the dme

Department:
Minerals and Energy
REPUBLIC OF SOUTH AFRICA

UNDERSTANDING RADIOACTIVITY
&
RADIATION IN EVERYDAY LIFE

APRIL 2005

Foreword

Our world is radioactive and has been since it was created. Over 60 radionuclides (radioactive elements) can be found in nature, and they can be placed in three general categories:

1. Primordial - from before the creation of the Earth
2. Cosmogenic - formed as a result of cosmic ray interactions.
3. Human produced - enhanced or formed due to human actions (minor amounts compared to natural)

Radionuclides are found naturally in air, water and soil. They are even found in our bodies, as we are products of our environment. Every day, we ingest and inhale radionuclides in our food, water and air. Natural radioactivity is common in the rocks and soil that makes up our planet, in water and oceans, and in our building materials and homes. There is nowhere on Earth that you can not find Natural Radioactivity.

Radiation is a general term and covers many different forms of radiation, e.g. visible light, ultraviolet light, microwaves, radio waves, X-rays, etc. Radiation can be divided into two broad categories – ionising and non-ionising radiation. Ionising radiation is the particular type of radiation emitted by radioactive substances. It differs from non-ionising radiation in that it is very energetic and has the capacity to ionise matter when it interacts with it. This booklet will only focus on ionising radiation.

The Department of Minerals & Energy developed the draft radioactive waste management policy and strategy in 2002. During the public comment phase of the draft radioactive waste management policy and strategy, it became clear that more education and awareness of nuclear in general should be provided to the public.

This booklet has been written to explain the nature of radioactivity, and to explain the protection measures that are undertaken in the use of radioactive material. This booklet is primarily an awareness-raising resource and been designed as an easy to read with colourful sections.

With proper understanding of the hazards and by obeying instructions, radiation doses can be kept well within acceptable safety limits.

The following are common abbreviations used in this booklet: **m** - meter, **m**^{3} - cubic meter, **g** - gram, **kg** - kilogram, **Bq** - becquerel, **Sv** - sievert, **Ci** - curie, **yr** - year, **hr** - hour, **L** - liter

Finally, to find definitions of terms you're not familiar with, look on the glossary pages at the back of the booklet.

This booklet was developed with input from the Department of Minerals and Energy.

For more information or if you have any questions on nuclear matters, you can contact the Chief Directorate: Nuclear at the Department of Minerals & Energy at (012) 317 8008 or visit the DME website at www.dme.gov.za or send an e-mail to nuclear@dme.gov.za

Atoms & Radiation

1

Radioactivity is a part of our earth -- it has existed all along. Naturally occurring radioactive materials are present in its crust, the floors and walls of our homes, schools, or offices and in the food we eat and drink. There are radioactive gases in the air we breathe. Our own bodies - muscles, bones, and tissue - contain naturally occurring radioactive elements.

Man has always been exposed to natural radiation arising from the earth as well as from outside the earth.

Most people, when they hear the word "radioactivity", only think about something harmful or even deadly, things such as the atomic bomb that was dropped on Hiroshima, or accidents like Chernobyl. We will be better equipped to understand ionizing radiation and its effects if we know what causes radiation. Radioactive atoms emit radiation.

All material in the universe is composed of combinations of different basic substances called chemical elements. There are 92 different chemical elements in nature. The smallest particles, into which an element can be divided without losing its properties, are called atoms. Everything in nature is composed of atoms.

An atom consists of two main parts namely a nucleus with a circling electron cloud. The nucleus consists of subatomic particles called protons and neutrons.

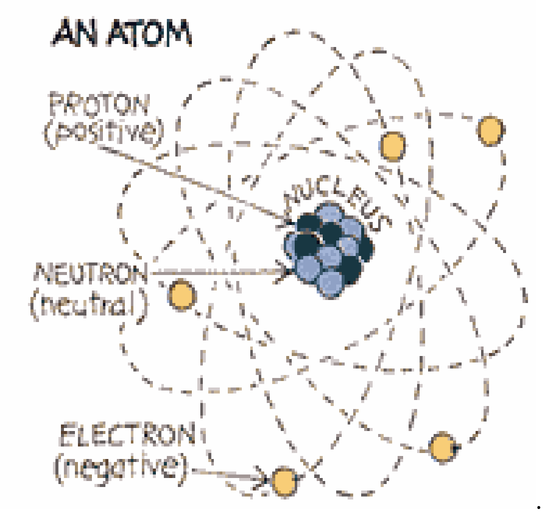


Fig 1: Schematic diagram of an atom

Atoms range in size from simple hydrogen atom, which has one proton and one electron to large atoms such as uranium, which has 92 protons, 92 electrons and 146 neutrons. Each element is made up of its own unique atoms.

Radioactive elements are those in which the atoms are unstable and break down (decay) to form atoms of another element. This decay is accompanied by the release of ionising radiation in the form of invisible small particles and high-energy waves. Uranium, thorium and potassium-40 are examples of naturally occurring elements that are radioactive.

WHAT IS RADIATION?

Radiation is energy that travels through space, in the form of particles or electromagnetic waves. The word 'radiation' refers to many forms of energy such as light, heat, radiowaves, microwaves, X-rays, radar, etc.

Radiation is also the general name given to the kind of energy given off by radioactive atoms such as uranium and thorium. This type of radiation is called ionizing radiation because it has enough energy to remove electrons from atoms in the materials they penetrate, for example our bodies.

Its ability to ionize is exactly what makes ionizing radiation potentially harmful to life. Ionisation causes chemical bonds to break up. When chemical bonds break, other new bonds may form. Some of the new chemical substances thus formed may be harmful. Ionising radiation can therefore harm the human body because it changes chemical bonds in the body. However, ionizing radiation cannot be felt, smelt, tasted, seen or heard.

The principal kinds of ionising radiation are:

Alpha (′α′) particles. These are heavy, positively charged particles which do not travel very far, even in air. Alpha particles are intensely ionizing but cannot penetrate the skin, so they can be harmful only if emitted inside the body. Entry of alpha particles inside the body can occur through inhalation of radioactive dust or ingestion of alpha emitting radioactive material.

Alpha particles are easily stopped by a thin sheet of paper or by the skin covering your body. However, if alpha emitting radioactive elements get inside the body they can pose a risk to sensitive body organs such as the lungs and bones. Fortunately this risk can be reduced by ensuring that the inhalation or ingestion of materials that emit alpha particles is kept to a minimum by either installing dust controls or by the appropriate use of respiratory protection devices such as dust masks.

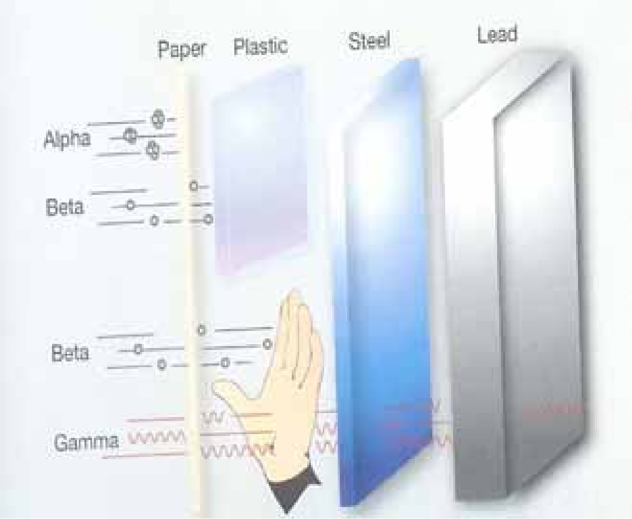


Fig 2: Penetrating power of alpha, Beta and Gamma

Beta (′β′) particles are fast-moving electrons emitted by many radioactive elements. They are smaller and more penetrating than alpha particles, but easily shielded.

They are negatively charged and can travel much further through air than alpha particles, but they can be stopped by a few millimeters of most materials. It is possible that the contamination of a person's skin by beta emitting radioactive elements could pose a risk to that person.

Gamma rays (′γ′). These are waves of energy similar to light, but they have much higher energy and can travel great distance through air. They are very penetrating and require shielding in the workplace. Thick shields of concrete or metal (lead) plating can stop them.

Gamma rays pose a risk whether the radioactive material is within or outside the body.

Neutrons are mostly released by nuclear fission - the splitting of atoms in a nuclear reactor, and hence do not pose a risk outside nuclear plants. However, fast neutrons can be very destructive to human tissue.

X-rays are generated by electronic machines and not by radioactive material. X-rays pass right through the body and X-ray photographs work on this principle.

RADIOACTIVE DECAY

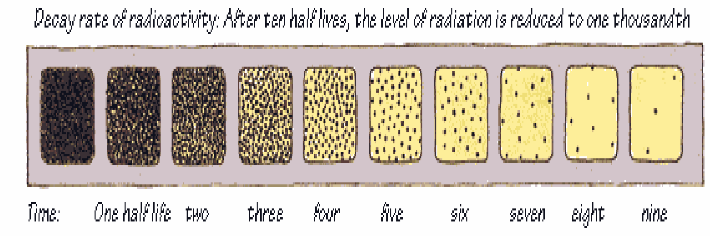
When the universe was formed, with uranium and Thorium as two of its constituents, the process of Radioactive decay (break down) began.

A substance is called "radioactive" when the nucleus is unstable, in other words when some atoms change by themselves and give out ionizing radiation in the process.

The emission of ionizing radiation by a radioactive atom is called radioactive decay. The radioactive material that changes and emits radiation is called a radionuclide. During the decay of a radionuclide its amount decreases and its radioactivity decreases proportionately. The time it takes for the activity of a radionuclide to decay to one half is called the half-life. During the process of decay the original radionuclide is transformed into another nuclide, which can itself be radioactive. If so, it will, in turn, emit radiation and turn into another nuclide, which may be radioactive. These emissions of radiation will continue until finally a stable (non-radioactive) nuclide is formed. The chain of nuclides formed is called a decay chain.

As an example, in the uranium series there are fourteen radioactive elements, including radon gas. Similarly the thorium series has eleven radioactive elements.

Uranium and thorium decay very slowly. For example, if we started with 1,000 atoms of uranium, it would take four and a half billion years (that is 4,500,000,000 years) for 500 of those uranium atoms to decay, which is the half-life for uranium. The half-lives for some other radionuclides are: Iodine-131, it is 8 days; cesium-137, 30 years; carbon-14, 5730 years.



Radioactivity cannot be destroyed. Radioactivity decay process cannot be slowed down or accelerated by any chemical or physical processes, e.g. cooling, heating or even melting the radioactive substance. The passage of time is all that is really able to decrease the radioactivity of a substance.

ISOTOPES

It was stated that each element has its own characteristic atoms, but there are a few variations of each element's atom. This can be illustrated with an example. This can be compared to the different models of a typical car, e.g. 1.4, 1.6, 1.8 or 2.0-litre capacity. These four models of the same car are called isotopes of that car. A series of nuclides having the same number of protons but with different nuclear masses are said to be isotopes of that element. The word isotope is made up from the Greek words "iso" (the same) and "topos" (place).

Isotopes of an element all have the same chemical characteristics. Isotopes have only slightly different nuclear masses, and their nuclear structures differ slightly from one another. For example, Uranium-235 and Uranium-238 are two isotopes of uranium with different nuclear masses.

ACTIVITY

The quantity of radioactive material present is generally measured in terms of activity rather than mass, where activity is a measurement of the number of radioactive disintegrations or transformations, an amount of material undergoes in a given period of time.

