Presidential address: The uranium story—an update

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Synopsis

Uranium is back on the radar. Uranium has always been a controversial metal, from its role in the arms race to its claim to be the only viable alternative to fossil fuel. This paper will cover its properties and use, its occurrence and production in South Africa, the current market drivers and its future role as a primary energy fuel. It will highlight the difference between uranium used to make a bomb and uranium used in a power station. The recent significant uranium price rise will be put into context of the market drivers including geopolitical issues. Planned expansions in nuclear power station capacity will be reviewed, as will new mine production. Future demand will also be speculated on.

Background

Martin Klaproth, a German chemist, discovered uranium, the last naturally occurring element in the periodic table, in 1789 in the mineral called pitchblende. It was named after the planet Uranus, which had been discovered eight years earlier. It is a dense (an SG of 18.7), silver-grey metal that is chemically highly reactive and forms a number of brightly coloured oxides and salts. Prior to the 1940s, uranium was used commercially in the form of salts to colour glass and ceramics. It was essentially only a scientific curiosity[1].

Uranium was apparently formed in super novae about 6.6 billion years ago. While it is not common in the solar system, today its radioactive decay provides one of the sources of heat inside the earth, causing convection and continental drift[2].

Like other elements, uranium occurs in slightly differing forms known as 'isotopes'. These isotopes (16 in the case of uranium) differ from each other in the number of particles (neutrons) in the nucleus. 'Natural' uranium is found in the earth's crust as a mixture largely of two isotopes: uranium-238 (U-238), accounting for 99.3% and U-235 about 0.7%. The isotope U-235 is important because under certain conditions it can readily be split, yielding a lot of energy. It is therefore said to be 'fissile' and hence the expression 'nuclear fission'.

Like all radioactive isotopes, uranium decays. U-238 decays very slowly, its half-life being the same as the age of the earth (some 4 500 million years). This means that it is barely radioactive, less so than many other isotopes in rocks and sand. The nucleus of the U-235 atom comprises 92 protons and 143 neutrons (92 + 143 = 235). When the nucleus of a U-235 atom captures a neutron it splits in two (fissions) and releases some energy in the form of heat, and two or three additional neutrons are thrown off. If enough of these expelled neutrons cause the nuclei of other U-235 atoms to split, releasing further neutrons, a fission 'chain reaction' can be achieved. When this happens over and over again, many millions of times, a very large amount of heat is produced from a relatively small amount of uranium.

Nuclear fuel has the highest energy density of any fuel known, for example one 7-gram uranium pellet contains energy equal to about 810 kilograms of coal or 3.5 barrels of oil. Nuclear fuel is more compact than any other energy source, making it very efficient and inexpensive to transport[3].

The main use of nuclear energy is to generate electricity. This is simply an efficient way of boiling water to make steam that drives turbine generators[2]. Except for the reactor itself, a nuclear power station works like most coal or gas-fired power stations. Nuclear energy is best applied to medium and large-scale electricity generation on a continuous basis (i.e. meeting base-load demand). The fuel for it is enriched uranium with a concentration of U-235 of some 3.5%. Bomb grade uranium has a U-235 concentration of some 90%.

Radiation and its impact on health

Ionizing radiation produces electrically charged particles called ions in the materials it strikes. This process is called ionization. In the large

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chemical molecules of which all living things are made the changes caused may be biologically important. There are several types of ionizing radiation described in the Appendix.

It is important to understand that radiation does not cause the body to become radioactive. However, most materials in their natural state (including body tissue) contain measurable amounts of radioactivity.

The human senses cannot detect radiation or discern whether a material is radioactive or not. However, radiation is very easily detected. There is a range of simple, sensitive instruments capable of detecting minute amounts of radiation reliably and accurately from natural and man-made sources. The amount of ionizing radiation, or 'dose', received by a person is measured in terms of the energy absorbed in the body tissue, and is expressed in gray. One gray (Gy) is one joule deposited per kilogram of mass.

Equal exposure to different types of radiation expressed as gray does not, however, necessarily produce equal biological effects. One gray of alpha radiation, for example, will have a greater effect than one gray of beta radiation. When we talk about radiation effects, we therefore express the radiation as an effective dose, in a unit called the sievert (Sv). Regardless of the type of radiation, one sievert (Sv) of radiation produces the same biological effect.

