populations exposed to high radiation doses from medical X-ray machines or from nuclear weapons explosions; secondarily, in the absence of human data, upon measured effects in experimental animals; and, thirdly, upon any other biological or biophysical data available. These assessments have not changed greatly over the past few years. The preliminary best estimates of radiation hazards produced by ICRP in 1966 (ICRP No. 8) are not very different from those published by ICRP and by UNSCEAR in 1977, at least for the sparsely ionizing radiations (X, gamma and beta rays) that are responsible for most of our radiation exposures. The most significant changes in risk estimates since the early 1960's have been (a) decreased emphasis upon the genetic hazards of ionizing radiation (see ICRP No. 8 and No. 26), (b) refinements in methods of calculating risks from densely ionizing radiations (ICRP No. 14 and No. 21) and (c) increased emphasis on the carcinogenic hazards associated with the inhalation of low levels of radon-222 and radon daughters (UNSCEAR, 1977).

(3) Evolution of ICRP Recommendations

There are legal limits to the doses persons may receive in the nuclear power industry. In recent years, Canada and many other countries have passed laws to enforce the recommendations made, after consideration of biological effects, by the ICRP.

The following is a brief chronology of the development of ICRP's dose limits and the concepts on which they were based:

1934 - 1 R per week, up to about 60 R per year was possible
1950 - 0.3 rem per week, 15 rem per year
1959 - 0.1 rem per week, 5 rem per year for persons commencing occupational exposures at age 18 (ICRP No. 1,2,6 and 9)
1977 - 5 rem per year whole-body dose retained but a refinement in concept of doses to other organs (ICRP No. 26)

1934: The limit of 1 R per week was chosen to avoid acute effects such as reddening of the skin. The concept of radiation protection was based on a threshold effect and the above dose was described as a "tolerance dose".

1950: The ICRP reduced the recommended dose to 0.3 rem per week to protect the so-called "critical organs" - blood or bone marrow, gonads and eyes. It followed that the dose accumulated in a given year could be 15 rem.

1959: Largely because of the proposal of the linear dose-effect relationship*, the ICRP reduced the annual whole-body occupational dose to 5 rem per year for persons commencing work at age 18. Other parts of the body could receive:

Gonads, red bone marrow, lens of eye	5 rem per year
Skin, thyroid	30 rem per year
Extremities	75 rem per year
Other organs	15 rem per year

*The linear dose-effect relationship assumes that the magnitude of the deleterious biological effects of radiation is directly proportional to the total accumulated dose of radiation. This proposal thus assumes that there is no "safe" or threshold dose. For individual young members of the general public, the dose limit was set at 0.5 rem per year, i.e., one-tenth of the maximum persmissible exposure to occupational radiation workers, with a further retriction that the accumulated genetic dose averaged over the whole population should not exceed 2 rem per 30 years for the general public.

1977: For whole-body exposures, the annual limit of 5 rem for occupational workers was retained, but the philosophy was altered substantially:
- each organ was regarded as contributing to the total risk, and
- the contribution from each organ was taken to be proportional to the dose received by that organ.

On the basis of epidemiological data, a weight was attached to the contribution from an organ to the total risk under conditions of uniform whole-body exposures. These weight factors* are as follows (ICRP No. 26, para. 105):

Gonads	0.25
Breast (ave. male & female)	0.15
Red bone marrow	0.12
Lung	0.12
Thyroid	0.03
Bone Surfaces	0.03
Remainder	0.30
	1.00

*In 1978 the ICRP recommended in addition a weighting factor of 0.01 for the assessment of risk of fatal cancers of skin resulting from exposures of population groups (ICRP 28). In practice this weighting factor has been used individually and collectively (NEA, 1980).

The recommended dose limitation system is based on the principle that the risk should be equal whether the whole body is irradiated uniformly or non-uniformly. Using the weight factors, non-uniform exposures of the body are to be limited so that the total risk from a year of work will not exceed that from a uniform whole-body dose at 5 rem. A moderate relaxation of the maximum dose limit for certain specified organs has thus been allowed for conditions where irradiation of a single organ is ensured.

Recommended doses to the extremities are no longer spelled out in ICRP No. 26. The ICRP believes that harmful effects will be minimized by applying a limit of 50 rem in a year to all non-specified tissues (e.g., skin) except the lens of the eye, for which the limit is 15 rem in a year.

The aim of the dose limitation is to ensure that the radiation worker will not be exposed to risks greater than those in occupations recognized as having high standards of safety. Such occupations are generally considered to be those with an average mortality of not greater than 10^{-4} per year of work (ICRP No. 26, para. 96). Canadian statistics for 1975 and 1976 indicate that about 80% of Canadian workers are in fact employed in occupations with an average annual fatality rate (occupational accidents plus occupational diseases) of 10^{-4} or less.