Activity is related to mass, however, because the greater the mass of radioactive material, the more atoms are present to undergo radioactive decay. It is very important to realize that sometimes even a very small quantity of radioactive matter can give out a lot of radiation, and may therefore be potentially very harmful.

For the same radioactive substance, a greater mass will have more radioactivity. For example, 2 kg of uranium will have twice as much radioactivity as 1kg of uranium.

However, equal masses of different radioactive substances can have very different activities. In other words, a given activity can be truckloads of one isotope, or a tiny speck of another isotope.

Activity is measured in the unit Becquerel (Bq). Another, older,unit that is often still used is the Curie (Ci). Bq and Ci are measures of radioactivity, and not of radiation or radiation dose.

Sources of Ionizing Radiation

2

All living creatures, from the beginning of time, have been, and are still being, exposed to radiation. All matter is made up of 92 elements some of which are naturally radioactive. This natural radioactivity may be found in rocks, in soil, in materials used for buildings construction, in foods and liquids that we eat and drink, and in the human body itself.

This chapter will discuss the sources of this radiation, which are:

- Natural background radiation
- Man made sources of radiation

Fig 3: Natural background radiation

NATURAL BACKGROUND RADIATION

We are all exposed to natural radiation to a greater or lesser extent, and for most people it is the major source of radiation exposure.

Background radiation is that which is naturally and inevitably present in our environment. Levels of this can vary greatly.

The highest known level of background radiation affecting a substantial population is in Kerala and Madras States in India where some 140,000 people receive doses which average over 15 millisievert per year from gamma radiation in addition to a similar dose from radon. Comparable levels occur in Brazil and Sudan, with average exposures up to about 40 mSv/yr to many people.

There are three sources of natural background radiation:

- Cosmic Radiation
- Terrestrial Radiation
- Internal Radiation

Cosmic Radiation

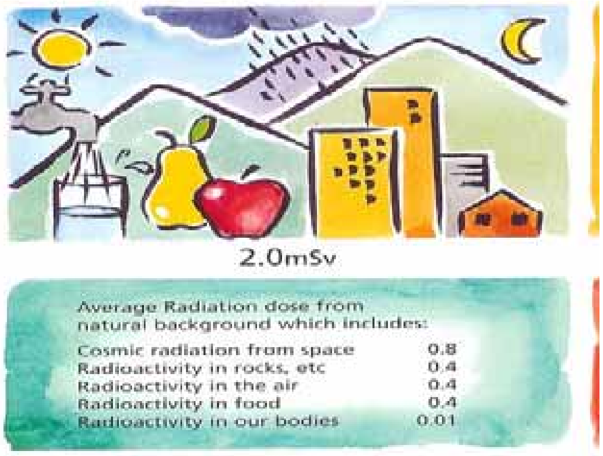
Cosmic radiation is naturally occurring ionising radiation arising from sources outside the Earth's atmosphere. It is one component of the natural radiation environment to which mankind is constantly exposed. Cosmic radiation increases with altitude and so flight crews and other frequent flyers are exposed to enhanced levels of this type of radiation.

Cosmic radiation reaches the Earth's atmosphere from outer space at a fairly constant rate. It undergoes a series of complex interactions within the atmosphere and is gradually absorbed.

Since cosmic radiation consists of charged particles it is deflected by the Earth's magnetic field with the result that cosmic particles enter the atmosphere in greatest numbers near the magnetic poles. The dose received onboard an aircraft operating close to the poles is, therefore, greater than that for an aircraft operating at a comparable altitude close to the equator.

Terrestrial Radiation

Radioactive material is also found throughout nature, in soil, water, and vegetation. Low levels of uranium, thorium, and their decay products are found everywhere. Some of these materials are ingested with food and water, while others, such as radon, are inhaled.



Average Radiation dose from natural background which includes:

Cosmic radiation from space	0.8
Radioactivity in rocks, etc	0.4
Radioactivity in the air	0.4
Radioactivity in food	0.4
Radioactivity in our bodies	0.01

Fig 4: Annual background radiation dose

The majority of natural radiation comes from radon-222 and its 'daughter' radionuclides, which arise from the decay of uranium-238. Radon gas emanates from the ground and from building materials at a rate which is dependent upon:

- the concentration of uranium;
- the extent to which the rocks in the ground are fractured;
- the nature and condition of the overlying soil - its degree of compaction, moisture content and temperature

Internal irradiation

In addition to cosmic and terrestrial sources, people also have radioactive potassium-40, carbon-14, lead-210, and other isotopes inside their bodies from birth until death.

Potassium-40 also comes into the body with the normal diet. It is the main source of internal irradiation apart from the radon decay products. In addition, the interactions of cosmic rays with the atmosphere create a number of radionuclides, such as carbon-14, which also contribute to internal irradiation.

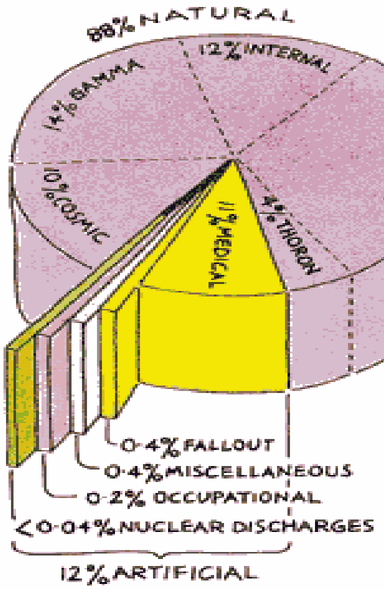


Fig 5: Various contributors to the total radiation dose

The average effective dose from these sources of internal irradiation is estimated to be 0.3 mSv in a year, with potassium-40 contributing about half. The amount of potassium, and hence potassium-40, varies with the amount of muscle in the body, and is about twice as high in young men as in older women. There is little anyone could do to affect internal irradiation from the other radionuclides except by avoiding any food and water with a high radioactive content.

Naturally occurring background radiation is the main source of exposure for most people. Levels typically range from about 1.5 to 3.5 millisievert per year but can be more than 50 mSv/yr in some countries. About 85% of the average individual radiation dose comes from natural sources.

MAN MADE RADIATION SOURCES

Although all people are exposed to natural sources of radiation, two distinct groups are exposed to man-made radiation sources:

- members of the public
- Occupationally exposed individuals

Exposures to the public

The use of radiation in medical procedures, such as diagnostic x-rays, nuclear medicine, and radiation therapy, is by far the most significant source of man-made radiation exposure to the public.

In addition, members of the public are exposed to radiation from consumer products, such as building materials, combustible fuels (gas and coal), televisions, luminous watches and dials, airport x-ray systems, smoke detectors, road construction materials etc.

Of lesser magnitude, the public is exposed to radiation from the nuclear fuel cycle (discussed in chapter 3), which includes the entire sequence from mining and milling of uranium to the actual production of power at a nuclear plant.

Radioactive discharges from nuclear sites account for about 0.0004mSv per year of the average dose. Radioactive materials discharged to the environment are carefully controlled. The National Nuclear Regulator (NNR) is responsible for authorising discharges from all authorised activities.

Members of the public must not receive a dose of more than 1mSv per year from nuclear facilities. To measure the risk to members of the public from radiation from nuclear sites, the radiation dose received by a "critical group" is calculated.

Occupational Exposure

Occupationally exposed individuals, on the other hand, are exposed according to their occupations, and to the sources with which they work. Occupationally exposed individuals, however, are monitored for radiation exposure with dosimeters to ensure that they do not exceed the prescribed dose limits.

The following are sources of occupational exposure:

- Nuclear Fuel cycle
- Radiography
- Nuclear medicine

Radiation Units

The degree of danger posed by ionizing radiation depends on:

- The rate at which the radiation is received, and
- The total amount of radiation received.

Should a person be exposed to either internal or external radiation only a portion of the radiation will be absorbed. This absorbed portion is called the "radiation dose", or the "effective dose". By definition, the effective dose is the biologically harmful radiation dose received by the whole body. This takes the following points into consideration:

- The amount of radiation energy absorbed per mass of irradiated tissue.
- The ability of each radiation type to cause damage to body tissue, and
- The sensitivity of each type of irradiated tissue to radiation damage.

Just as length is measured in units of metres, radiation dose is measured in units of sieverts (Sv). Since one sievert is a large quantity, it is more common to show doses in millisieverts (mSv) or even microsieverts (μSv) which are one-thousandth or one millionth of a sievert. For example, one chest X-ray will give about 0.2 mSv of radiation dose.

Dose rate is the "speed" at which a radiation dose is received, that is, the effective dose per unit time. Dose rate is normally measured in units of microsievert per hour (μSv/h) or millisievert per hour (mSv/h). A dose rate can be used to estimate the amount of radiation dose a person will receive if that person spends a certain period of time in a radiation area.

The Nuclear Fuel Cycle

3

Uranium is not a scientific creation or the product of a laboratory. It is a natural resource that, like coal, oil and natural gas, is extracted from the earth. Uranium, as it is mined from the earth's crust, is not directly useable for power generation. Much processing through a series of steps must be carried out to concentrate uranium before it can be used efficiently to generate electricity.

The nuclear fuel cycle is the series of industrial processes which involve the production of electricity from uranium in nuclear power reactors. To prepare uranium for use in a nuclear reactor, it undergoes the steps of mining and milling, conversion, enrichment and fuel fabrication.

The diagram below depicts the various steps that together make up the entire Nuclear Fuel Cycle:

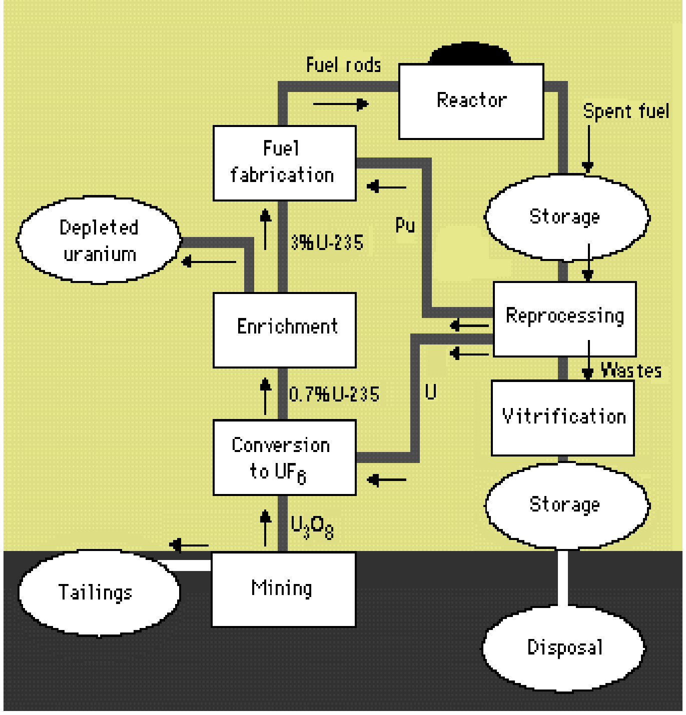


Fig 6: Schematic diagram of the nuclear fuel cycle

1. Mining and milling

These two processes are the first in the 'front end' of the nuclear fuel cycle. Uranium is usually mined by either surface (called open cut mining), underground mining techniques, or using in situ leaching depending on the depth at which the ore body is found.

