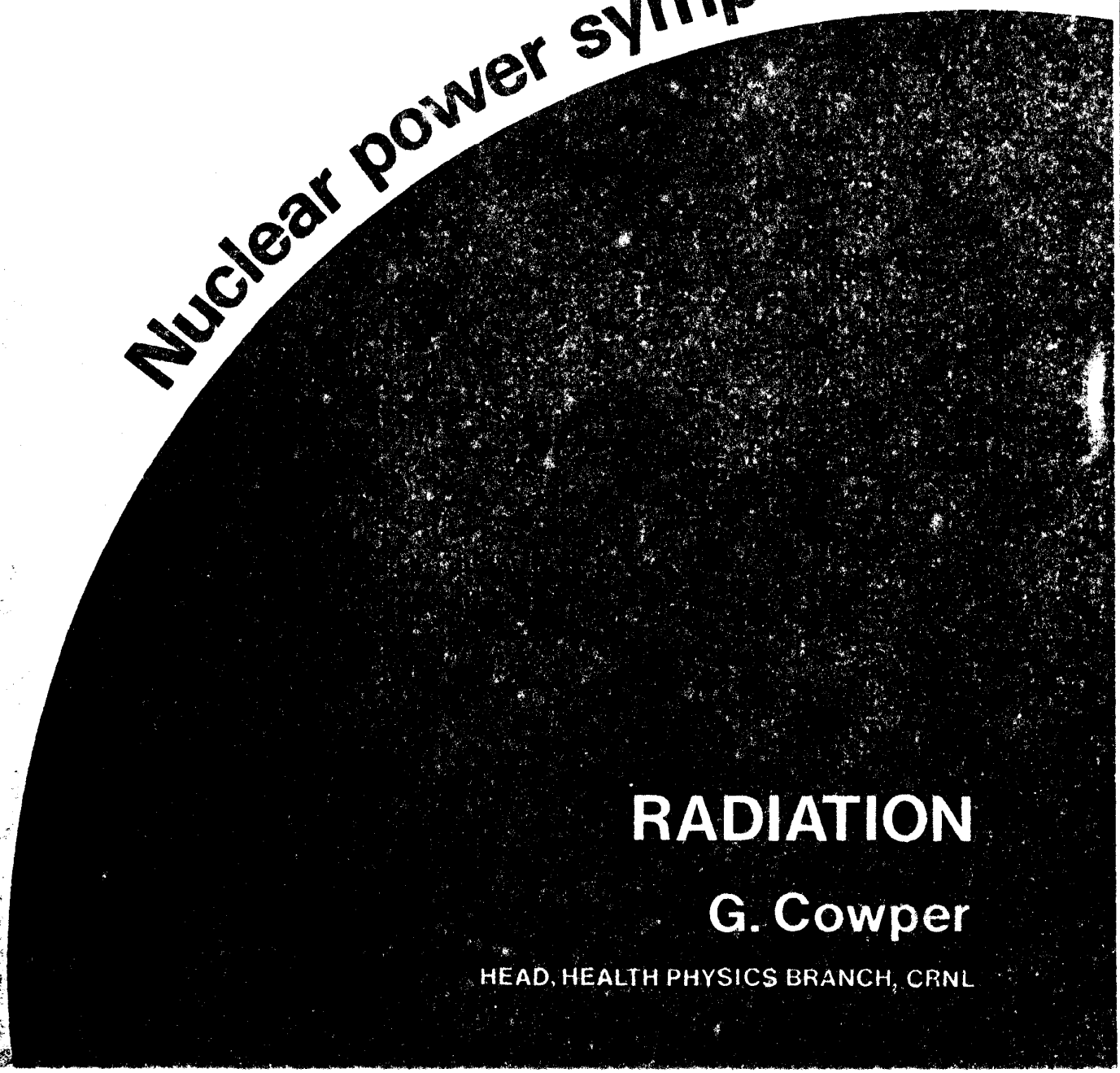
ATOMIC ENERGY OF CANADA LIMITED
Power Projects, Sheridan Park, Ontario

Lecture 2

Nuclear power symposium



RADIATION

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NUCLEAR POWER SYMPOSIUM

LECTURE NO. 2: RADIATION

by

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Within the context of nuclear energy the term radiation is understood to include those photons and particles, charged and uncharged, which are emitted by nuclei of atoms undergoing various forms of radioactive disintegration and which have the ability to cause, either directly or indirectly, ionization in matter.