It has been known for many years that large doses of ionizing radiation, very much larger than background levels, can cause a measurable increase in cancers and leukaemias ('cancer of the blood') after some years' delay. It must also be assumed, because of experiments on plants and animals, that ionizing radiation can also cause genetic mutations that affect future generations, although there has been no evidence of radiation-induced mutation in humans[4]. At very high levels, radiation can cause sickness and death within weeks of exposure, as described in Table I.

Table I

Effects of whole-body radiation doses

mSv	Effect
10 000	A short-term and whole-body dose would cause immediate illness, such as nausea and a decreased white blood cell count, and subsequent death within a few weeks.
1 000	A short-term dose is about the threshold for causing immediate radiation sickness in a person of average physical attributes, but would be unlikely to cause death. Above 1 000 mSv, severity of illness increases with dose. If doses greater than 1 000 mSv occur over a long period they are less likely to have early health effects but they create a definite risk that cancer will develop many years later.
50	Conservatively, the lowest dose at which there is any evidence of cancer being caused in adults. Dose rates greater than 50 mSv/year arise from natural background levels in several parts of the world but do not cause any discernible harm to local populations.
20	Averaged over 5 years is the limit for radiological personnel such as employees in the nuclear industry, uranium or mineral sands miners and hospital workers in most parts of the world (who are all closely monitored).
10	The maximum actual dose rate received by any South African uranium miner.
3	The typical background radiation from natural sources, including an average of almost 2 mSv/year from radon in air.
0.3-0.6	A typical range of dose rates from artificial sources of radiation, mostly medical.
0.05	A very small fraction of natural background radiation, is the design target for maximum radiation at the perimeter fence of a nuclear electricity generating station. In practice the actual dose is less.

The degree of damage caused by radiation depends on many factors, for example, dose, dose rate, type of radiation, the part of the body exposed, age and health, but embryos, including the human foetus, are particularly sensitive to radiation damage.

But what are the chances of developing cancer from low doses of radiation? The prevailing assumption is that any dose of radiation, no matter how small, involves a possibility of risk to human health. However, there is no scientific evidence of risk at doses below about 50 millisieverts in a short time or about 100 millisieverts per year[4]. At lower doses and dose rates, up to at least 10 millisieverts per year, the evidence suggests that beneficial effects are as likely as adverse ones.

Higher accumulated doses of radiation might produce a cancer that would be observed only up to twenty years after the radiation exposure. This delay makes it impossible to say with any certainty which of many possible agents were the cause of a particular cancer. In western countries, about a quarter of people die from cancers, with smoking, dietary factors, genetic factors and strong sunlight being among the main causes. Although radiation is a weak carcinogen, undue exposure could certainly increase health risks.

The body has defence mechanisms against damage induced by radiation as well as by chemical and other carcinogens. These can be stimulated by low levels of exposure, or overwhelmed by very high levels.

On the other hand, large doses of radiation directed specifically at a tumour are used in radiation therapy to kill cancerous cells, and thereby often save lives (usually in conjunction with chemotherapy or surgery). Much larger doses are used to kill harmful bacteria in food, and to sterilize bandages and other medical equipment. Radiation has become a valuable tool in our modern world.

As exposure to high levels of ionizing radiation carries a risk, should we attempt to avoid it entirely? Even if we wanted to, this would be impossible. Radiation has always been present in the environment and in our bodies. However, we can and should minimize unnecessary exposure to significant levels of man-made radiation.

There are four ways in which people are protected from identified radiation sources:

- ***Limiting time:*** for people who are exposed to radiation in addition to natural background radiation through their work, the dose is reduced and the risk of illness essentially eliminated by limiting exposure time.
- ***Distance:*** in the same way that heat from a fire is less the further away you are, the intensity of radiation decreases with distance from its source.
- ***Shielding***: barriers of lead, concrete or water give good protection from penetrating radiation such as gamma rays. Radioactive materials are therefore often stored or handled under water, or by remote control in rooms constructed of thick concrete or lined with lead.
- ***Containment:*** Radioactive materials are confined and kept out of the environment. Radioactive isotopes for medical use, for example, are dispensed in closed handling facilities, while nuclear reactors operate within closed systems with multiple barriers that keep the radioactive materials contained. Rooms have a reduced air pressure so that any leaks occur into the room and not out from the room.