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APPENDIX 2
DETECTION OF LATE EFFECTS OF RADIATION

(1) Current Risk Estimates: Estimates of the risks of cancer induction are based on measured increases in cancer incidence (notably leukemia) in human populations exposed to radiation doses in the region of 100 rem, either as a result of the nuclear weapons explosions at Hiroshima and Nagasaki or as a result of medical X-ray treatment for various diseases. There is no detectable increase in the incidence of genetic defects in the children of these irradiated humans and estimates of the risks of genetic defects are based largely on experiments with mice and other mammals. Estimates for genetic risks are thus less certain than those for cancer risks but are thought to involve some margin of safety (Newcombe, 1975).

The only other late biological effect of low-level radiation which is thought to be potentially significant is the induction of abnormalities in the growth and development of a fetus exposed to radiation during development. This problem was considered in detail in the UNSCEAR (1977) report but no definitive risk estimates were derived for low-level radiation. Dose-effect curves are frequently curvilinear, implying little or no effect at radiation doses below 5 rem to the fetus. In ICRP No. 27 (para. 73), the total carcinogenic, genetic and developmental harm resulting from exposures of the fetus was considered to contribute about 11% to the total index of harm to occupational workers, assuming that half the working population were female, that pregnancies occurred at normal rates in the working population and that radiation exposures were not specially restricted during pregnancy. In practice, radiation exposures to female occupational workers may be restricted during pregnancy.

(2) The Mega-Mouse Experiment: Studies of hereditary effects of irradiation in mice at the Oak Ridge laboratories started in 1947.

They were initiated because of widespread concern over genetic hazards to man. Specifically the aim was to investigate the numerous variables that might affect the yield of hereditary changes (in particular: total dose, protraction of the dose, sex, and cell stage, as relating to coat-colour mutations). Recently the emphasis has shifted to genetic harm in the form of skeletal anomalies in offspring from irradiated parents. Also, the experiments are no longer concerned wholly with radiation, but have been extended to include other mutagens, i.e., chemical agents.

The budget for the mouse genetic work was initially in the vicinity of 0.3 million dollars per year, which later rose to at least 0.7 million. The cost of raising one mouse was initially in the vicinity of 45 cents and is now more than double this value.

The work from this study is referred to whenever serious consideration is given to estimating genetic hazards. For example 47 papers by W.L. Russell and/or L.B. Russell, on work in this study, are quoted in the UNSCEAR (1977) report. The greatest use is made of their figure of 100 rem as the dose of chronic gamma-irradiation which would produce as many mutations as occur spontaneously (i.e., a 1% increase in mutation rate per rem). For acute gamma-irradiation at higher doses the effect is 3 times as great.

The setting up of this study was originally not supported by the biology advisory committee of the Oak Ridge National Laboratories, on the grounds of expense. However, the director of the laboratories told the advisers that if the results were needed they should not let the cost stand in the way. A typical experiment, comparing three different radiation doses (300, 600 and 1000 rad) published in 1958, used 375,000 offspring from irradiated and control parents, but yielded only 168 mutations. Large numbers of offspring from both irradiated and control parents are required in order to arrive at statistically significant results.

(3) Size of Populations Required to Detect Radiation Effects: When experimental animals are exposed to high doses, induced cancers are frequent enough so that large numbers of animals are not required to detect an effect. One of the current experiments with rats at Chalk River, for example, uses 100 animals per dose, for skin doses ranging from 800 to 12,800 rad (McGregor, 1976, 1979).

Studies of the genetic effects in mice are much more laborious because a breeding test is required in order to detect an effect, and because the particular mutations that one plans to screen (e.g. coat colour changes) are usually rare. Thus, as many as 100,000 offspring from irradiated parents may be required in order to test for the effect of a given dose, even where the dose is in the range from 300-1000 rad.

Where the dose is lower than this, the numbers of experimental animals must be increased substantially in order to detect any effect. And so, when an investigator wants to explore the shape of the dose effect curve, he will frequently resort to the use of smaller organisms.

Even with fruitflies, however, the business of determining the dose-mutation curve down to 25 rad proved exceedingly laborious. In the Chalk River laboratories, dose-effect curves for eye-colour mutations in wasps (Baldwin, 1972), and for congenital malformations in fish embryos from irradiated sperm (McGregor and Newcombe, 1972), have been pushed back to 15 and 25 rad, respectively. The numbers of individuals examined to detect an effect at the lowest dose in these two studies were about 500,000 and 40,000, respectively. The dose-effect curves were linear in both of the above studies.