The forms of radioactive disintegration are characterized by the names of the charged particles which are emitted. Thus in a α decay and β decay the radioactivity is due to the emission of positively charged helium nuclei (α particles) and fast moving electrons (β particles). In some cases positively charged electrons (positrons) are emitted. In most instances, the emission of such charged particles is accompanied by energetic photons (γ rays) and frequently the product atom will emit X-rays in achieving final stability of its electron orbits.

In a small number of heavy elements fission may occur in which the nucleus divides into approximately equal parts. This process is accompanied by the release of a significant amount of energy in the form of kinetic energy carried by the two nuclear fragments and in addition some gamma radiation and a few neutrons are produced in each fission event. In some nuclei this fission process occurs spontaneously and can be regarded as a kind of radioactivity like α and β decay but from the viewpoint of power generation the more important phenomenon is neutron stimulated fission in which the absorption of a neutron causes the fission of the target nucleus. Since more than one neutron is emitted on the average in the fission process, herein lies the basis of the controlled chain reaction, the nuclear reactor and nuclear power.

The energy carried by the fission fragments is absorbed in the fissile material essentially at the site of the fission event and in being absorbed is degraded to thermal energy. When the fission rate is high, the fissile material becomes hot so that steam can be raised to perform useful work.

The remaining energy carried by the gamma radiation and neutrons is much more penetrating and requires the placing of massive shielding around the reactor core to prevent the serious radiation exposure of people. Whereas a fission fragment may travel a distance of only a few microns in a solid material

before being brought to rest, the gamma rays and neutrons can pass through many inches of concrete before their intensity is reduced to 10%.

An essential difference between charged particle and photon or neutron absorption is that whereas the former have a finite range in an absorber beyond which no particles will pass, the latter are absorbed by a process of the form

$$I = BI_o e^{-\mu a}$$

where μ is a characteristic of the absorber and the energy of the radiation

a is the thickness of the absorber

B is dependent upon both the energy of the radiation and the properties of the absorber

I_o is the intensity of the unshielded radiation

I is the intensity of the emerging radiation.

Thus I can never be brought to zero intensity but for all practical purposes a value of a can be found where I/I_o can be made extremely small so that the remaining radiation is of no consequence.

The distance from a radiation source exerts a profound effect upon its intensity. Consider a point source of I_o photons per second emitted isotropically from a point in space. At a distance r from this point the flux of photons will be

$$I = \frac{I_o}{4\pi r^2} \quad \text{per cm}^2 \text{ per sec}$$

This the intensity falls with the square of the distance.

These two expressions may be combined for the case of a point source at a distance r from an observer and when an absorber of thickness a lies in between, giving an expression for the radiation intensity at the observer of

$$I = \frac{B.I_o e^{-\mu a}}{4\pi r^2}$$

In practical situations we will rarely deal with point sources and for cases such as a reactor assembly or a long fuel element more complicated expressions can be derived for radiation intensities at distances from the source which are comparable with the source dimensions. However, when the distances to the observer are large compared with the source dimensions such expressions reduce to the simple case shown where the inverse square law is obeyed.

Shielding materials for neutrons and gamma rays require certain different characteristics.

(a) Gamma rays are absorbed most effectively by elements of high atomic number and density such as lead, bismuth, tungsten or mercury.

(b) Neutrons are absorbed by elements of low atomic number.

The energy of the neutron is reduced in collision processes in which the kinetic energy of the neutron is shared with the collided atom. When its energy has been reduced sufficiently, it is likely to be captured. In the case of a water absorber, the neutron which has been slowed down by collisions with hydrogen atoms is eventually captured by a hydrogen atom to produce a deuterium atom. Certain materials have a considerable capability for capturing slow neutrons and this property can be used in neutron absorbers. Thus an aqueous solution of a cadmium or a boron compound is an effective neutron absorber since the fast neutrons are slowed down by collisions with hydrogen and when they are reduced to low energy are captured by the cadmium or boron.