From these, the mined uranium ore is sent to a mill which is usually located close to the mine. At the mill the ore is crushed and ground to a fine slurry. The uranium is then dissolved from the other materials using sulphuric acid.

The uranium-rich solution is filtered, and the uranium separated and dried to produce a solid uranium concentrate called yellowcake. The solid uranium oxide concentrate (U_3O_8) is now exported and ready for the next step - conversion.

U_3O_8 is the uranium product which is sold. About 200 tonnes is required to keep a large (1000 MWe) nuclear power reactor generating electricity for one year. A single tonne of uranium will generate the same electricity as 15000 tonnes of coal or 9000 tonnes of oil..

2. Conversion

Because uranium needs to be in the form of a gas before it can be enriched, the U_3O_8 is converted into the gas uranium hexafluoride (UF_6) at a conversion plant in Europe, Russia or North America. There is no operating plant in South Africa anymore.

3. Enrichment

Enrichment is the process of concentrating or increasing the amount of the U-235 isotope, compared with the U-238 isotope.

The vast majority of all nuclear power reactors in operation and under construction require 'enriched' uranium fuel in which the proportion of the U-235 isotope has been raised from the natural level of 0.7% to about 3.5% or slightly more. The enrichment process removes about 85% of the U-238 by separating gaseous uranium hexafluoride into two streams: One stream is enriched to the required level and then passes to the next stage of the fuel cycle. The other stream is depleted in U-235 and is called 'tails'. It is mostly U-238.

So little U-235 remains in the tails (usually less than 0.25%) that it is of no further use for energy, though such 'depleted uranium' is used in metal form in transport containers for medical isotopes, yacht keels, as counterweights, and as radiation shielding, since it is 1.7 times denser than lead.

4. Fuel fabrication

The enriched uranium, which has been milled to separate it from the ore, converted and enriched, is now sent to a fuel fabrication plant where it is changed into uranium dioxide powder.

The powder is pressed into small pellets, which are then put into metal tubes, forming fuel rods. The rods are then sealed and assembled in clusters to form fuel assemblies for use in the core of the nuclear reactor.

The fuel assemblies are put into the core of the nuclear reactor along with a moderator, such as graphite or water. Control rods are used to slow down or stop the chain reaction inside the reactor. They absorb neutrons. Water carries the heat away from the core and makes steam. The steam turns the turbines that generate the electricity. Electricity generation from nuclear power is discussed in the next chapter.

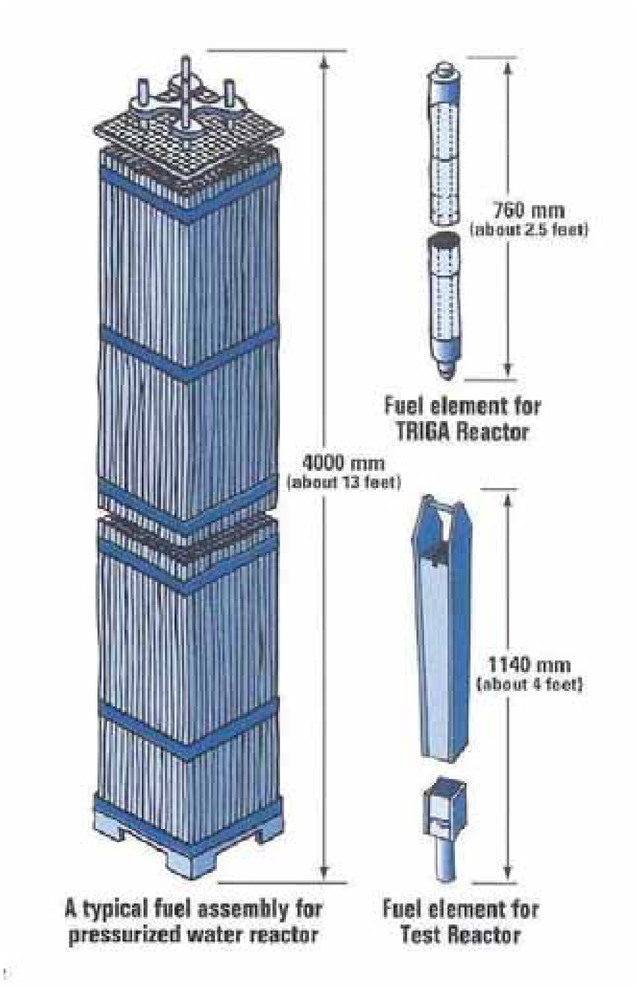


Fig 7: Various types of fuel elements

5. Spent fuel storage

To maintain efficient reactor performance, about one-third of the spent fuel is removed every year or 18 months, to be replaced with fresh fuel. When the spent fuel is removed from the reactor, it is hot and very radioactive. It must be cooled and shielded from people. It is put into storage ponds at the reactor site. The storage ponds are steel-lined concrete tanks, about 8 metres deep and filled with water.

The water cools the spent fuel rods and acts as a shield. The heat and radioactivity decrease over time - after about 40 years they are down to about 1/1000 of what they were when taken from the reactor.

Spent fuel can be stored safely in these ponds for long periods. It can also be dry stored in engineered facilities, cooled by air. However, both kinds of storage are intended only as an interim step before the spent fuel is either reprocessed or sent to final disposal. The longer it is stored, the easier it is to handle, due to decay of radioactivity.

There are two alternatives for spent fuel:

- reprocessing to recover the usable portion of it.
- long-term storage and final disposal without reprocessing.

It should be highlighted that reprocessing and vitrification steps in the nuclear fuel cycle (discussed below) are not undertaken in South Africa.

6. Reprocessing

Spent fuel still contains approximately 96% of its original uranium, of which the fissionable U-235 content has been reduced to less than 1%. About 3% of spent fuel comprises waste products and the remaining 1% is plutonium (Pu) produced while the fuel was in the reactor and not "burned" then. Approximately 97% of spent fuel can therefore be recycled for further use. This is done by several countries in the world.

Reprocessing separates uranium and plutonium from waste products (and from the fuel assembly cladding) by chopping up the fuel rods and dissolving them in acid to separate the various materials.

Recovered uranium can be returned to the conversion plant for conversion to uranium hexafluoride and subsequent re-enrichment.

7. Vitrification

After reprocessing the liquid high-level waste can be calcined (heated strongly) to produce a dry powder which is incorporated into borosilicate (Pyrex) glass to immobilise the waste. The glass is then poured into stainless steel canisters, each holding 400 kg of glass. A year's waste from a 1000 MWe reactor is contained in 5 tonnes of such glass, or about 12 canisters 1.3 metres high and 0.4 metres in diameter. These can be readily transported and stored, with appropriate shielding.

8. Final disposal

Wastes from the nuclear fuel cycle are categorised as high-, intermediate- or low-level waste by the amount of radiation that they emit. These wastes come from a number of sources and include:

- low-level waste produced at all stages of the fuel cycle;
- intermediate-level waste produced during reactor operation and by reprocessing;
- high-level waste, which is waste containing fission products from reprocessing, and in many countries, the spent fuel itself is not reprocessed.

Radioactive waste management is discussed in detail in part 8 of this booklet.

Nuclear Power Reactors

4

Nuclear reactors have been producing electricity since the 1950s. Nuclear power plants provide about 17 percent of the world's electricity from more than 400 nuclear power plants. In South Africa, nuclear power supplies about 6,5 percent of the overall electricity mainly to the Western Cape province whilst the electricity of the other provinces comes mainly from coal fired power stations.

A reactor is the nuclear equivalent of the furnace part of a steam-raising boiler. Whereas a conventional boiler uses heat produced by burning coal or gas, a reactor uses the heat generated by fission (see Fission below). This heat is removed by a coolant (gas or water) which then produces steam, either indirectly through steam generators (boilers) or by boiling the water coolant. The steam drives turbine generators which produce electricity.

There are five main types of nuclear reactors:

- **Magnox**, this uses natural uranium in the form of a fuel rod that is made from a magnesium alloy.
- **Advanced Gas Cooled Reactors (AGR's)** use more concentrated U-235 and operate at higher temperatures than the Magnox reactor, they also extract more energy from the fuel rods.

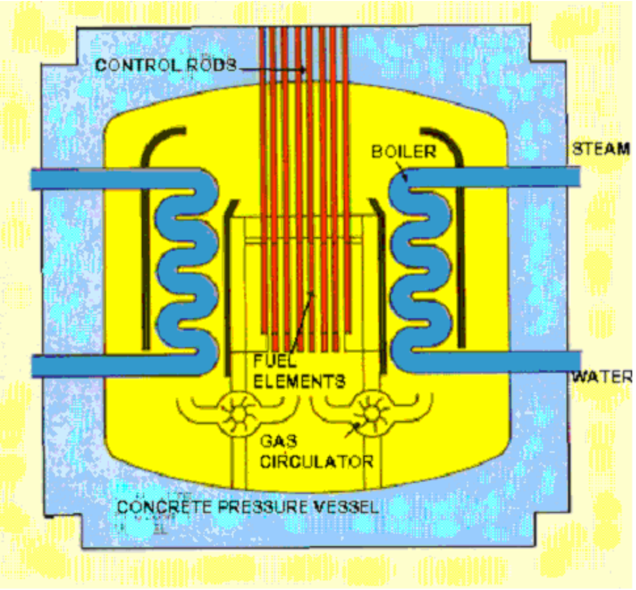


Fig 8: Schematic diagram of an advanced gas cooled reactor

- **Pressurised Water Reactor (PWR)**. This is the most common type of commercial reactor and the fuel is uranium dioxide enriched to about 3.2%, contained in Zircaloy (zirconium alloy) tubes.
- **Heavy Water Cooled Reactor (CANDU)**. The CANDU reactor is so called because it is a CANadian design using DeUterium oxide (heavy water) as both coolant and moderator. Fuel is natural uranium oxide contained in Zircaloy tubes.
- **Boiling Water Reactor (BWR).** The Soviet designed reactor is a hybrid of the graphite moderated and water cooled reactors. The fuel is uranium dioxide, enriched to about 2%, contained in Zircaloy tubes.

In this chapter, we will examine how a nuclear reactor work and also explain nuclear fission.

Fig 9: The dome-shaped containment building at the Nuclear Power Plant

WHAT IS NUCLEAR FISSION?

The most commonly used fuel in nuclear power plants is U-235, a naturally occurring radioactive isotope of uranium.

Energy is released when a U-235 nucleus absorbs a neutron and undergoes fission, that is, it splits into two large energetic fragments or fission products and also throws off two or three new neutrons (the number of ejected neutrons depends on how the U-235 atom happens to split).

The two new atoms then emit gamma radiation as they settle into their new states. There are three things about this induced fission process that make it especially interesting:

- The probability of a U-235 atom capturing a neutron as it passes by is fairly high. In a reactor working properly (known as the **critical state**), one neutron ejected from each fission causes another fission to occur.
- The process of capturing the neutron and splitting happens very quickly.
- An incredible amount of energy is released, in the form of heat and gamma radiation, when a single atom splits. The two atoms that result from the fission later release beta radiation and gamma radiation of their own as well.