In order to detect radiation effects at still lower doses in the laboratory, it is usually necessary to utilize microorganisms. Experiments with microorganisms can be carried out with much greater precision at low radiation doses in part because millions of bacteria can be grown in a single test tube, making the cost of an experiment with 10^6 microorganisms roughly similar to that of using one mouse.

Statistical methods are used to assess the size of the population required to detect radiation effects. From the curves given by Goss (1975), one can for example calculate the number of mice required to detect genetic effects at low doses of chronic radiation. Assuming (a) 50% chance of detection with 95% confidence, (b) a natural mutation frequency of 1 per 20,000 (i.e., for coat-colour mutations at 7 loci in mice), (c) a "doubling dose" of 100 rem (i.e., 100 rem produces as many mutations as occur naturally), and (d) unirradiated control population equal to irradiated, then the total population required can be calculated as follows:

Dose (rem)	Fractional increase	"Cases" required	Irradiated population required	Total population required
100	1	10	20,000 x 10 x 1	4×10^5 mice
10	1×10^{-1}	60	20,000 x 60 x 10	2.4×10^7 mice
1	1×10^{-2}	600	20,000 x 600 x 100	2.4×10^9 mice
0.1	1×10^{-3}	6,000	20,000 x 6,000 x 1,000	2.4×10^{11} mice

If the natural mutation frequency were 1 per 200 or 1 per 2,000,000, the numbers of animals required would be 10-fold smaller or larger, respectively. If the doubling dose were 10 rem or 1000 rem, the lowest dose yielding a detectable effect with a given number of animals would be 10-fold smaller or larger, respectively.

On the same basis, it would require a human population approximately equal in size to the present world population (four billion) to develop a statistically significant basis for proving the carcinogenic effects of low levels of radiation on man. For example, in order to have a 50% chance of detecting an effect at one-quarter of a rem with a 95% confidence limit, one would have to irradiate a population of about two billion individuals and compare this with a control, unirradiated population of a similar size for several decades, on the assumption that 2000 rem is required to double the natural incidence of cancer in humans and that cancer is responsible for 1 in every 5 deaths. Specific types of cancer, notably leukemia (which is responsible for 1 in every 12000 deaths in Canada and the USA), are more susceptible to induction by radiation. The radiation dose required to double the natural incidence of leukemia is probably about 26 rem (BEIR, 1972) and the effects of one-quarter of a rem might therefore be detected in about 20 years with a total population of about 100 million persons. Since this type of data is not readily available, quantitative estimates of radiation hazards are necessarily based on smaller groups of persons exposed to much higher radiation doses.

(4) Human Populations Exposed to Low-Level Radiation: Reissland (1976) has considered the specific question: "How long would it take to detect an effect in 50,000 radiation workers exposed to 0.5 rem per year?"

He assumes (a) 50,000 workers at any one time, (b) a 5% annual rate of workers leaving radiation work, and (c) a risk of death from cancer of 1 per 10^4 man-rem (or of death from leukemia of 0.3 per 10^4 man-rem). He calculates the time required in order to have a 50% chance of observing an excess with a confidence of 95% or 80%. This time would be:

for all cancers and 95% confidence	- 1260 years
for all cancers and 80% confidence	- 330 years
for leukemias alone, and 95% confidence	- 130 years
for leukemias alone, and 80% confidence	- 34 years

If the risk is higher than predicted, the time would be shorter, and if the risk is lower the time would be longer. For example, if the true risk were 5 times higher, the times estimated above would be reduced by a factor of 25 (approximate square relationship for complex reasons) once the latent period of 5 to 25 years was over. Similar calculations for radiation workers in Canada have been carried out by Newcombe (1976) and computer systems for linking radiation exposure records with national and provincial health records have been developed, so that the health risks (if any are discernible) can be re-checked when sufficient man-rem of radiation exposure has been accumulated.

There are of course also areas of the world where natural background radiation levels are considerably higher than average, either due to the effects of increasing altitude and/or to higher concentrations of radioactive materials in the soil. The most recent and extensive survey on populations living at high altitude is by Frigerio and Stowe (1976). Causes of death in 7 states of the USA with average natural background of 0.21 rem per year (0.105 from cosmic rays, 0.080 from terrestrial sources and 0.025 from internal sources) were compared with causes in other groups of states with different average background levels and with the total US population. Mortality rates from all causes were 1% lower in the 7 states with highest radiation levels (0.21 rem per year) than in the 14 states with lowest radiation levels (0.12 rem per year); mortality rates from all cancers were 14% lower; mortality rates from leukemia were 2% higher. The data of Frigerio involve comparisons of groups containing 6 to 60 million persons and are thus reasonably accurate; the standard deviations on the data are quoted as being 1% or less. The data do not prove that low doses of radiation are beneficial but simply that low-level radiation does not seem to represent a major environmental health hazard. The decreased values observed at higher altitudes are not explained as yet.