In practice, shielding is required in vast quantities so expensive materials can rarely be used, and such substances as iron, concrete and water are used according to their suitability for the particular purpose. Concrete containing a mixture of many elements is suitable both for photon and neutron shielding. In the case of intense radiation sources such as a reactor the thermal effects of radiation prohibit the use of concrete as the primary shield which will be made of iron. When the radiation intensity has been reduced to the level where adverse thermal effects are eliminated, the subsequent shielding can be made of concrete. In some situations water is the most suitable shielding material as, for example, in the spent fuel storage facility of a reactor. The optical transparency of water enables highly radioactive fuel elements to be manipulated with long handling tools. Sometimes glass of several feet in thickness will be used for shielding windows of examination cells where the properties of irradiated material can be tested.

TERMINOLOGY OF RADIATION

The quantity of a radioactive substance could be expressed in terms of its mass and, in some cases, this notation is used. For example, one speaks of a radium source of so many milligrams and radioactive materials such as uranium, thorium or plutonium are referred to by their mass, but these are the exceptions.

A quantity of radioactive material is quantified by the rate at which it is disintegrating, the unit of measurement is the curie (Ci) and amounts to

3.7×10^{10} dis/sec exactly. [Originally 1 Ci was the disintegration rate of 1 g of radium which is approximately 3.7×10^{10} dis/sec.]

The magnitudes of very small sources are frequently referred to as so many dis/sec or min.

The other principal quantity of interest in relation to the strength of a radiation source is the measure of its energy output and there are several units in common use which are appropriate to particular situations. All of these units involve the product of the activity of the source in Ci and the energy released in each disintegration.

The first unit to be considered is the Roentgen and is applicable to the measurement of the intensity of X- and γ-ray sources.

The Roentgen is the quantity of ionization produced in a volume of air exposed to the source. 1 R produces 1 c.s.u. of charge per 0.001293 g of air or in modern units

$$1 \text{ R} = 2.58 \times 10^{-4} \text{ c/kg}$$

Of greater interest in most cases is the energy deposition from an exposure of 1 R. 1 R deposits in air about 87 erg/g and tissue exposed to 1 R of radiation has an energy absorption of about 97 erg/g.

The energy absorbed per unit mass is known as the absorbed dose. The special unit of absorbed dose is the rad and amounts to an energy deposition in the material exposed of 100 erg/g.

Whereas the exposure unit, the Roentgen, was restricted to measurement of radiation in terms of an effect produced in air and was appropriate for photon radiation, the concept of energy absorption and absorbed dose is applicable to all forms of radiation and all absorbers.

Finally, there is the matter of the biological effectiveness of a radiation dose and this is a product of the energy absorption and one or more factors which relate the details of how the energy deposition is distributed in space and time. Thus 1 MeV of electron energy will be absorbed in a few millimetres of tissue whereas 1 MeV of alpha particle energy will be absorbed in about one percent of this distance. In order to put radiation doses from all sources on a common scale of evaluation, the unit known as dose equivalent has been established. It is the product of absorbed dose D in rads and a quality factor (QF), a dose distribution factor (DF) and any other necessary factors.

$$(\text{DE}) = \text{D}(\text{QF})(\text{DF}).....$$

The unit of dose equivalent is the rem.

MEASUREMENT OF RADIATION AND RADIOACTIVITY

A radiation measurement is one in which the result of the measurement is expressed in a unit of exposure (R), absorbed dose (rad) or dose equivalent (rem).

A radioactivity measurement is one in which the result is expressed in an appropriate unit of activity, in curies or actual rates of disintegration (dps or dpm).

The intensity of radiation can be measured as a means of monitoring the fission rate (i.e., the power) of a reactor, or it may be done to estimate the radiation hazard in a working area, or to indicate the occurrence of a malfunction in equipment such as a leak of radioactive liquid from a coolant system or a release of gaseous or particulate radioactive material from a failed fuel element. Measurements will be made of the radioactivity of the effluent gases and liquids from a reactor system in order to determine that no hazard to the environment is being generated.