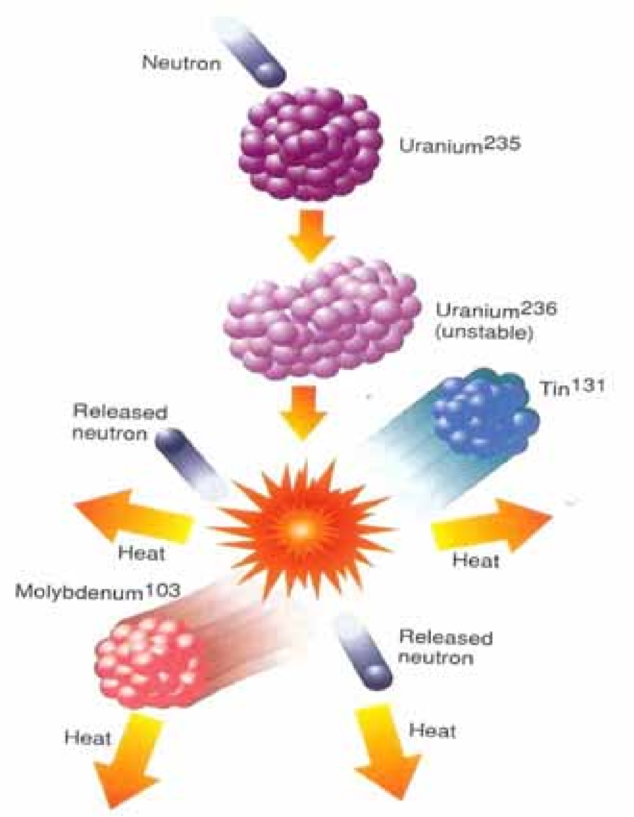


Fig 10: Fission process

In order for these properties of U-235 to work, a sample of uranium must be **enriched** so that it contains 2 percent to 3 percent or more of U-235. Three-percent enrichment is sufficient for use in most nuclear reactors used for power generation.

INSIDE A NUCLEAR POWER PLANT

To build a nuclear reactor, what you need is some mildly enriched uranium. Typically, the uranium is formed into pellets. The pellets are arranged into long rods collected together into bundles. The bundles are then typically submerged in water inside a pressure vessel. The water acts as a coolant. In order for the reactor to work, the bundle, submerged in water, must be slightly **supercritical**. That means that, left to its own devices, the uranium would eventually overheat and melt. To prevent this, **control rods** made of a material that absorbs neutrons are inserted into the bundle using a mechanism that can raise or lower the control rods.

Raising and lowering the control rods allow operators to control the rate of the nuclear reaction. When an operator wants the uranium core to produce more heat, the rods are raised out of the uranium bundle. To create less heat, the rods are lowered into the uranium bundle.

The rods can also be lowered completely into the uranium bundle to shut the reactor down in the case of an accident, for maintenance purposes or to change the fuel.

The uranium bundle acts as an extremely high heat-energy source. It heats the water and turns it to steam. The steam drives a steam turbine, which spins a generator to produce power. In some reactors, the steam from the reactor goes through a secondary, intermediate heat exchanger to convert another loop of water to steam, which drives the turbine.

OUTSIDE A NUCLEAR POWER PLANT

Once you get past the reactor itself, there is very little difference between a nuclear power plant and a coal-fired except for the source of the heat used to create steam.

The reactor's pressure vessel is typically housed inside a concrete liner that acts as a **radiation shield**. That liner is housed within a much larger steel containment vessel.

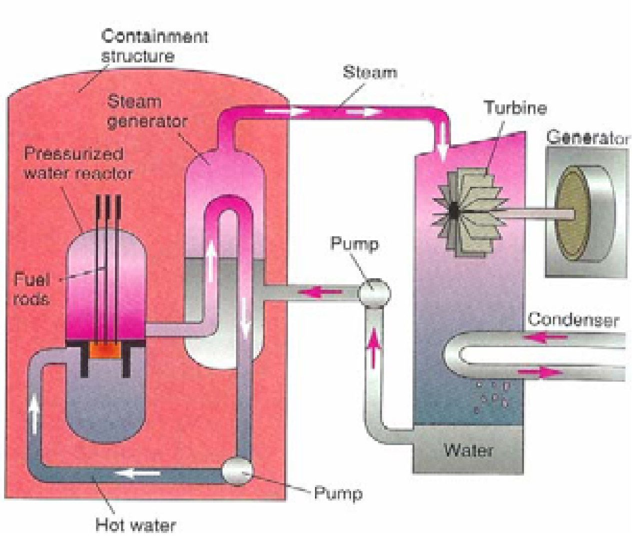


Fig 11: A pressurised water reactor

This vessel contains the reactor core as well the hardware (cranes, etc.) that allows workers at the plant to refuel and maintain the reactor. The steel containment vessel is intended to prevent leakage of any radioactive gases or fluids from the plant.

Finally, the containment vessel is protected by an outer concrete building that is strong enough to survive such things as crashing jet airliners. These secondary containment structures are necessary to prevent the escape of radiation/radioactive steam in the event of an accident like the one at Three Mile Island. The absence of secondary containment structures in Russian nuclear power plants allowed radioactive material to escape in an accident at Chernobyl.

Fig 12: Operators in the control room of a nuclear power plant

Uranium-235 is not the only possible fuel for a power plant. Another fissionable material is **plutonium-239**. Plutonium-239 can be created easily by bombarding U-238 with neutrons -- something that happens all the time in a nuclear reactor. The plutonium recycled from reprocessing spent fuel is used by some countries in an alternative fuel called MOX (mixed oxide) fuel.

WHAT CAN GO WRONG?

If the nuclear fuel cycle is not properly regulated and operated, there is potential for a negative impact on the safety of persons and the environment. History has shown that things can go wrong for example the Chernobyl accident in Russia.

Biological Effects of Radiation

5

Soon after the discovery of X-rays in 1895 and radioactivity in 1896, the use of x-rays and radioactivity for their beneficial properties became widespread. Only some years later, did people start to realize that radiation can also have adverse effects on health.

Radiation exposure can be either harmful or beneficial, depending on how it is used, how much is used, and how long it is used. To see the dangers of radiation in the right perspective, you should be well informed on the effects that radiation may have on your body.

Uncontrolled radiation in the form of natural background is present in our every day lives. This so-called 'background' radiation is something our ancestors and us have lived with since life first appeared on Earth. Since we are already subjected to background radiation, we should not unnecessarily increase our exposure to additional radiation. This is because it is known that exposure to radiation carries a risk.

Risk is something we live with daily. Whenever we drive a vehicle, there is a risk of accidents and possible injury or death. Most of us consider the risk is acceptable and we continue to drive because the benefit outweighs the risk.

The same argument can be applied to the use of radiation: If the benefits outweigh the risks, and the risks are acceptably small, we should use it. Risks can be looked at in many ways.

One way often used is to look at the number of "days lost" out of a population due to early death from separate causes, then dividing those days lost between the population to get an "Average Life expectancy lost" due to those causes. The following is a table of life expectancy lost for several causes:

Health Risk*	Estimated life expectancy lost*
Smoking 20 cigarettes a day	6 years
Overweight (15%)	2 years
Alcohol (US Ave)	1 year
All Accidents	207 days
All Natural Hazards	7 days
Occupational dose (3 mSv/year)	15 days

You can also use the same approach to looking at risks on the job:

Industry type*	Estimated life expectancy lost*
All industries	60 days
Agriculture	320 days
Construction	227 days
Mining	167 days
Manufacturing	40 days
Occupational radiation (3 mSv/year)	15 days

*The above estimates are taken from the NRC Draft guide DG-8012 and were adapted from B.L Cohen and I.S. Lee, "Catalogue of Risks Extended and Updates", *Health Physics*, Vol. 61, September 1991.

WHAT HAPPENS TO OUR BODIES?

The atom is the basic building block of all chemical matter. Our bodies are made up of atoms, formed into groups called molecules, which are themselves arranged in patterns that forms cells. Cells are the building blocks that are grouped together to form our tissues and organs.

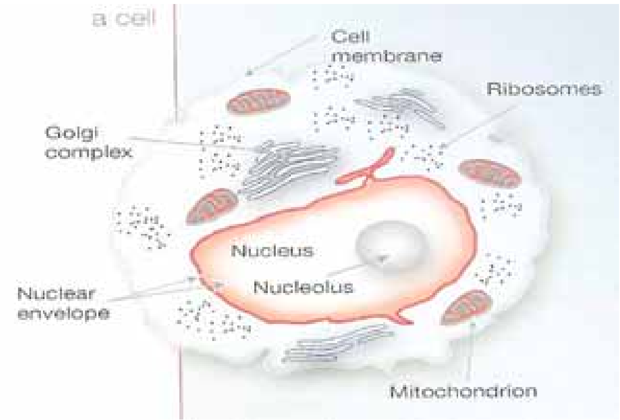


Fig 13: Diagram of a cell

This complex structure relies on the correct functioning of each part of the structure, right down to the atoms. When an atom is hit by radiation it absorbs some energy. With this extra energy the atom is set to be 'excited', and if the excess energy is sufficient, the atom may give up some energy by ejecting an electron from clouds around it.

This leaves the atom with one less electron and it is said to be 'ionized' hence the term 'ionizing radiation'. An ionized atom behaves in a different chemical and electrical way to an ordinary atom.

Ionization may change chemical bonds in cells and may even cause the formation of toxic substances within cells. In this way ionizing radiation may change the functioning of the cell, or it may permanently damage it.

The body's natural ability to repair itself can counter radiation damage. However, if too many cells are damaged or killed, the body's repair function cannot cope.

Depending on the severity and how many cells are damaged, the effects of radiation on the body may vary from anything between nothing and death. It may also happen that children conceived and born after the parent's exposure are affected.

It is important to realize that radiation does not make our bodies radioactive and that any damage caused by radiation in one person cannot be passed on to people around them.

WE CANNOT PASS OUR RADIATION DOSE ON TO OTHER PEOPLE.

Studies have shown that the effect of radiation is dependent on many factors including:

- the type of radiation (alpha, beta or gamma);
- the amount received;
- the rate at which it is received;
- which part of the body is exposed;
- whether the exposure is chronic (regular, low doses) or acute (short time, high dose); and
- the age of the irradiated person.

Radiation exposures can be divided into three categories:

- **High-level** radiation exposure from atomic weapons, as an example, causes such a massive damage the body cannot repair affected cells fast enough and the dose may quickly kill the exposed person.

  In some cases, high level of exposure in controlled situations can be beneficial. In cancer therapy, concentrated beams of radiation are directed to affected areas of the body to destroy cancer cells.

  High level radiation doses are doses of more than 1000 mSv.

- **Medium-Level radiation exposure,** which does not kill the exposed person, may cause damage to reproductive cells or other body cells. Cells which have been permanently damaged or changed may go on to produce abnormal cells when they divide. Under some circumstances, these cells may become cancerous. However, cancer may take many years to appear.

  Medium level radiation doses are of the order of hundreds of mSv.

- **Low-level radiation exposure** such as natural background radiation or radiation at mines where radioactive ores are dealt with, may also result in damage to reproductive cells or in cancer.

  Low-level radiation doses are down in the tens of mSv

RADIATION EFFECTS

There are two types of effects, which could result from exposure to ionising radiation:

Chance (Stochastic) effects

Chance effects are those effects that have a possibility of occurring, and the larger the radiation dose, the bigger the possibility of the occurrence of the effect. These effects can be caused by both chronic and acute exposures.

Note: Stochastic effects occur among both exposed and unexposed individuals. Receiving a dose of radiation does not make the manifestation of cancer or having a descendent with altered genetic information a certainty, it merely increases the likelihood of such an effect, and the greater the dose, the greater is the increased likelihood. If the effect does occur, its severity is not influenced by the size of the dose.