There is also considerable interest in a group of about 70,000 persons living on thorium-rich monazite sands in Kerala, India, where background radiation levels are in the region of 0.4 to 1.5 rem per year. Previous studies failed to show abnormalities in wild rodents living in the area and exposed to an estimated total genetic dose of about 500 rem accumulated over many generations (UNSCEAR, 1972). This finding substantiates the more extensive laboratory studies with rodents (see, for example, Green, 1968; Newcombe, 1971). Previous studies on humans in the Kerala area (Gopal-Ayengar et al., 1972; George et al., 1976) failed to reveal significant differences between areas with low and high background. Kochupillai et al. (1976) have recently claimed a high incidence of Down syndrome among children born in this area. This claim has been disputed by Sundaram (1977); both reports were considered by the UNSCEAR committee (1977). Even if Kochupillai et al. were correct, Down syndrome only accounts for about 1% of all genetic disorders and their data would therefore not lead to a marked change in current estimates of the total genetic risk of low-level radiation.

The studies on the Kerala population are complicated by the relatively small numbers of persons involved and the variability in reported incidence of cancers and genetic defects from one portion of a country to another and from one country to another in the world (even when background radiation levels are the same in the areas compared). If the international risk estimates are correct, one would need to collect very accurate data on the numbers of each different type of genetic defect and cancer in the Kerala population over a time span of several decades in order to detect any significant effects of radiation; these data are simply not available as yet.

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APPENDIX 3
MEASUREMENT OF LOW RADIATION EXPOSURES

The two major sources of radiation exposure from nuclear reactors in Canada are external gamma-radiation and internal tritium beta-radiation.

Extremely sensitive instruments have been developed to measure low levels of ionizing radiation or of specific radioactive nuclides. Consequently, specific radioactive elements can be accurately measured in amounts that are so minute as to be undetectable by any other chemical or physical method. For example, liquid scintillation counters, which are in common use in many research laboratories, are currently capable of measuring within a few hours a variety of specific radionuclides (e.g., tritium, carbon-14) in concentrations which would produce radiation exposures of 10^{-5} rem per year, or 10^{4} times less than the total natural background radiation level of 0.1 rem per year.

(1) Monitoring of External Radiation: Monitoring equipment has been under development at Chalk River since 1945. However, it is noteworthy that the Geiger counter, developed in Europe about 70 years ago, was already sensitive enough to detect small variations in the natural radiation background and is still being used in many of our most sensitive portable detectors. Subsequent development in monitoring equipment has been primarily in reliability, accuracy, ease of use, and in the determination of gamma-ray energies (e.g., with scintillation or solid state detectors) and thus the identification of specific radionuclides.

We currently have environmental monitors that record each increment of 1 microrem (10^{-6} rem) in the background. The main difficulty associated with measuring increments in environmental radiation levels is detecting a small fractional increase above a natural background that is continually varying.

Radiation monitoring equipment commonly in use around nuclear reactors reads dose rates down to 200 microrem per hour. This lower limit is not set by instrumental capabilities and could be reduced. Pocket dosimeters are also available to record accumulated doses of 400 microrem (0.0004 rem) and to sound an alarm after a predetermined level (e.g., a few hundred millirem) of total accumulated dose (Jones, 1975).

All radiation workers carry a badge containing thermoluminescence dosimeters (TLD's) to measure total accumulated dose of external beta-radiation (non-penetrating) and external gamma-radiation (penetrating). Permanent records are kept of all radiation exposures received by radiation workers. Lithium fluoride TLD's for gamma monitoring were developed in the USA; AECL was one of the first establishments in Canada to switch completely from films to TLD's for routine personal dosimeters, and the Chalk River Nuclear Laboratories (CRNL) had one of the first fully automated systems for reading large numbers of TLD dosimeters (Jones, 1971). This system has been adopted by the utilities and other government agencies in Canada. The practical sensitivity level of the TLD personal dosimetry system at AECL and Ontario Hydro is about 0.01 rem of total accumulated dose. This limitation is determined by the inherent accuracy of the system and the amount of effort that is considered justified. Under carefully controlled conditions, the current TLD's could detect 0.003 rem of total accumulated dose over any given period of time. An accumulated total dose of 0.01 rem, it might be noted, is one five-hundredth of the maximum permissible dose of 5 rem per year for radiation workers and is 10^4 times smaller than the smallest dose (about 100 rem) which might be expected to cause any detectable signs of radiation sickness if the whole dose were received in a very short period of time. As a conservative policy all detectable TLD doses are listed on the radiation dose records in AECL.