There are many ways of detecting radiation and radioactivity and a few which are applied to nuclear power plant operations will now be discussed.

The measurement of ionization in a gas is carried out in an ionization chamber which is simply a defined volume containing polarized electrodes to which are attracted the ions created by the radiation. The rate of ion collection constitutes a current which, after amplification, may be used to indicate the radiation situation or control a process or function such as the power level of a reactor or the sounding of a radiation alarm.

The materials and gas of the ionization chamber can be chosen to suit the radiation of interest.

Thus a volume of a high atomic number gas such as argon at high pressure can be used to measure gamma radiation. Neutron intensities may be measured by incorporating in the ion chamber a material such as boron which when exposed to slow neutrons undergoes the reaction

$$n + {}^{10}B \rightarrow Li + \alpha$$

The lithium nucleus and the alpha particle carry several MeV of energy between them and these particles can then cause ionization in the gas of the ion chamber.

Thus the walls of the ion chamber may be coated with boron enriched in ^{10}B and such a chamber with an appropriate filling gas may be used at high

radiation levels. For lower intensities the boron may be used in a gaseous form, $^{10}BF_3$, and such a filling is frequently employed in the gas proportional counter.

Radiation fields and quantities of radioactivity may also be measured with the Geiger-Mueller (GM) counter. This counter is constructed so that by a process of gas multiplication caused in a high internal field in the counter volume a large single pulse is produced by every ionization which occurs in the counter volume. By having a quenching gas in the counter volume only one pulse rather than a continuous discharge is initiated by each ionization. Such counters are in very common use both in radiation protection work and in control of processes. They are available in a wide variety of sizes with different sensitivities and are the most versatile of all radiation detectors in their application. Some are used to measure radiation fields up to levels of a few hundred R/h and others, equipped with thin windows are used to measure very low levels of radioactivity of the order of a few disintegrations per second. Coupled with suitable filter paper arrangements they are commonly employed to determine levels of airborne particulate radioactivity.

Scintillation counters are often in service when it is necessary to obtain additional information about the radioactivity of interest. A crystal of sodium iodide with thallium activation has the property of giving a pulse of light when an ionizing event occurs in the crystal volume. The rate of pulses indicates the activity of the source and the amplitude of the pulse is proportional to the energy deposited in the crystal. Thus the scintillation counter is an energy spectrometer and may be used to identify the presence and relative amounts of activities from several radiation sources.

Today there is an increasing use of semi-conductor radiation detectors. These are made from either silicon or germanium crystals which have been doped with small amounts of trace elements to give the structure the characteristic of a diode rectifier. When a reverse bias is placed upon such a structure there is no conduction until an ionizing effect occurs in the crystal volume whereupon the charge released by the ionization is collected as a pulse. The germanium detector which must be operated at liquid nitrogen temperatures can be used as a spectrometer having a very fine resolution for the identification of gamma radiation sources and the silicon diode, while not possessing the excellent spectrometric properties of germanium, has the virtue of being operable at room temperatures. It is particularly useful for the measurement of radiation dose rates and can be built into portable monitoring equipment. Another form of the silicon diode is a very convenient detector of alpha particles and has excellent spectrometric characteristics.

Another type of semi-conductor radiation detector is now used to measure the accumulated radiation doses received by atomic energy workers. Such a detector is lithium fluoride. This material has the property of trapping

some of the radiation energy it absorbs rather than allowing it to decay as thermal energy. Upon subsequent heating this stored energy is released at a critical temperature (about 250°C) and the magnitude of the light emission is proportional to the accumulated radiation dose. Workers wear such dosimeters which are inspected at regular intervals to ensure that excessive radiation doses are not being accumulated. Previously, radiographic films were used for the same purpose but are now being retired in favour of the thermoluminescent dosimeter which is superior on many counts.

A radiation detection problem which is peculiar to the heavy water reactor arises through the fact that when D_2O is irradiated by neutrons the third isotope of hydrogen, tritium (^3H or T), is produced. The radioactive half life of tritium is 12 years so that there is a continuous growth of tritium concentration throughout the actual lifetime of a reactor.