During mining operations, it is not the direct radiation from uranium that is the danger but rather the potential for the exposure to a radioactive gas known as radon (Rn) or more specifically its daughter isotope Rn-222 (part of the uranium decay series). The major hazard of this daughter is the inhalation deep into the basin of the lung tissue of the products that have attached themselves to surfaces such as dust and to aerosols present in the atmosphere. The inhalation of these radon daughters is injurious to health, and in high concentrations can result in a increased incidence of lung cancer. Fortunately, the provision of normal ventilation standards and the use of wet mining techniques are more than adequate to ensure these radon daughters do not reach dangerous concentrations[5].

Nuclear energy

As mentioned earlier, the fissile material within naturally occurring uranium is U-235 accounting for some 0.7% of the total naturally occurring isotopes of uranium. However, to produce a material that is capable of a chain reaction and thus providing the heat source in a power station, requires that the concentration of U-235 be increased to between 3% and 4%. This process is known as 'enrichment'. It is important to note that U-235 weapons grade concentration is in the region of 90% and the technology required to produce this highly enriched uranium is both very complex and very expensive and poses a very serious technical barrier to nuclear weapon proliferation. A concentration of U-235 above 20% is deemed to be 'highly enriched'.

The whole process of mining uranium ore to the final disposal of waste nuclear fuel is known as the nuclear fuel cycle. This cycle is summarized in Figure 1.

The product from a typical uranium mine and milling operation is ammonium diuranate or ADU. This product is calcined, in South Africa by Nufcor, to reduce its mass for shipment. The final product for export to the conversion and enrichment plants is uranium oxide or U_3O_8, commonly referred to as yellow cake.

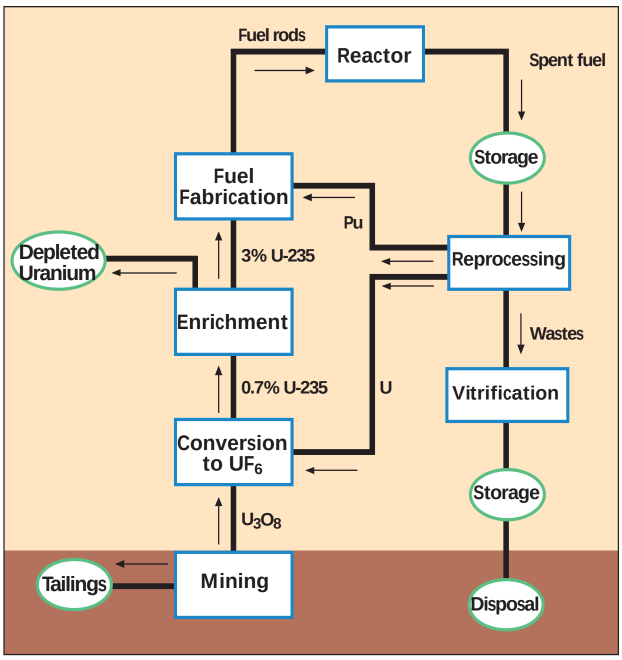

Figure 1—The nuclear fuel cycle

In the **enrichment process** U_3O_8 is first converted to a gas—uranium hexaflouride (UF_6). There are two enrichment processes in large-scale commercial use, each of which uses uranium hexaflouride as feed—gaseous diffusion and gas centrifuge. They both use the physical properties of molecules, specifically the 1% mass difference, to separate the isotopes. The product of this stage of the nuclear fuel cycle is enriched uranium hexaflouride, which is reconverted to produce enriched uranium oxide. The excess U-238, known as depleted uranium, has very little radioactivity. The high density of depleted uranium means that it has many commercial uses such as in the keels of yachts and as counterweights for aircraft control surfaces (rudders and elevators), as well as for radiation shielding and other applications. Its melting point is 1 132°C.

Reactor fuel is generally in the form of baked uranium oxide ceramic pellets. The pellets are then encased in metal tubes to form fuel rods, which are arranged into a fuel assembly ready for introduction into a reactor. The dimensions of the fuel pellets and other components of the fuel assembly are precisely controlled to ensure consistency in the characteristics of fuel bundles. In a fuel fabrication plant great care is taken with the size and shape of processing vessels to avoid criticality (a limited chain reaction releasing radiation). With low-enriched fuel criticality is most unlikely.