(2) Monitoring for Internal Contamination: Bioassay for radioactivity in samples (mainly urine and feces) from Chalk River employees has been carried out since the late 1940's, and *in vivo* monitoring

using gamma spectroscopy for internally deposited gamma emitting radioactivity has been done since late 1958. These measurements, combined with work place monitoring, have been used to ensure that Chalk River employees have not received significant doses from internally deposited radioactivity.

We currently do routine bioassay on selected (by work place) employees for a wide range of radioisotopes, which include tritium, carbon-14, phosphorus-32,33, sulfur-35, cobalt-60, strontium-90, cesium-134,137, iodine-125,131, natural and enriched uranium, thorium-232, 228, plutonium-238, 239, 240, americium-241 and curium-244. The only radioisotope routinely detected at significant levels is tritium, and doses to exposed individuals from tritium are routinely calculated and recorded (Johnson, 1976).

Possible contamination by other radioisotopes is controlled by calculating a "derived investigation level" (DIL) for activity in the urine or fecal sample. This level corresponds to the smallest of (a) an intake of radioactivity immediately after the previous sample was submitted that would result in a committed dose equal to one-twentieth of the annual limit on dose, and (b) an amount in the body that would give an annual dose rate at the time of sampling equal to the annual limit on dose.

If this investigation level is exceeded for any radioisotope, the individual involved is asked to cease working with possible sources of radioactive contamination until the significance of the contamination can be evaluated, either by *in vivo* whole-body monitoring and/or by subsequent bioassay measurements.

Whole-body measurements are made in a low background building situated about 5 miles from CRNL. Prior to the completion of the building in late 1975, monitoring was done in the plant area itself, and the performance of the detection equipment suffered from the effects of a variable and frequently high background, mainly caused by argon-41. A higher than normal background at the low background building has been noticed only once since monitoring began there. The two main detection systems in routine use are the shadow-shield whole-body monitor (Evans, 1975), suitable for radionuclides that emit photons about 100 keV, and the phoswich detectors (Johnson, 1976), suitable for radionuclides that emit photons below 100 keV. These combined detection systems give us the capability of measuring in vivo all radioisotopes, including "pure" beta emitters (Johnson, 1977) but excluding tritium, that are present in significant quantities at CRNL, at a level below that which would result in a dose rate equal to the annual limit on dose. The detection limit for many isotopes is orders of magnitude below this level. Detectors suitable for wound and thyroid monitoring are also available. In addition to monitoring those individuals that excrete measurable amounts of radioactivity, and those that are identified from work place monitoring as being at risk for uptake of internal radionuclides, we routinely monitor selected groups of employees to insure that internal contamination does not occur at a significant level.

Present research and development effort in the area of estimating internal contamination and doses from these internal radionuclides include improving methods of radiochemical analysis for lanthanides and actinides in biological samples, reducing the background of surface barrier alpha detectors, improving the sensitivity and calibrations of the phoswich detector system (particularly for alpha emitting radionuclides that are produced in advanced fuel cycles), and improving the metabolic and dosimetric models used to calculate doses from internally deposited radioactivity.

(3) Tritium Monitoring: Research at Chalk River on this topic has been concerned mainly with the protection of occupational radiation workers against exposure to excessive concentrations of tritium. Currently, in an operating Canadian nuclear power station, 20-30% of the total dose received is from tritium. The energies of the beta rays emitted by tritium (there are no gamma rays from tritium) are too low for tritium outside the body to be a hazard.

For radiation protection purposes, the following basic data (Osborne, 1972) are applicable:

- The dose commitment from 1 mCi (3.7×10^7 Bq) taken into the body is equal to 0.1 rem.
- A maintained concentration in the body of 50 Ci/L of body fluids (1.85×10^6 Bq/L) delivers an annual dose of 5 rem.
- The maximum permissible concentration for tritiated water vapour in air is 10 Ci/m^3 (3.7×10^5 Bq/m^3).
- The intake rate through the unprotected skin is similar to that through lungs when breathing is at the normal rate of 10 L/min.
- Tritiated water is about 10^4 times more hazardous per Ci or Bq than tritiated hydrogen because the hydrogen is largely exhaled and not absorbed.

The magnitude of the rate of intake of tritiated water vapour through the total body skin area was established by a series of exposures of volunteers at CRNL (Osborne, 1966). The results obtained are used by ICRP, and the average retention time determined (10 days) has replaced the former 12 day retention in international recommendations. Using volunteers, the efficacies of ordinary clothing, rubber gloves and plastic suits for reducing tritium intakes have been estimated. The commonly used suits reduced the intake by about a factor of 100.