The detection of tritium is an important problem for two reasons:

(a) As produced in the reactor heavy water, it exists in the chemical form DTO, i.e., a water molecule, and if this tritiated heavy water then escapes into the surroundings an exchange process with atmospheric moisture (typically 10 g per m^3 of air) leads to the formation of tritiated and deuterated light water.

$$DTO + H_2O \rightarrow HDO + HTO$$

In the form of water it may enter the body of a radiation worker and distribute itself through the body fluids and proceed to deliver a radiation dose to the individual from the beta radiation which is emitted in its decay

$$^3H \rightarrow {}^3He + \beta^-$$

Since there is a continuous exchange of body water with the environment, permanent retention of tritium in the body does not occur but instead it has an effective half life for elimination of about 10 days.

Tritiated water is eliminated in urine, perspiration and in exhaled breath.

Since we are anxious to control both internal as well as external radiation exposure, it is necessary to monitor the air in the vicinity of a reactor for its tritium content, and also to analyse specimens of body fluids such as urine for evidence of tritium intake. Since the processes of water metabolism have been determined, it is possible to estimate from the tritium content of urine the radiation dose which has been received.

(b) The ability to detect tritium is important because its presence is an indicator of the presence of heavy water. Since heavy water is valuable, leakages must be stopped,so that continuous monitoring is required. After a comparatively short period of operation of a reactor, its heavy water will contain sufficient tritium so that concentrations of heavy in light water of only a few ppm are measurable. Typically, tritium monitoring for heavy water will be done routinely on light water streams from heat exchangers and in all air spaces into which heavy water may escape.

The detection of tritium presents something of a challenge for two reasons. The beta particle emitted in a tritium decay has a remarkably small energy (E_{max} = 16 keV) and is incapable of penetrating the window of a GM counter. Therefore the sample to be counted must be incorporated in some way in the sensitive volume of the detector. Secondly, it is frequently necessary to make estimates of tritium concentrations in the presence of competing radiation sources. Two methods in general use involve either the circulation of the air to be examined through the volume of an ionization chamber or the mixing of the sample which has been accumulated or obtained in a volume of water with a liquid scintillator.

BIOLOGICAL ASPECTS OF RADIATION EXPOSURE

Shortly after the discovery of X-rays in 1895 and the demonstration that details of the human anatomy could be displayed on fluorescent screens and recorded on radiographic film, there was a tremendous effort by medical workers to take advantage of the new tool using very primitive X-ray equipment. Not surprising to us, but without being expected at the time, it was soon found that serious injuries could result from X-ray exposure. Many workers and patients suffered skin burns and, in some cases, the damaged tissue became malignant. The benefits and dangers of ionizing radiation were both established within a very short period.

Following the discovery of X-rays, Becquerel discovered radioactivity in uranium in 1897, and later radium was extracted from uranium. Its ability to cause luminescence in fluorescent substances was quickly applied on a commercial scale in the production of self-luminous dials for time-pieces and other indicators. The inscription of luminous characters involved hand-painting and it was a common practice to 'sharpen' the paint brush between the lips. As a result, there accumulated quite large numbers of workers who absorbed and retained in their bodies damaging amounts of alpha emitting radioactive substances. Whereas some ingested radioactive materials are eliminated from the body in a short period, either because of having a short physical half life such as ^{131}I (8 days) or because of a short biological life time such as tritium (10 days), others have a long physical half life and a long biological half life,

the latter being through incorporation in permanent body tissue. Radium is such an element, having a chemical similarity to calcium, and it is deposited in bone.

The result is that now, some 40-60 years after the period in which luminizing was carried out by primitive techniques, there is a known population of several hundred women in North America who show radiation-induced injuries to the skeleton including both malignancies and brittleness of bone structure giving rise to spontaneous fracture.

While little is known about the magnitudes of the early X-ray exposures, much work has been done to establish the amount of radium ingestion which leads to an observable effect within a lifetime. Such work is based upon estimates of total body Ra activity made in recent years of both survivors and those already dead by examination of remains and autopsy specimens. Some workers with detectable body burdens have been found who show no adverse radiation effects and, while it is tempting to speculate from such data that there may be a threshold for radiation injury, it must be kept in mind that the total population in the sample available is small and it is not reasonable to extrapolate such data to large populations.