Threshold (Deterministic) effects

Threshold effects occur only when one receives more than a so-called threshold or minimum dose, and the larger the dose, beyond the threshold level, the more severe the effect will be.

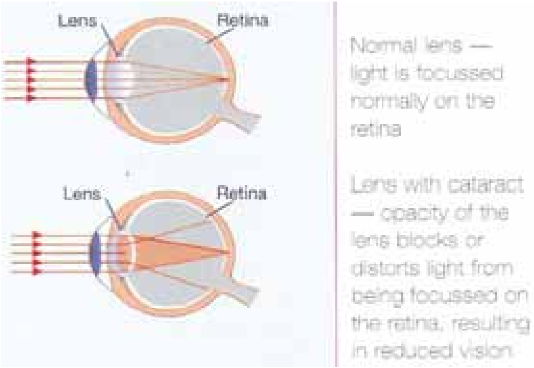


Fig 14: Deterministic effects on vision

If one receives less than the specific threshold dose there will be no effect. Should one receive more than the threshold dose there is a definite effect.

Note: If the threshold dose for a specific deterministic effect is exceeded, it is certain that the effect will occur to some degree of severity; the degree of severity depends on the exact dose and dose rate, as well as the individual involved. Deterministic effects are caused by acute (high level, short duration) exposures.

EFFECTS OF CHRONIC EXPOSURES

Radiation workers are normally chronically exposed, i.e. they repeatedly receive small doses over long periods (years).

The human body is better equipped to tolerate a chronic dose than an acute dose. The body has time to repair damage because a smaller percentage of the cells need repair at any given time. Apart from this, the body also has time to replace dead or non-functioning cells with new, healthy cells.

Chronic external or internal exposure causes only an increased possibility of the following stochastic effects:

- Cancer;
- Producing children or grandchildren with hereditary abnormalities or diseases, if they are conceived after a parent's exposure to radiation.

Note: cancer and hereditary diseases occur naturally among people and are caused by many other things apart from radiation. If the disease does strike it is difficult to prove the cause beyond reasonable doubt.

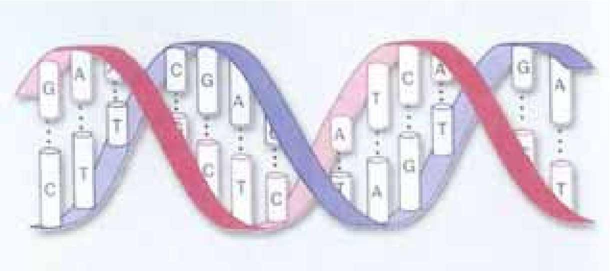


Fig 15: Diagram of DNA

Some of the effects of chronic exposure are indicated below:

- **Somatic effects** i.e. effects which are observable in the exposed individual. An example of a somatic effect would be the formation of cataracts in the lens of the eye or blood pH changes.
- **Teratogenic effects** i.e. effects, which occur, in the developing fetus during gestation.
- **Mutagenic effects** i.e. those effects which involve the disruption of the base par sequence in DNA molecules, which may result in a genetic defect or mutation.
- **Genetic effects**, similar to mutagenic effects but the genetic aberration occurs in one or both of the cells, which may affect the offspring.

EFFECT OF ACUTE EXPOSURES

Acute exposure occurs when one receives a large radiation dose within a short period (few minutes or hours). If acute radiation dose exposure is large, it may result in effects, which are observable within a period of hours to weeks.

Fig 16: Injury to the hand

The overriding effect of acute expose is the threshold effect. There is also the possibility of a chance effect some years later. The threshold effect can appear (without further radiation) after a so-called latent period, which may vary from a few hours to weeks.

Which threshold effect will occur depends in particular on the dose and which part of the body has been overexposed. The threshold effects of radiation are presented in the table below.

Irradiated tissue & effect	**Threshold Dose (mSv to irradiated tissue) – Acute Exposure**
Whole Body	
Radiation sickness	
• Blood changes	250
• Nausea, diarrhea, fatigue, fever	1000
• Loss of hair	2000
• 50% chance of death within 60 days	3000 - 5000
• 100% chance of death within 10 to 20 days	5000 – 15000
• 100% chance of death within 1 to 5 days	> 15000
Skin	
• Reddening	3000 – 5000
• Septic burns	20 000
• Tissue dies	50 000
Testes	
Permanent sterility	3500 – 6000
Ovaries	
Sterility	2500 – 6000
Eye lens	
• Clouding	500 – 2000
• Cataracts	5000

EFFECTS OF RADIATION ON UNBORN BABIES

The risks of children irradiated while in the womb deserve special mention. If an embryo or foetus is exposed to radiation at the time when organs are forming, developmental defects may be caused. If the unborn child receives a dose more than 100 mSv, he may be born deformed or mentally retarded. For smaller doses there is a possibility of chance effects.

For this reason a female radiation worker MUST report her pregnancy to her radiation protection officer as soon as she knows she is pregnant so that she can be withdrawn from any occupational exposure.

Note: These effects of radiation on unborn babies are something different than the hereditary effects mentioned earlier, which is the result of radiation to the reproductive cells of anyone of the parents.

System of Radiological Protection

6

SYSTEM OF RADIOLOGICAL PROTECTION

Approaches to protection against ionizing radiation are remarkably consistent throughout the world. This is due largely to the existence of a well established and internationally recognised framework.

The limitation of radiation doses deals with more than just the dose limits. It really deals with an entire system of radiation protection, i.e. all the measures that may be taken to keep doses as low as possible.

The system of radiological protection is based on three central requirements i.e. justification, optimization and dose or risk limitation. Each of these involves social considerations – explicitly in the first two and implicitly in the third – so there is considerable need for the use of judgement.

Justification of an action

No action involving exposure to radiation should be adopted unless it produces at least sufficient benefit to the exposed individuals or to society to offset the radiation detriment it causes.

Justification means that a company planning activities involving radioactive material must demonstrate that there are benefits associated with radiation.

There must be a good reason why people need to be exposed to ionising radiation. The advantages must be weighed up against the dangers associated with the exposure. The advantages must be significantly greater than the possible disadvantages.

Optimization of protection

Optimisation means making sure that all practical and cost-effective steps are taken to reduce radiation risks.

The aim is to ensure that all radiation doses are kept as low as reasonably achievable, economic and social factors being taken into account. This is usually called the 'ALARA' principle.

Optimisation is mainly applied at the design stage, prior to construction and operation, but the general principles of optimisation also apply in day-to-day radiation protection procedures.

Application of individual dose limits

A limit should be applied to the dose received by any individual as the result of all the practices (other than medical diagnosis or treatment) to which he or she is exposed.

Limitation of dose or risk is used to place bounds on risk to individuals so that risks do not exceed a value that would be considered unacceptable for everyday, long-term exposure to radiation.

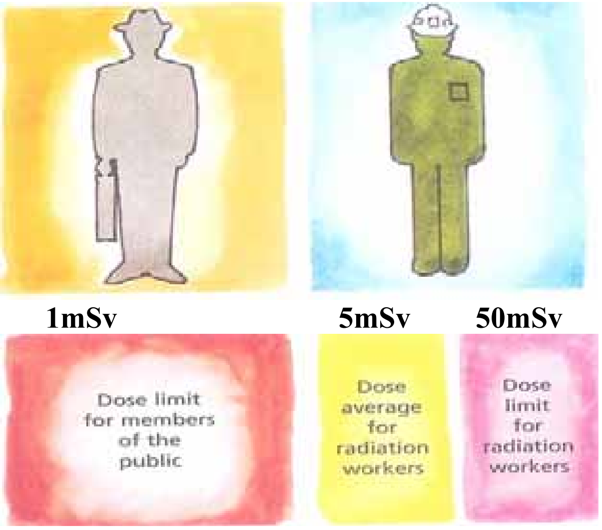


Fig 17: Dose limits to members of the public and occupationally exposed persons

The dose limit to workers is 20 mSv averaged over 5 years with a maximum of 50 mSv in any year.

SOUTH AFRICAN NUCLEAR INDUSTRY

In South Africa, there are three main sites related to nuclear:

- **South African Nuclear Energy Corporation (NECSA);**

Necsa is a state-owned company that applies its technology skills in the areas of nuclear science and technology, fluorine chemistry and engineering. It was formerly known as the Atomic Energy Corporation (AEC).

Necsa was first established in 1948 as the Atomic Energy Board to assess uranium reserves in the country and to develop nuclear research and expertise. Over the years Necsa successfully constructed and operated uranium enrichment plants, and produced nuclear power fuel. Necsa was also involved in South Africa's strategic nuclear weapons program, which has subsequently been closed down.

Today Necsa focuses solely on peaceful application of nuclear and radiation technology for the betterment of South Africa and its people. This is achieved through high-level research and development. Necsa houses and operates a nuclear research reactor - known as SAFARI-1. SAFARI-1 is used to produce radioisotopes for medical and industrial purposes and to perform the doping of silicon by nuclear transmutation for the semiconductor industry.

Some of the important peaceful radiation activities at Necsa include:

- Commercial Isotope production;
- Commercial Radiation induced modification of materials;
- Development of analytical techniques and instrumentation based on the interaction of radiation with matter;
- Management and safe disposal of low and intermediate radioactive waste arising from Koeberg Nuclear Power Station.

- **Vaalputs**

A programme to select a suitable site for the disposal of nuclear waste, entailing the examination of a variety of socio-economic and geology related parameters over large parts of South Africa, commenced in 1978.

Initial investigations indicated that the northwest Cape was the most likely candidate area. Further detailed studies showed that a locality some 100 km southeast of Springbok (600 km north of Cape Town) was ideally suited for the disposal of low- and intermediate-level wastes.

The initial stage of investigations culminated in 1983 when three farms which now constitute the Vaalputs Radioactive Waste Disposal Facility were acquired by the State on behalf of Necsa, which is responsible for its management. The first low- and intermediate-level waste was scheduled for delivery in October 1986.

Vaalputs covers an area of about 10 000 ha, measuring 16,5 km from east to west and 6,5 km from north to south at its narrowest point. Approximately 500 - 1 000 ha is occupied by the sites being developed for low- and intermediate-level waste, an interim spent fuel storage facility, housing, roads, power lines and the airstrip.

- **Koeberg Nuclear Power Station**

Koeberg Power Station is the only nuclear power station on the African continent. It is situated at Duynefontein, 27km north of Cape Town on the Atlantic coast. Koeberg ensures a supply of electricity to the Western Cape. It has operated for more than 20 years and has a further active life of 20 - 30 years.

The stations' two reactors supply 1 840MW or 6.5% of South Africa's electricity needs. Koeberg has produced more than 81 000 million kWh of electricity since 1984 using seven and a half tonnes of uranium.

Fig 18: Koeberg Nuclear Power Station

Koeberg's two reactor containment buildings are made of concrete 1m thick, lined with steel. They are designed to ensure that no radiation escapes under any conceivable circumstances, from an earthquake to a jumbo jet collision.

NUCLEAR LEGISLATION

The South African nuclear industry is governed mainly by the Nuclear Energy Act (Act No. 46 of 1999) and the National Nuclear Regulator Act (Act No. 47 of 1999).

According to the National Nuclear Regulator Act, any person wishing to engage in any action which is capable of causing nuclear damage may apply to the National Nuclear Regulator for a nuclear authorization (nuclear installation licence, certificate of registration or a certificate of exemption).