The measurement of tritium concentration in urine is a widely used method of estimating how much tritium is in the body. So that workers might be able to measure this concentration rapidly themselves, an automatic analyser using liquid scintillator was designed and developed at CRNL (Osborne, 1968, 1970). The first unit is still in daily operation in a nuclear power station after 8 years of continuous use. Analogous to the pocket chamber for gamma radiation, the analyser allows workers to associate tritium intakes with particular locations, habits or jobs.

Tritium is easy to detect. The practical problems are the interferences from other radiations when on-line measurement of tritiated water vapour in air is needed. Water-filled gas-washing bottles and desiccants are widely used in sampling techniques for tritiated water vapour. The applicability and accuracy of the former was established both experimentally and theoretically at Chalk River (Osborne, 1973). An arrangement of concentric ionization chambers, and one sealed to ensure a response only to gamma radiation, was developed and has been used in several designs, including portable monitors and stack effluent monitors (Osborne and Cowper, 1966; Osborne and Coveart, 1973). Such monitors typically measure down to one-tenth of the maximum permissible concentration in air and reduce the interference from gamma radiation by 50-fold.

A realization that the noble gas fission products might be released with tritiated heavy water from a reactor system prompted the development of tritium monitors that are insensitive to these fission products (Osborne, 1971). Two designs have been pursued. One, now installed as the main monitor at Bruce Generating Station A, uses a patented air/water exchange device to collect the tritium in water that subsequently flows through a cell packed with plastic scintillator to detect the tritium (Osborne, 1975). The other design uses a drying/self-purging system to provide a tritium-free air flow for comparison of the ionization current from it with that from the original sample; the difference indicates the tritium concentration. This design, already used at Douglas Point, is being developed as a transportable monitor (Osborne and Coveart, 1977).

Radiation protection requirements for tritium in aqueous effluents from power reactors are easily satisfied by periodic sampling and measurement of the tritium with liquid scintillation counting. However, on-line monitoring for very low levels of tritium in ordinary water used in the power stations is also desirable for economic reasons since the tritium is a tracer for heavy water. A plastic scintillator detector was designed (Osborne, 1970) to measure tritium concentrations down to 1 Ci/L (3.7 x 10^4 Bq/L) and has been used at power stations for the last 7 years. To improve the sensitivity and allow measurement of tritium in very dirty water streams, a new technique using liquid scintillator in a continuous flow device has been designed and is being developed at CRNL (Osborne and Tepley, 1978). The expected sensitivity is 0.1 Ci/L (3.7 x 10^3 Bq/L), i.e., 300 times less than the maximum permissible concentration of tritium in drinking water.

(4) Radon Monitoring: Exposure to radon daughters is not confined to underground miners. In recent years, there has been a marked increase in measurements of radon and radon daughter concentrations in the air in private dwellings and public buildings, in order to assess the potential hazards associated with the inhalation of this naturally occurring radioactivity (UNSCEAR, 1977; Cliff, 1978). Risk estimates for radon daughters are still open to some question (particularly for non-smokers) but it now appears that radon daughter levels in buildings may present at least as much hazard to human populations as do all of the other natural radiation sources combined.

Radon-222 is formed by the decay of radium-226, which is itself a decay product of uranium. Since both uranium and radium are widely distributed in the earth's crust, radon is constantly produced in minute amounts by essentially all building materials as well as by the soil. However, in contrast to uranium and radium, radon-222 is a chemically inert gas which is able to diffuse from the soil and from building materials into the air. Most of the inhaled radon is exhaled again, i.e., radon-222 is relatively non-toxic. However, radon daughters are adsorbed on the lining (epithelium) of the lung and thus expose the bronchial epithelium to appreciable doses of ionizing radiation. In an average dwelling, the concentration of radon daughters in the air is about 5-8 times the average concentration in the outside air, if the ventilation rate in the dwelling is equivalent to about one room change of air per hour (UNSCEAR, 1977;Cliff, 1978). A reduction in ventilation rate to 0.1 room changes per hour (e.g., in order to economize on heating costs) is expected to increase the concentration of radon daughters inside the dwelling to about 70 times the average concentration in the outside air (Cliff, 1978), or to more than twice the maximum recommended levels (0.02 WL) for buildings in Canada.

An instrument has recently been designed at CRNL to measure long-term average concentrations of radon in air. It is intended for use in homes and public buildings where abnormal radon levels exist as a result of using radium-contaminated building materials or because construction has occurred on ground containing high levels of radioactive minerals. Since radon daughter concentrations in buildings may vary over wide limits within short periods of time depending upon both meteorological conditions and the actions of the occupants, measurements must be made over sufficiently long periods of a week or more to obtain realistic estimates of chronic hazards.