Other significantly exposed populations include those who have had radiation treatments for non-malignant diseases, victims of nuclear warfare and workers involved in radiation accidents. In addition, a category of workers who received appreciable radiation exposure extending over many years are the radiologists who were in practice during the first half of this century. In many instances only very rough estimates can be made of the probable magnitude of the exposures involved and comparison with appropriate control populations is difficult to establish.

Radiation effects which occur within the lifetime are called somatic and they may occur shortly after the exposure (acute effects) or after a long interval of time (late effects). Radiation effects upon the germ cells of the exposed individual may appear in his progeny in later generations (genetic effects). Somatic injuries from radiation include leukemia and cancers of other organs - thyroid, bone and skin. Irradiation in utero may cause abnormalities in the subsequent fetal development, and for this reason abdominal X-irradiation of women who may possibly be pregnant is avoided. Observations on life spans of American radiologists in comparison with members of other medical specialities seem to indicate that they have a greater mortality rate from all causes and at all ages. However, it should be kept in mind that there is considerable difficulty in interpreting data on non-specific injuries from large radiation exposures of people for several reasons.

(a) Large numbers of cases are not available for study.

(b) The radiation exposure may have been given for known clinical conditions and it is difficult to estimate the fraction of subsequent effects which are only due to radiation.

(c) In comparisons of Japanese population survival rates after 1945, socio-economic factors which differentiate the exposed population and the non-exposed control population who were outside of the bombed cities in 1945 may possibly exist.

Given only rather imperfect data on radiation effects following large exposures, it is difficult to arrive at risk estimates for low levels of exposure such as occur in the occupation of an individual in nuclear energy or at much lower levels in the general population in the vicinity of nuclear power plants. Conservatively one can choose to assume that there is a linear relationship between exposure and effect, and there is no threshold level of exposure below which no effect occurs. Linearity of dose effect has not been established at low dose levels and may well never be even in experimental animal populations simply because of the magnitude and cost of such an experiment; but without evidence we may only assume that there is a linear effect. With such an assumption and using all available data on high level exposures, it is possible to arrive at rough estimates of risk per unit of radiation dose.

Thus the risk of fatal cancer over a 10-20 year period following exposure is of the order of 40 per 10^6 persons exposed to 1 rem of whole body radiation. This risk can be compared to the annual death rate from cancer in the U.S., which is of the order of 1500 per 10^6 persons and a total death rate of about 9500 per 10^6 persons.

Similarly an estimate of the genetic detriment to the first generation of 10^6 offspring in a population where the whole parental generation had received 1 rem of dose can be expressed as a fraction of the natural incidence of such events and amounts to a less than one percent increase.

Another comparison which can be made is between the risk of death from occupational radiation exposure to the risk of death from all occupational accidents. In the United Kingdom, the occupational injury death rate is about 10 times greater than the estimated risk of death for continuous radiation dose of 1 rem/year through a working lifetime. (The average annual dose of those occupationally exposed in a wide range of occupations is on the average about 0.5 rem/year.)

Ionizing radiation exposure of man is not simply a product of the inventions of this century, but has been occurring since creation. The sources of radiation are both terrestial and extra-terrestial, and of the former some are found in the tissue of man himself.

Naturally occurring radioactive materials on earth include, as well as the elements uranium and thorium and their daughter products, both potassium and carbon. Potassium, which is an element found in lean tissue, has a naturally occurring radioactive isotope ^{40}K and each g of potassium undergoes about 30 disintegrations per second. A man of standard build contains about 140 g of potassium. Relatively speaking, women contain less potassium because of their greater proportion of fatty tissue. Likewise, carbon has a radioactive isotope ^{14}C which exists in all carbonaceous material in a small proportion and contributes along with the ^{40}K to the internal dose of the human. The average natural radiation dose to a person living at sea level amounts to a total of about 140 mrem/y. Two factors may increase this in particular situations. The extra-terrestial radiation, so called cosmic radiation incident upon the earth, is absorbed and attenuated by the atmosphere so that populations who live at high altitudes receive greater than the sea level dose rates. The second factor relates to the geology of the location in which we live and the materials used in the construction of our houses. Granite bearing rocks (and concrete made from such rocks) contain small quantities of uranium and thorium, and as a result increased radiation dose levels exist in the vicinity of such materials. In general, only small increases above average natural background levels are found in such circumstances (less than a factor of two) so it is out of the question to expect to find obvious radiation effects in such exposed populations. In two particular locations, one in Brazil and the other on the southwestern coast of India, due to the occurrence of large deposits of thorium in beach sands, significant populations have been exposed for many generations to natural radiation levels which are several times the normal value. Much work has been done in the past decade or so in making measurements and observing such populations but no significant radiation effects have yet been found.