Dose limits are applicable to a nuclear authorisation holder. The aim of the dose limits are:

- To keep within acceptable limits the possibility of a chance effect as a result of exposure to radiation; and
- To protect against any of the threshold effects of radiation exposure.

RADIATION MEASURE

Sunlight feels warm because our body absorbs the infra-red rays it contains. But, infra-red rays do not produce ionization in body tissue.

In contrast, ionizing radiation can impair the normal functioning of the cells or even kill them.

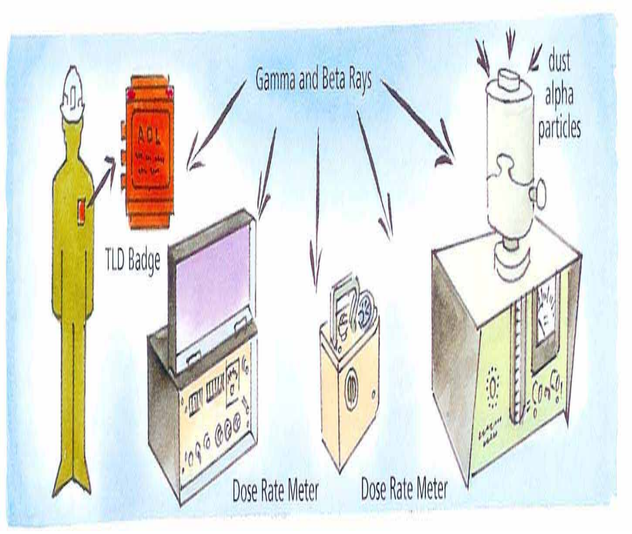


Fig 19: Measurement of doses

Because there are different types of radiation and different ways from which radiation doses can be received, there are several methods of detecting and measuring radiation. Since it is not always possible to measure doses directly (for instance, in the lungs) a calculation is usually required before an individual's total radiation dose can be estimated.

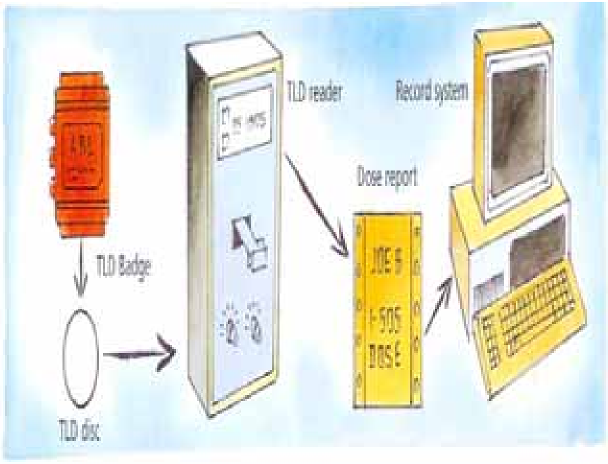


Fig 20: Analysis of the readings from the dosemeters

Radiation dose owing to external radiation is measured by means of personal dosimeters carried on the body. One will be issued with a personal dosimeter only if external radiation is a potential hazard in the workplace. There are different types of dosimeters depending on the type of radiation that must be measured and the purpose of the measurement. Some dosimeters are meant to provide a record, others are meant to provide an early warning, etc.

Note: Dosimeters do not protect one against radiation.

To measure the amount of gamma radiation received over a period of time, a TLD (Thermo-Luminescent dosimeter) badge can be worn. The badge contains small disks of chemically treated plastic which reacts to gamma radiation. The disks are 'read out' on an instrument that measures the amount of radiation received by the TLD.

Fig 21: A Personal dosimeter

The concentration of radon decay products in air and radioactivity in airborne dust are measured by pumping air through a filter and then measuring the radioactivity left on the filter with radiation detection equipment.

Some types of radiation instruments used for measuring dose, that is, dosimeters, are also dose rate meters. Such instruments are called survey meters.

Modern dose rate meters are generally calibrated to read in microsievert per hour (μSv/h). Most dose rate meters are battery operated.

RADIATION CONTROL MEASURES

External Sources

External radiation, as the name implies, means radiation that comes from a radioactive source that is outside the body. Since alpha particles and beta particles do not travel very far in air, external radiation usually refers to gamma rays.

Three precautions are taken against external radiation sources:

Time – If you decrease the amount of time you spend near the source of radiation, you will decrease the amount of radiation exposure you receive.

To imagine this, think of a trip to the beach as a comparison. For instance, if you spend a lot of time on the beach, you will be exposed to the sun, and ultimately, get a sunburn. If you spend less time in the sun and more time in the shade, your sunburn will be much less severe. This is similar to the way radiation exposure works.

Distance – keep your distance from the radiation source as large as possible. This ensures that you will be exposed to weaker and smaller amounts of radiation. In simple terms, the farther away you are from a radiation source, the less exposure you will receive.

Compare this to a person sitting closer to the fire place; the intensity of heat experienced by this person will be different from the one experienced by any other person not closer to the fire.

Radiation exposure is similar. The closer you are to the source, the greater your chances for developing some damage to your body. If you are far from the source, your exposure would be much lower.

Shielding – This is to place some material between you and the radiation, for example concrete or lead. Shielding can reduce gamma radiation. If you increase the shielding around a radiation source, it will decrease your exposure. For example, if you stand out in the rain without an umbrella, you will get wet. But, if you use an umbrella to shield you from the rain, you will remain dry and protected. This is similar to the idea of shielding in radiation protection.

Internal Sources

Internal radiation is the name given to radiation that comes from a source inside the body such as from radioactive dust in lungs, or from air containing radioactive gases or from ingestion.

Once inside the body, alpha and beta particles from these sources do not have to travel very far before they irradiate sensitive cells.

Precautions taken to reduce exposure to internal radiation include:

- minimizing dust in the work place by proper watering, washing down and by good ventilation;
- wearing appropriate respiratory protection devices in areas where dust is inevitable;
- ventilation of areas where radon or thoron may build up. This does not normally apply in open cut mines where even a slight wind will disperse the radon;
- keeping work areas clean. Surface contamination is the start of a pathway that can lead to radioactive materials being resuspended in the air and inhaled, or transferred from dusty or unclean surfaces to the mouth and ingested.

Uses of Radiation

7

Radioactive material is used to improve the quality of life in many more ways than people realize. Radioactive materials have a variety of important uses in medicine, industry, agriculture, and sterilisation, as well as in our homes. Whenever or wherever it is used, it is incumbent on qualified individuals and responsible organizations to ensure that the radioactive material is prepared, used, and disposed of in a safe manner.

Medicine

Perhaps the most important use of radioactive materials is in medicine. Radiopharmaceuticals – therapeutic drugs that contain radioactive material – are important in the diagnosis and treatment of many diseases. They can be injected into the body, inhaled, or taken orally as medicines or to enable imaging of internal organs and bodily processes. Millions of people in South Africa and around the world have benefited from the diagnostic and therapeutic qualities of radioactive materials.

There are many applications of nuclear technology in the medical field, ranging from diagnostics, to treatment, to disease management. Many of these use radionuclides produced from either reactors or cyclotrons. Examples include: thyroid studies; brain studies; tumour studies; brain imaging, etc. The table below provides some of the radiopharmaceuticals and their uses.

Radiopharmaceutical	Primary Uses
Indium-111 Capromab pendetide	monoclonal antibody for imaging prostate cancer
Indium-111 satumomab pendetide	imaging of metastatic disease associated with colorectal and ovarian cancer
I-131sodium iodide	thyroid uptake, imaging, & therapy
Tc-99m albumin colloid	imaging of RES (liver/spleen)
Tc-99m exametazine (HMPAO)	cerebral perfusion imaging
Tc-99m Gluceptate	renal imaging
Tc-99m Medronate (MDP)	bone imaging
Tc-99m Sestamibi	myocardial perfusion imaging breast tumor imaging

Diagnostic techniques

There are two distinct methods used in diagnostics. The first is to use the isotope as an *in vivo* tracer. Here, a carefully chosen radiopharmaceutical is administered to a patient through inhalation, injection, or ingestion, to trace a specific physiological phenomenon in the living body. Detection is accomplished with special detectors such as a gamma camera placed outside the body.

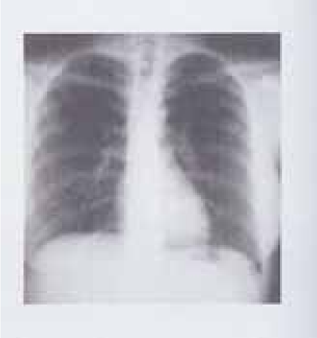


Fig 22: Chest X-ray

The radiopharmaceutical can be selected to seek out only desired tissues or organs. There are hundreds of radiopharmaceuticals used in this way. The second method is to use an *in vitro* technique. For example, blood can be taken from the body and studied, outside the living body, using nuclear methods to assess exposures to infection by evaluating antibodies. It can also be used to provide detection of cancer (tumours) by studying some two dozen tumour markers.

Treatment of disease

Radiation is widely used for the treatment of diseases such as cancer. The radiation is used to destroy the cancerous cells. A typical radionuclide used for this is Cobalt-60. In addition to teletherapy, where the radiation source has no physical contact with the tumour, the radiation source may be placed in immediate contact with the tumour. This form of treatment is called brachytherapy.

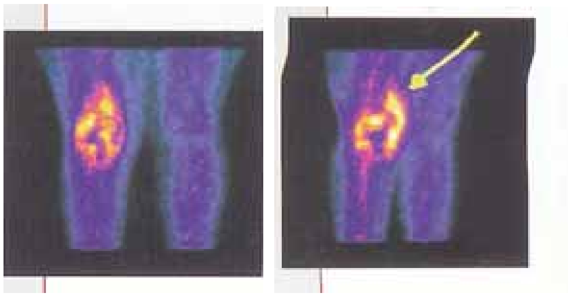


Fig 23: Technetium-99m scintigram of a patient with a right knee prosthesis and signs of infection (arrow)

Disease management

In addition to the sterilisation of medical equipment discussed below, nuclear medicine is also being used to reduce pain. Radiotherapy is administered to patients to palliate the pain, thus replacing pain-killing drugs, which eventually lose their effectiveness.

Industry

Industries around the world uses radioactive materials in a variety of ways to improve productivity, safety and to obtain information that could not be obtained in other ways.

Radioactive materials are used in industrial radiography, civil engineering, materials analysis, measuring devices, process control in factories, oil and mineral exploration, and checking oil and gas pipelines for leaks and weaknesses. These uses directly and indirectly influence our everyday lives.

For example, measuring devices containing radioactive materials are used in tasks ranging from testing the moisture content of soils during road construction, to measuring the thickness of paper and plastics during manufacturing, to checking the height of fluid when filling bottles in factories. Radioactive materials are even used in devices designed to detect explosives.

Radioisotopes are employed in smoke detectors, and as lasting, fail-safe light sources for emergency signs in aircraft and public buildings.

Sterilisation

Sterilisation is one of the most beneficial uses of radiation. Syringes, dressings, surgical gloves and instruments, and heart valves can be sterilised after packaging by using radiation. Radiation sterilisation can be used where more traditional methods, such as heat treatment, cannot be used, such as in the sterilisation of powders and ointments and in biological preparations like tissue grafts.

Gamma rays from sources such as Cobalt 60 and Caesium 137 are commonly used to irradiate health care and other consumer products. The prevention of infection through this sterilisation technique complements the basic healing goal of medicine. About 180 facilities located in 47 countries worldwide provide sterile medical devices using gamma irradiation techniques.