The portable, battery-operated instrument which has been developed (Cowper and Davenport, 1978) is capable of measuring average concentrations of less than 0.5 pCi/L ($\sim$0.02 Bq/L) over a one-week period. Allowing for the lack of equilibrium between radon and its daughters under normal circumstances, this concentration is equivalent to roughly 0.002 WL or a total exposure in the region of 0.07 WLM/year if the building is occupied for 80% of a person's time.

An air sample of about eight litres is defined by a cylindrical volume which has a porous foam wall through which the surrounding air containing radon may diffuse but which traps radon daughter products existing in the air. Daughter products born within the volume and carrying a positive charge are collected electrostatically on a thin aluminum foil behind which is located a TLD chip. The instrument contains a second TLD chip not exposed to radon daughters to allow corrections for background gamma radiation exposure to be made.

Six prototype models of this radon monitor were originally developed and commercial production has now begun. The concentrations of radon in air which can be measured accurately over periods of several days correspond to less than one-tenth of the maximum recommended levels of radon daughters (0.02 WL) for homes and public buildings in Canada.

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APPENDIX 4
ENVIRONMENTAL PATHWAY ANALYSIS

(1) Routine Operation of Nuclear Power Plants: Canadian nuclear reactors have been designed so that they have a minimal effect on the environment. There are at least four different barriers designed into the CANDU reactor system to prevent release of radioactivity to the environment. Only extremely small amounts of radioactive elements (radionuclides), in low concentrations, are released into the environment where they mix with other naturally present radionuclides (e.g., with the tritium and carbon-14 that are always present in the biosphere as a result of cosmic radiation).

The design target for the increment in radiation exposures to persons living permanently at nuclear power plant boundaries is less than 0.005 rem per year. As noted above, this design target is routinely achieved at the CANDU power stations in Ontario and the natural radiation dose of 0.1 rem/year is not increased by more than about 0.005 rem per year at the boundary.

Routine monitoring is carried out at AECL research sites by AECL personnel, at all nuclear power stations in Ontario by Ontario Hydro, and in public areas outside the plant boundaries by Department of National Health and Welfare. The data are published and are generally available to the public. Appreciable increments in external gamma-radiation doses at the plant boundary, if they occurred, could be measured with TLD's (Jones, 1974, 1977); however, measurable increments in natural background radiation levels are not detectable at the boundary of CANDU power stations. The effects of tritiated water vapour are readily calculated since the tritiated water behaves in essentially the same manner as ordinary water during passage through plants, animals and humans. More complex problems in pathway analysis are involved in assessing the fate of other radionuclides which may be released in trace amounts from nuclear reactors.

The movement, dispersion and concentration of a radionuclide in the air, soil, water and living organisms are identical to those of its stable counterpart, for example, radioactive strontium behaves like stable strontium. Some elements are subject to biological concentration in plants and animals. Thus there are a large number of potential environmental pathways by which radioactivity can reach humans. The concentration factors for most elements (either radioactive or stable forms) in plants and animals are fairly well established (see, for example, Ophel and Judd, 1969; Havlik, 1970; Ophel, Fraser and Judd, 1972; Thompson et al., 1972; Ophel and Fraser, 1973; UNSCEAR, 1977) and a great deal of effort in many countries has been devoted to an accurate assessment of the fate of radionuclides in the environment. Regulatory limits on permissible releases of radionuclides into the environment have been established for protection of the health of the general public.

In AECL publications (e.g., Barry, 1962), methods are given for the calculation of rates of release of radionuclides to the atmosphere and fresh water so that specified dose limits to members of the public will not be exceeded. Values, or methods for calculating values, for the various environmental parameters used in the equations are also given. Emphasis throughout is placed on the phrase "will not be exceeded". In most cases, the calculated dose which would be received by people living near an operating nuclear facility following releases of these radionuclides is much less than the prescribed dose limits.

Estimation of the actual doses that members of the public may receive as a result of releases of radionuclides from operating nuclear facilities requires the use of complex computational models and the parameter values used have to be determined locally. AECL has already produced the RAMM program which will form the basis of a computer-based methodology for the assessment of radioactive discharges on a regional and national basis. In addition, AECL scientists are producing information on critical pathways and radionuclides in Canada, important environmental factors, transfer coefficients and methods of dose calculations.

By way of illustration, such an analysis has been carried out for releases from the Whiteshell plant in Manitoba. The dispersal of released radioactivity was calculated by the program for the various regions and the doses were estimated for individuals in several locations, living on various diets. For example, the dose was estimated for individual persons eating fish from the Winnipeg River, Lac du Bonnet system, and drinking water from this system. By summing the doses received, based upon the actual distribution of radionuclide releases from the plant, it could be shown that the dose commitments to these individuals are well below the regulatory limit. It was also possible by this analysis to identify the isotopes that are the main contributors to this dose, and to determine which individuals and which locations receive the highest dose.