The largest contributor to the radiation exposure of the general population other than natural background is due to medical X-ray diagnosis. At the present time this contribution amounts to about a 60% increase in the natural radiation level. A significant effort is being made to reduce this contribution by better techniques, more careful operation of equipment and better planning of patient examinations.

We are in the position of knowing that large doses of radiation given in short periods of time can produce adverse effects in living creatures, and it is prudent to assume that any exposure to radiation entails a risk of deleterious effect. At the same time, we know that life has evolved to its present state in the presence of ionizing radiation. If we wish to make use of the benefits which arise from the use of man-made radiation such as X-ray diagnosis, and other medical procedures and cheap sources of power, then we must recognize there is a risk and limit radiation doses to a level at which the risk is acceptable in view of the benefits derived. The radiation exposure standards in world-wide use at the present time are the result of the deliberations on this problem of

the International Commission on Radiological Protection (ICRP) whose standards have in turn been adopted in individual countries.

The Maximum Permissible Doses recommended cover the cases of both the radiation worker, individual members of the population at large and large population groups. Special groups within these several populations have been given particular treatment, and in the case of the radiation worker radiation dose limits are set for both the whole body and fractions or organs of it. Thus while the body of a radiation worker as a whole may be exposed to a dose of 5 rems in a year, the skin may receive up to 30 rems and the extremities (the hand and forearms) up to 75 rems. Individual organs (such as may be exposed by the ingestion of a radioactive substance) may be exposed to 15 rems/y.

Members of the public are, in general, limited to 1/10 of these exposure levels and the exposure limit for populations is 1/30 of the occupational level. There is no contradiction between these two levels for the population and its individual members from man-made and non-medical uses of radiation. The larger represents a limit of the extreme individual case and if the former is satisfied the exposure of a large population group of which that individual is a member will be very much less than the limit set.

In particular, working situations radiation protection is secured through careful training of workers and proper design of facilities which contain or generate radiation sources. Judicious use of shielding and distance enable the largest fixed sources to be handled safely. If loose radioactive materials escape into a working area, safety is ensured by having the means to give an adequate warning of the event and such measures as protective clothing and respirators to prevent the ingestion of the radioactive substances into the body. In one rather special situation a medication, if taken immediately upon exposure, can lead to a reduction in the dose received. This is the case of ingestion of radioactive iodine. Normally iodine entering the body proceeds to the thyroid and remains there with a biological half life of 138 days. [The physical half lives of radioiodines are short. Thus the effective half life of ^{131}I (whose physical half life is 8 days) is only 7.6 days.] The uptake of further iodine by the thyroid can be blocked if it is already saturated and this can be achieved by the worker eating a small tablet of KI. Such a prophylactic measure could be recommended if work had to proceed (even with protective clothing and respirators) in an area known to be heavily contaminated with radioiodine. Likewise if an ingestion of tritium has occurred, the biological half life can be reduced by an increased intake of fluids. Such measures would only be taken under medical advice which would take into account the benefit to be achieved by having a reduced radiation dose against the risk of adverse effects from the treatment.

While the effects of radiation upon living tissue can be destructive or lead to changes which cause disease, these effects are simply the recognizable consequences of basic radiation reactions which may occur in all materials to a greater or lesser extent. Thus the effect of radiation upon water causing its dissociation into free H and OH radicals with the liberation of hydrogen and the formation of hydrogen peroxide may cause cell death in a living tissue, but in a reactor water system presents an awkward problem for chemical control, and requires the employment of recombination units to prevent the build-up of explosive gas concentrations in the atmosphere above the reactor. Recombination of hydrogen and oxygen is effected by catalytic recombination using a platinized aluminum catalyst and it may be necessary to add extra oxygen to recombine the available hydrogen because some of the radiolytically produced oxygen will be held up as peroxide and not available.