Food irradiation

The use of gamma rays and electron beams in irradiating foods to control disease causing micro-organisms and to extend shelf life of food products is growing throughout the world. For example, recent steps are leading to the expanded use of meat irradiation in the United States. Food sterilization has been approved by 40 countries and is encouraged by the World Health Organization.

Agriculture

In agriculture, radioactive materials are used to improve food crops, preserve food, and control insect pests. They are also used to measure soil moisture content, erosion rates, salinity, and the efficiency of fertiliser uptake in the soil.

Insect control

Radioisotopes assist in enhancing animal and food production. One method is the control of insects, including the control of screwworms, fruit flies, and the Tsetse fly through the Sterile Insect Technique. The Tsetse fly causes the transmission of a parasitic disease, trypanosomiasis, which slowly destroys livestock herds, in sub-Saharan Africa. It also causes the spread of the human form of the disease, known as sleeping sickness.

In our homes

Most first-aid kits found in our homes contain items sterilised by radiation, including cotton wool, bandages, and burn dressings.

One of the most common uses of radioactive materials in the home is in smoke detectors. These devices contain tiny amounts of radioactive material which make the detectors sensitive to smoke. The radiation hazard to the occupants of the house is negligible.

Environment

Radioactive materials are used as tracers to measure environmental processes, including the monitoring of silt, water and pollutants. They are used to measure and map effluent and pollution discharges from factories and sewerage plants, and the movement of sand around harbours, rivers and bays. Radioactive materials used for such purposes have short half-lives and decay to background levels within days.

Radioactive Waste Management

8

Radioactive waste, like any waste, needs to be managed to protect people and the environment. Waste containing or contaminated with radionuclides arises from a number of activities involving the mining of certain ores and use of radioactive materials, in industry, medicine and research.

Radioactive waste is also generated in the cleanup of sites affected by radioactive residues from various operations, and can arise in the processing of raw materials containing naturally occurring radionuclides.

For legal and regulatory purposes, radioactive waste is defined as material that contains or is contaminated with radionuclides at concentrations or activities greater than clearance levels as established by the regulator, and for which no use is foreseen. Radioactive waste management involves government, regulatory bodies, generators/operators and civil society.

Radioactive waste occurs in a variety of forms with very different physical and chemical characteristics, such as the concentrations and half-lives of the radionuclides. The waste may occur in gaseous, liquid or solid form.

Such wastes may range from slightly radioactive, such as those generated in medical diagnostic procedures, to the highly radioactive, such as those in spent radiation sources used in radiography, radiotherapy or other applications. Radioactive waste may be very small in volume, such as a spent sealed radiation source, or very large and diffuse, such as tailings from the mining and milling of uranium ores.

There has been, and continues to be considerable research to investigate methods of reducing and minimising the risk of contamination and damage from radioactive waste.

International classification of radioactive waste

Radioactive waste is generally classified on the basis of how much radiation it emits and what form of radiation it emits, as well as the length of time for which it will continue to emit radiation. Radioactive waste is commonly referred to as radwaste.

The purpose of the classification system is to ensure that radioactive waste is handled, stored and disposed of in ways that are appropriate to its characteristics.

Radioactive materials are described as low level, intermediate level, or high level depending on how much radiation they emit.

Radioactive materials are described as short-lived or long-lived depending on the length of time over which they emit radiation.

Short-lived radioactive materials have a half-life of less than thirty years. This means that half the unstable atoms in short-lived radioactive materials will change into the stable decay product in less than thirty years. Long-lived radioactive materials have a half-life of greater than thirty years.

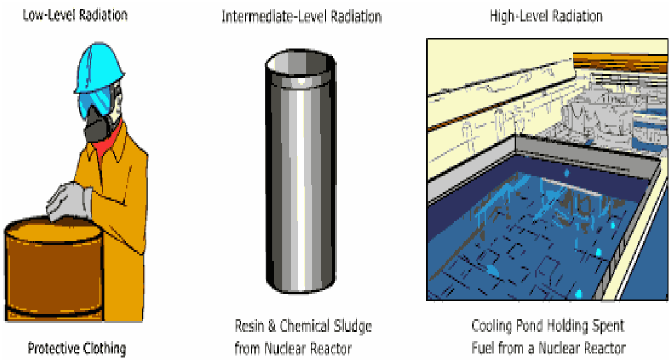


Fig 24: Various types of waste

Low level waste

Low-level radioactive waste is generated from hospitals, laboratories and industry, as well as the nuclear fuel cycle. It comprises paper, equipment, tools, clothing, filters etc. which contain small amounts of mostly short-lived radioactivity. Although it does not need to be shielded, it needs to be disposed off in a different manner than when disposing of every-day waste.

Usually it is buried in shallow landfill sites. To reduce its volume, it is often compacted or incinerated (in a closed container) before disposal. Worldwide it comprises 90% of the volume but only 1% of the radioactivity of all radwaste.

Low-level radioactive waste contains enough radioactive material to require action for the protection of people, but not so much that it requires shielding during handling, storage or transportation.

Intermediate level waste, long-lived

Waste that requires shielding, but needs little or no provision for heat dissipation. The radionuclides generally have a half life of more than thirty years.

Intermediate level waste, short-lived

Waste which requires shielding, but needs little or no provision for heat dissipation and contains low concentrations of long-lived radionuclides (less than 4000 Becquerel/gram of alpha-emitters). The radionuclides generally have a half-life of less than thirty years.

Examples of Intermediate-level radioactive wastes are resins, chemical sludges, metal fuel cladding, and materials from nuclear electricity plants. It is generally short-lived, but usually needs to be shielded. Intermediate-level waste can be solidified in concrete and put into a waste repository.

High level waste

Once uranium has been used to generate electricity in the reactor, it becomes 'spent fuel'. If it is decided that the spent fuel will not be reprocessed it must be managed as high-level radioactive waste. This type of waste contains large concentrations of both short- and long-lived radionuclides and is sufficiently radioactive to require both shielding and cooling.

As this spent fuel is highly radioactive and generates a considerable amount of heat, it cannot be, and definitely is not, simply dumped. It is temporarily stored in special ponds that allow the fuel to 'cool down' and decrease its radioactivity. It cannot cause significant damage in these storage ponds.

While only 3% of the volume of all radwaste, it holds 95% of the radioactivity. It contains the highly-radioactive fission products and some heavy elements with long-lived radioactivity.

The three principles used by the generator during the Management of Radioactive waste

Three general principles are employed by the generator in dealing with radioactive wastes:

- delay-and-decay
- concentrate-and-confine
- dilute-and-disperse.

Delay and decay applies to waste containing radionuclides with short half-lives, which decay to stable elements if stored for sufficient time. Once the radioactivity is below clearance levels, the waste can be disposed of as non-radioactive waste. This approach is very attractive since it reduces the volume of radioactive waste for storage or disposal. However, to be successful, short lived radionuclides need to be kept separate from long lived radionuclides.

Concentrate and confine implies that the volume of the radioactive waste is reduced but the waste is then isolated from the environment. The confinement can be absolute, as in most storage situations, or partial, as in an engineered disposal site. In the latter case, the disposal site must be designed so that the waste does not pose a significant risk to humans or the environment. This generally requires a formal safety assessment and authorisation by the regulatory authority.

Dilute and disperse involves release of very low levels to the environment in a controlled manner. This release is appropriate for some low level wastes, especially gases which are difficult to confine (e.g. noble gases) or liquid wastes after treatment. Before radioactivity is released to the environment, it is necessary to do a safety assessment. Operational radioactive liquid & gaseous effluent (waste discharges) is permitted to be released to the environment routinely under the authority of the relevant regulator.

Residual materials from the "front end" of the nuclear fuel cycle

Radioactive wastes occur at all stages of the nuclear fuel cycle. The nuclear fuel cycle is often split into two parts - the "front end" which stretches from mining through to the use of uranium in the reactor - and the "back end" which covers the removal of spent fuel from the reactor and its subsequent treatment and disposal.

The annual fuel requirement for a l000 MWe light water reactor is about 200 tonnes of enriched uranium oxide. This requires the mining and milling of some 50,000 tonnes of ore to provide 200 tonnes of uranium oxide concentrate (U_3O_8) from the mine.

At uranium mines, dust is controlled to minimise inhalation of radioactive minerals, while radon gas concentrations are kept to a minimum by good ventilation and dispersion in large volumes of air. At the mill, dust is collected and fed back into the process, while radon gas is diluted and dispersed to the atmosphere.

Residual wastes from the milling operation contain the remaining radioactive materials from the ore, such as radium. These wastes are discharged into tailings dams.

Eventually the tailings may be put back into the mine or they may be covered with rock and clay, then revegetated.

Uranium oxide (U_3O_8) produced from the mining and milling of uranium ore is only mildly radioactive - turning uranium oxide concentrate into a useable fuel has no effect on levels of radioactivity and does not produce significant waste. First, the uranium oxide is converted into a gas, uranium hexafluoride (UF_6), as feedstock for the enrichment process.

The enriched UF_6 is finally converted into uranium dioxide (UO_2) powder and pressed into fuel pellets which are encased in zirconium alloy tubes to form fuel rods.

Wastes from the "back end" of the fuel cycle

These are wastes produced after the fuel has been used for power generation i.e. spent fuel and wastes from decommissioning activities.

About 25 tonnes of spent fuel is taken each year from the core of a l000 MWe nuclear reactor. The spent fuel can be regarded entirely as waste, or it can be reprocessed (as in Europe).

Whichever option is chosen, the spent fuel is first stored for several years under water in large cooling ponds at the reactor site. The concrete ponds and the water in them provide radiation protection, while removing the heat generated during radioactive decay.

Waste disposal

Low and Intermediate-level waste

The intermediate-level waste (ILW) along with the low-level waste represent some 90% of the total volume of radioactive waste generated during the lifetime of a nuclear power plant. This relatively large volume of long-lived and short-lived ILW contains only about 1% of the total radioactivity.

Only a small proportion of the intermediate-level waste remains significantly radioactive for years but all ILW requires shielding when it is handled. Low-level waste (LLW) and short-lived intermediate-level waste is of three kinds:

Process wastes result from the treatment, purification and filtration systems of fluids in direct contact with the parts of the reactor that may be contaminated by radioactivity. These wastes include:

- filters in the cooling water circuits of the nuclear power plant;
- resins that trap radioactive materials in the water circuits.
- radioactive particulates that are retained by air-filters installed in the ventilation stacks of nuclear facilities

Technological wastes arise from the necessary maintenance carried out on a nuclear power plant. Technological waste represents half the volume of LLW and short-lived ILW, but contains little radioactivity.

Solid technological wastes might contain rags, cardboard, plastic sheets, bags, tools and protective clothing. Liquid technological wastes comprise mainly oils, small amounts of lubricants and organic solvents used for decontamination.

Decommissioning wastes occur at the end of a nuclear reactor's life. After the spent fuel is removed the plant is decommissioned and eventually demolished. During this process, large amounts of wastes are generated, though most is not radioactive. About a tenth of it contains some radioactivity up to the intermediate level.

Plant operators make constant efforts to reduce the quantities of waste that are generated. Waste is collected, sorted and then conditioned. The management strategy chosen depends upon the origin and radioactivity level of the waste. LLW, with the lowest concentrations of radioactivity, is usually retained in metal drums, which are often compacted after filling to reduce the volume. Other techniques may also be used to effect volume reduction.