Inside a **nuclear reactor** the nuclei of U-235 atoms split (fission) and in the process release energy. This energy is used to heat water and turn it into steam. The steam is used to drive a turbine connected to a generator, which produces electricity. Some of the U-238 in the fuel is turned into plutonium in the reactor core. The main plutonium isotope is also fissile and it yields about one third of the energy in a typical nuclear reactor. The fissioning of uranium is used as a source of heat in a nuclear power station in the same way that the burning of coal, gas or oil is used as a source of heat in a fossil fuel power plant. Typically, more than 45 million kilowatt-hours of electrical energy are produced from one ton of natural uranium. The production of this amount of electrical power from fossil fuels would require the burning of over 20 000 tons of high grade black coal (considerably more for low grade coal typically burnt in South Africa) or 30 million cubic metres of gas. Figure 2 is a simplified diagram of a nuclear power station.

Used fuel is about 95% U-238 but it also contains about 1% U-235 that has not fissioned, about 1% plutonium and 3% fission products, which are highly radioactive, with other transuranic elements formed in the reactor. In a **reprocessing** facility the used fuel is separated into its three components: uranium, plutonium and waste, containing fission products. Reprocessing enables recycling of the uranium and plutonium into fresh fuel, and produces a significantly reduced amount of waste (compared with treating all used fuel as waste).

At the present time, there are no **disposal facilities** (as opposed to storage facilities) in operation into which used fuel, which is not destined for reprocessing, and the waste from reprocessing can be placed. Although technical issues related to disposal have been addressed, there is currently no

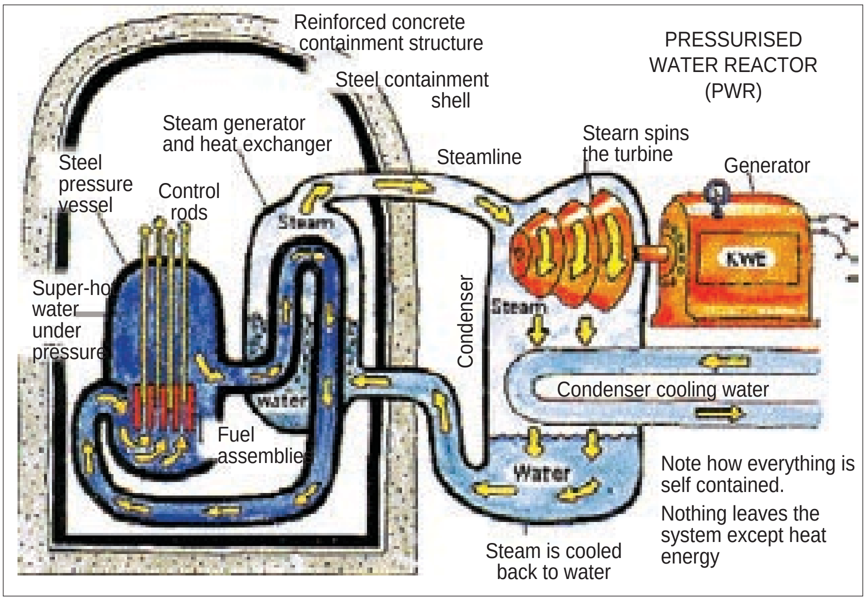

Figure 2—A nuclear power plant

pressing technical need to establish such facilities, as the total volume of such wastes is relatively small. Furthermore, the longer the used fuel is stored the easier it is to handle, due to the progressive diminution of radioactivity. There is also a reluctance to dispose of used fuel because it represents a potentially significant energy resource, which could be reprocessed at a later stage to allow further recycling of the uranium and plutonium. A number of countries are carrying out studies to determine the optimum approach to the disposal of spent fuel and wastes from reprocessing. The general consensus favours its placement into deep geological repositories, initially designed for subsequent recovery.

Currently the percentage of electricity generated by nuclear energy is approximately 16% of total world electricity generation. On a country-by-country basis the percentage ranges from almost 80% in France to 20% in the USA and UK and 7% in South Africa. Table II shows a selection of countries, the number of reactors and their percentage of nuclear generated electricity for 2004.

Of significance are the relative low levels of nuclear power generation in India and China. The possible impact of this will be discussed later.

There are currently (2004) 441 nuclear power reactors in operation around the world with a further 26 under construction. The total capacity of these reactors is some 388 300 MW. They supplied some 2 619 TW-h of electricity in 2004[6]. Of note is that by 2000 there was as much electricity produced from nuclear energy as from all other sources worldwide in 1961.

The economics for operating nuclear reactors is opposite to fossil fuel power stations in that they are expensive to construct (high capital) but very cheap to run although, overall, the life cycle costs area similar. A fossil fuel power station is relatively cheap to construct but expensive to run, with a high proportion of running costs being fuel, for example coal. Conventional nuclear power stations are more appropriate to supply base load demand rather than peak demand.