Another problem which arises from the radiation decomposition of water is the production of nitrogen oxides when water is irradiated with a free air volume above it. These products are undesirable because they lead to nitric acid formation which may cause corrosion of structural materials. The situation may occur in a reactor in the gas space above the moderator and is prevented by maintaining a helium atmosphere above the moderator. Gas production in irradiated water is kept low by keeping purity high. Impurities have the characteristic of scavenging free radicals (H and OH) produced by irradiation and leading to the formation of hydrogen gas molecules in the water.

In recirculating coolant systems such as in a power reactor it may be necessary to add hydrogen to the coolant to restore the correct proportions of hydrogen and oxygen to allow recombination. In this situation hydrogen can be lost from the system through its diffusion through carbon steel piping in heat exchangers.

Radiation damage can result from the fission process in the reactor fuel due to two secondary effects. Since in fission two atoms are produced where one existed previously, an increase in volume of the irradiated material takes place. Such a swelling of the fuel material causes excessive strain and possibly failure of the cladding material which may then interfere with the flow of coolant and cause a catastrophic failure. If the temperature of the irradiated fuel is sufficiently high,diffusion and aggregation of fission product gas atoms can occur so that internal gas pockets may be formed. High internal pressures are the result and failure of sheathing material may follow. The particular advantage of oxide over metal fuels is that they have much higher melting points and the gaseous fission products are less mobile.

Certain radiation induced chemical reactions can be used as a means of measuring radiation doses. Such a useful reaction is the oxidation of ferrous sulphate to ferric sulphate in aqueous solution. The extent of the radiation effect

can be accurately measured by optical absorption of the solution in a spectrophotometer. Benzoic acid irradiated in the presence of water is oxidized to produce salicylic acid and the magnitude of the dose may be estimated in a fluorimeter since the product of the reaction is fluorescent.

While some reactions of radiation upon materials are useful in dosimetry, many materials are destroyed by radiation and can therefore not be used in a radiation environment. Plastic materials used as insulators can withstand only limited radiation doses before loss of resistivity and change of mechanical properties occur. Thus in a reactor those electrical circuits which of necessity have to be exposed to high radiation doses such as ion chamber insulators and connecting cables use mineral materials such as quartz, aluminum oxide and magnesium oxide for insulators which are less sensitive to radiation than plastics. The adverse effects of radiation are well illustrated in the simple case of the GM counter. The quenching agent used in the first self-quenching counter tubes was ethyl alcohol. However, some of this material is dissociated into simpler molecules by each radiation event counted and when more than a critical quantity is consumed the counter no longer possesses any quenching capability and is put into continuous discharge in a radiation field. Similarly, a semi-conductor material has its characteristics modified by the introduction of lattice defects when exposed in a radiation field. While some use of this property has been made in the design of a silicon diode dosimeter it also means that a semi-conductor amplifier may not be used for extended periods in high radiation fields. In the silicon diode dosimeter the effect of the dose is shown by a decrease in its forward conductivity.

In this discussion it has only been possible to point out various characteristics of radiation and their consequences in the production of electrical energy. The objective in radiation management is to keep it under control at all times and to design plant and equipment so that no hazard results to the operators and those in the vicinity of the plant as a result of the escape of radiation or radioactive materials through failure of materials or errors in procedures. So that adequate warning may be received when hazardous situations occur, either of a catastrophic nature or due to small scale effects which can continue for extended periods, much effort is spent on radiation monitoring. Such surveillance includes the providing of all workers with personal dose recording devices, the measurement of contamination levels and radiation intensities in working areas, the continuous monitoring of effluent materials both gaseous and liquid from the reactor system, and the provision of facilities such as air filters and liquid holding tanks to prevent the escape of active materials when failures occur. The record over many years shows that containment of radioactive materials is a practical proposition and very large quantities of radioactive substances can be safely controlled.