Low level wastes that contain slightly higher radioactivity levels are stabilised by cement or an organic solid (bitumen or resin) and then placed in concrete containers for shielding. Disposal sites for such wastes are in operation in many countries. Typically, these are shallow earth burial sites, which provide a suitable facility to contain the wastes safely. A 1000 MWe nuclear power reactor can be expected to produce around $100 m^3$ of low level waste every year.

Long-lived intermediate level waste

Typically, these wastes arise from dismantled internal structures of the reactor core, which become radioactive after prolonged operation. They also include: the control rods, which regulate the nuclear reaction, the source assemblies, which are used to initiate a nuclear reaction after new fuel has been loaded, and other rods that limit the reactivity of fresh fuel.

ILW is treated and conditioned by incorporating it into cement and then placing it in concrete containers. In some instances, the conditioned waste might subsequently be placed into an additional container, made of metal. Special packages are used for transporting long-lived intermediate level waste. These packages meet internationally approved standards that ensure that the waste is safely contained.

Ultimately long-lived ILW will go to the same disposal site as with high-level waste.

In most countries, long-lived waste is being safely stored and contained at interim storage facilities. The maintenance of a 1000 MWe nuclear power reactor produces less than 0.5m^3 of long-lived ILW each year.

High level waste

Final disposal of high-level waste is delayed to allow its radioactivity to decay. Forty years after removal from the reactor less than one thousandth of its initial radioactivity remains, and it is much easier to handle. Hence canisters of vitrified waste, or spent fuel assemblies, are stored under water in special ponds, or in dry concrete structures or casks for at least this length of time.

The ultimate disposal of vitrified wastes, or of spent fuel assemblies without reprocessing, requires their isolation from the environment for long periods. One method is burial in dry, stable geological formations some 500 metres deep. Several countries are investigating sites that would be technically and socially acceptable.

One purpose-built deep geological repository for long-lived nuclear waste is in operation in New Mexico (USA), though this only takes defence wastes. Deep geological repositories for high level waste are under investigation in several countries.

Layers of protection

To ensure that no significant environmental releases occur over periods of tens of thousands of years after disposal, a 'multiple barrier' disposal concept is used to immobilise the radioactive elements in high-level (and some intermediate-level) wastes and to isolate them from the biosphere. The principal barriers are:

- Immobilise waste in an insoluble matrix, eg borosilicate glass, Synroc (or leave them as uranium oxide fuel pellets - a ceramic)
- Seal inside a corrosion-resistant container, eg stainless steel
- In wet rock: surround containers with bentonite clay to inhibit groundwater movement
- Locate deep underground in a stable rock structure;
- Site the repository in a remote location.

Transportation of Radioactive Material

9

Like any other potentially hazardous material, the transportation of radioactive materials is subject to strict regulation to ensure the safety of workers and members of the public who may come into contact with a consignment.

Because much of this transport is international, transport safety was one of the first areas in which the IAEA developed safety standards. These are published as the IAEA Regulations for the Safe Transport of Radioactive Material, which are implemented by all member states.

The IAEA Regulations for the Safe Transport of Radioactive Material govern the necessary packaging, shielding, labeling and other precautions that must be taken when transporting various types of radioactive material. In general, more hazardous radioactive materials need more extensive and more robust packaging and stricter quality and administrative controls.

In South Africa, the types of materials that are transported include:

- New nuclear fuel to Koeberg Nuclear Power Station (KNPS);
- Low and intermediate level radioactive waste transported from KNPS to the Vaalputs national radioactive waste repository;
- Medical radioisotopes (national & international destinations);
- Sealed radiography sources used in industry;
- Radioactive ores, wastes and products from the mining industry;
- Contaminated soils etc.

Spent nuclear fuel elements produced by the KNPS and SAFARI reactors are not transported on public roads as these items are stored on their respective sites.

The volume of this type of waste is very low, but its activity is so high that it generates considerable heat. Therefore, after removal from the reactor, the spent fuel must be cooled to prevent melting, as well as shielded to reduce radiation exposure.

National competent authority

In South Africa, the NNR is responsible for regulating the safe transport of radioactive materials that fall within the ambit of the National Nuclear Regulator Act (Act No. 47 of 1999). These materials include nuclear fuel, low level radioactive waste and mineral concentrates.

The Directorate of Radiation Control within the national Department of Health is also responsible for regulating the safe transport of radioactive materials that fall within the ambit of the Hazardous Substances Act (Act No. 15 of 1973). These materials include sealed and unsealed radioactive sources outside of nuclear installations and mainly used for medical, scientific, agricultural and industrial purposes.

The primary role of competent authorities in transportation is to ensure the safety of people, property and the environment against possible hazards involved in the transport of radioactive material.

Modes of Transport

Radioactive materials are routinely transported all around the world by air, sea, road and rail. These materials include those associated with the nuclear fuel cycle – from uranium ores to spent fuel and radioactive waste – but also radionuclides for nuclear medicine and research, and radioactive sources for industry and radiotherapy.

The table below provides information on the estimated fraction of all dangerous goods that are radioactive per mode of transport.

Modes of transport	Estimated fraction of all goods that are Dangerous Goods	Estimated fraction of all Dangerous Goods that are Radioactive
Road	15%	< 2%
Rail	20%	< 2%
Air	3 – 4 %	< 10%
Sea	50%	< 1%

Potential hazards during transportation of radioactive material

Radioactive material in packages may potentially expose workers and to a lesser degree the public, to ionizing radiation. There are five main categories of potential hazard:

- External radiation hazards
- Internal radiation hazards

- Criticality hazards
- The release of heat
- Contamination

All consignments carried by road, rail and air are required to carry emergency phone numbers and details of the consignment in order to immediately notify the appropriate regulatory authority, the consignor, the police and emergency services of the incident

Controls in transport

The controls during transport are put in place to protect persons, property and the environment by:

- controlling external radiation levels; and
- preventing a criticality event.

The following controls are used to manage the hazards:

- conveyance activity limits
- use of exclusive use conveyance
- transport index
- criticality safety index
- contamination limits
- separation and segregation

Types of transport packages and labelling

A range of packages is used for transport. The choice of package depends upon the type and quantity of radioactive material: the greater the hazards, the stronger the container.

Special containers, resistant to accidents, are used for the most radioactive material. They are subject to mechanical, thermal and immersion tests to demonstrate their ability to withstand severe accidents.

Fig 25: Labels used in packages with radioactive contents

Fig 26: Typical shipping packages

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Glossary of Terms

Activity
The rate at which nuclear transformations occur in a radioactive material. It is used as a measure of the amount of a radionuclide present.

Alpha particle (alpha radiation, alpha ray)
A positively charged particle (a Helium-4 nucleus) made up of two neutrons and two protons. It is the least penetrating of the three common forms of radiation, being stopped by a sheet of paper.

Atom
A particle of matter indivisible by chemical means. It is the fundamental building block of elements.

Atomic number
The number assigned to each element on the basis of the number of protons found in the element's nucleus.

Atomic weight (atomic mass)
Approximately the sum of the number of protons and neutrons found in the nucleus of an atom.

Background radiation
The radiation of man's natural environment originating primarily from the naturally radioactive elements of the earth and from the cosmic rays.

Becquerel (Bq)
The SI unit of measurement of radioactive activity defined as one radioactive disintegration per second.

Beta particle (beta radiation, beta ray)
An electron of either positive charge (ß+) or negative charge (ß-), which has been emitted by an atomic nucleus or neutron in the process of a transformation.

Contamination
Radioactive material deposited or dispersed in materials or places where it is not wanted.

Curie (Ci)
The basic unit used to describe the intensity of radioactivity in a sample of material. One curie equals thirty-seven billion disintegrations per second, or approximately the radioactivity of one gram of radium.

Daughter
A nucleus formed by the radioactive decay of a different (parent) nuclide.

Decay (radioactive)
The change of one radioactive nuclide into a different nuclide by the spontaneous emission of alpha, beta, or gamma rays, or by electron capture.

Decommissioning
Administrative and technical actions taken to allow the removal of regulatory controls from a facility. Typically, it includes dismantling of the facility, but this need not be the case.

Decontamination
The removal of radioactive contaminants by cleaning and washing with chemicals.

Dose
A general term denoting the quantity of radiation or energy absorbed in a specific mass.

Electron
An elementary particle with a unit electrical charge and a mass 1/1837 that of the proton. Electrons surround the atom's positively charged nucleus and determine the atom's chemical properties.

Electron capture
A radioactive decay process in which an orbital electron is captured by and merges with the nucleus.

Enriched uranium
Uranium containing a greater mass percentage of uranium-235 than the 0.7 percent found in natural uranium.

Excited state
The state of an atom or nucleus when it possesses more than its normal energy. The excess energy is usually released eventually as a gamma ray.

Fission
The splitting of a heavy nucleus into two roughly equal parts (which are nuclei of lighter elements), accompanied by the release of a relatively large amount of energy in the form of kinetic energy of the two parts and in the form of emission of neutrons and gamma rays.

Fission products
Nuclei formed by the fission of heavy elements. They are of medium atomic weight and almost all are radioactive. Examples: strontium-90, cesium-137.

Gamma ray
A highly penetrating type of nuclear radiation, similar to x-radiation, except that it comes from within the nucleus of an atom, and, in general, has a shorter wavelength.

Half-life
The time in which half the atoms of a particular radioactive nuclide disintegrate. The half-life is a characteristic property of each radioactive isotope.

Ion
An atomic particle that is electrically charged, either negative or positive.

Ionizing radiation
Radiation that is capable of producing ions either directly or indirectly.

Irradiate
To expose to some form of radiation.

Isotope
Isotopes of a given element have the same atomic number (same number of protons in their nuclei) but different atomic weights (different number of neutrons in their nuclei). Uranium-238 and uranium-235 are isotopes of uranium.

Neutron
One of the basic particles which make up an atom. A neutron and a proton have about the same weight, but the neutron has no electrical charge.

Nuclear reactor
A device in which a fission chain reaction can be initiated, maintained, and controlled. Its essential components are fissionable fuel, moderator, shielding, control rods, and coolant.

Nucleus
The core of the atom, where most of its mass and all of its positive charge is concentrated. Except for hydrogen, it consists of protons and neutrons.

Nuclide
Any species of atom that exists for a measurable length of time. A nuclide can be distinguished by its atomic weight, atomic number, and energy state.

Proton
One of the basic particles which makes up an atom. The proton is found in the nucleus and has a positive electrical charge equivalent to the negative charge of an electron.

Radioactive waste
Materials which are radioactive and for which there is no further use.

Radioactivity
The spontaneous decay of disintegration of an unstable atomic nucleus accompanied by the emission of radiation.

Radioisotope
A radioactive isotope. A common term for a radionuclide.

Radionuclide
A radioactive nuclide. An unstable isotope of an element that decays or disintegrates spontaneously, emitting radiation.

Radon
Radon is the heaviest of the ‘noble’ or inert gases. The predominant isotope, radon-222, is the decay product of radium-226. It has a half-life of 3.82 days and decays to polonium-218 by the emission of an alpha particle.

Shielding
A protective barrier, usually a dense material, which reduces the passage of radiation from radioactive materials to the surroundings.

Sievert (Sv)
The SI unit of measurement of effective dose. One sievert is equal to the product of the absorbed dose by the quality factor and any modifying factor(s).

Source
A radioactive material that produces radiation for experimental or industrial use.

Stable
Non-radioactive.

Tailings
The waste material remaining after the processing of finely ground ore.