The results of the pathways analysis can be used in several ways. (a) For a given release of activity from a facility (either an actual release or some sort of design target release), the calculation can be carried through to ensure that the release is acceptable, i.e., within the regulatory limit. (b) The calculation may also be carried out in reverse, beginning with a permissible dose to man and working back to a release limit as a design target for the facility. (c) The results from such analyses may be used to determine which releases (i.e., which isotopes and pathways) make the dominant contribution to the dose commitment, and thereby to indicate in which areas the greatest savings in dose commitment can be obtained.

This type of analysis is not new. However, the system being developed by AECL is already highly sophisticated and is getting more so. These advances are a consequence of the inception of the computer era in the last decade or so, which permits much more detailed consideration of the movements of nuclides through the environment.

(2) Waste Management: The field tests have been underway at the Chalk River Nuclear Laboratories since 1958 and 1960. One set of twenty-five glass blocks, containing four hundred curies of fission products were buried in sand below the water table in 1958. No

leaching of radioactivity has been detected. Another set of twenty-five glass blocks, containing one thousand curies of fission products were buried in the same way at another location in 1960. Ground water and soil samples from the area have been monitored for radioactivity regularly over the past twenty years (Merritt, 1967, 1976). As predicted from preliminary laboratory studies, only trace amounts of radionuclides have been leached from the surface of this insoluble glass. This practical test has thus confirmed the supposition that insoluble materials of this type would be suitable for the storage of high level wastes, if this option were considered desirable.

Particular attention is currently being directed to a proposed waste disposal facility deep underground in rock in the Canadian Shield (Hare, 1977; Boulton, 1978). The only process that seems to have any chance at all of carrying radionuclides from the repository to the biological environment is one where groundwater dissolves the radionuclides from the waste and subsequently carries them to the surface environment.

In the Canadian program, great care will be taken in the site selection process to choose rock which has few cracks and faults. However, there are circumstances in which water could conceivably reach the repository. Access and ventilation shafts provide connected pathways from the surface environment directly to the repository. They will be backfilled but it may not be possible to guarantee a perfect seal. Heating from radioactive decay may cause more cracks, and may cause existing cracks to link up into a continuous pathway. An estimate of the possible amount of water movement through the repository has been made for one set of assumptions; the conclusions were that any water would take ten thousand years to reach the surface environment, and that the quantity of water flowing through the repository would be less than a tenth of a cubic metre per annum.

The pathway analysis can be used to calculate what would happen if water did get into the waste disposal facility by any means. In the time it takes for the water to reach the surface environment after leaving the repository, many of the radionuclides, including strontium-90 and cesium-137, will have decayed to insignificant levels, so it is not necessary to consider them further in the calculation. In addition, most radionuclides interact chemically with the rock surfaces in the cracks and will be removed from the water, perhaps not permanently, but long enough to make their movements to the surface much slower than the movement of the water which carries them. This resulting delay enables us to drop more radionuclides from further consideration. For the remaining radionuclides, computer programs are being used to predict the rates at which these nuclides would enter the surface environment, given the various assumptions about water flow rates, and taking into account radioactive decay and chemical interactions with rocks.

The surface environment is then considered to be divided into large compartments such as:

- The surface environment in the vicinity of the repository, comprising about a square kilometre of soil, ground-water and vegetation;
- The fresh-water bodies encountered in the passage of a radionuclide from the land surface to the ocean;
- The sediments in the fresh-water and in the ocean; and
- The shallow and deep ocean.

Movement of radionuclides between each of these compartments and between these compartments and man can be estimated. For example, the transfer from the surface environment to fresh-water bodies has been derived from information on the residence times of fall-out plutonium and stable elements in drainage basins. More information is currently being sought to refine the calculations. The end results of these calculations will be estimates of the doses to humans over all time.

A preliminary estimate produced for the U.S. Nuclear Regulatory Commission (GESMO, 1976) indicates that any radiation doses received from waste management would be extremely minute, i.e., 0.000002 man-rem to the general public plus 0.0003 man-rem to occupational workers per MW-year, out of an annual total of 2 man-rem per MW-year for a full-scale nuclear power industry. UNSCEAR (1977) suggests a total of

3-6 man-rem per MW-year for a full-scale nuclear power industry but states that "the Committee feels that it is unable at this stage to make an adequate assessment of collective dose commitment for the world population from disposal of these wastes". The Canadian effort described above is intended to provide data to permit an adequate assessment of this kind and to determine independently whether the preliminary US assessment is correct for Canadian conditions.

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