The price of electricity from a nuclear reactor would increase by 7% if the price of U_3O_8 doubles. However, the price of electricity from a gas-powered plant would increase by 70% if gas prices were to double. This is illustrated in Figure 3 as a result of work done in Finland by Tarjanne and Luostarinen[7].

Table II

Electricity produced by nuclear energy in 2004

Country	Number of reactors (current and in construction)	Production of nuclear power
France	59	78%
South Korea	20	38%
Hungary	4	34%
Japan	54	29%
USA	104	20%
UK	23	19%
Russia	35	16%
South Africa	2	7%
India	23	3%
China	11	2%

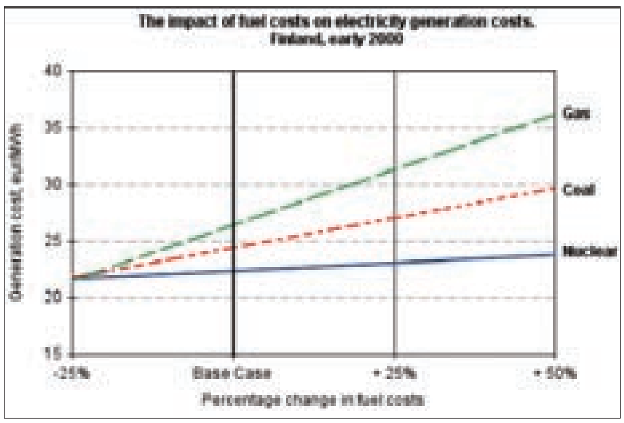

Figure 3—Impact of fuel costs

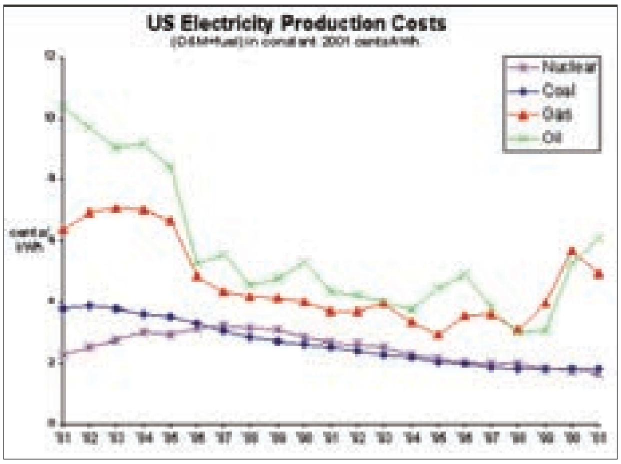

Figure 4—Production costs

Overall lifetime costs are similar for both coal and nuclear but considerably more expensive for gas and oil fired stations. Production costs, which include operating, maintenance and fuel costs, are illustrated in Figure 4.

As nuclear reactors have a high capital cost component, the overall utilization and life have a marked impact on costs. An improvement on either of these factors makes nuclear power a significantly cheaper option than any fossil fuel option.

South Africa's energy supply shortage and PBMR

No paper on South Africa's role in nuclear energy would be complete without a comment on the current electricity supply crisis and the Pebble Bed Modular Reactor (PBMR)[14]. At present the electricity demand on a coldest day in South Africa is 34 GW. Eskom has the capacity to generate 36 GW. It is estimated that we will run out of electricity generating capacity during the evening peak within the next two years. Some may say this already happening. The electrification of rural areas and the growth in the economy will push demand to 40 GW of electricity by 2011 or in less than five years. Solutions include decommissioning mothballed power stations, building new power stations, examining alternative sources of energy and bringing the PBMR project to fruition. In the short-term demand side management, helping consumers use less electricity in the peak (expensive) periods and use more in the off-peak (inexpensive) periods, is an essential interim measure. This has come into its own in the mining industry with, for example, some mines managing their pumping systems more effectively.

The PBMR is a high temperature reactor (HTR), with a closed-cycle, gas turbine power conversion system[15]. Although it is not the only HTR currently being developed in the world, the South African project is internationally regarded as the leader in the power generation field. Very high efficiency and attractive economics are possible without compromising the high levels of passive safety expected of advanced nuclear designs.

The main motivation for PBMR is its inherent safety features and the corresponding impact on simplicity of design and therefore costs. Too much heat principally drives nuclear accidents. This surplus or residual heat is called decay heat and is caused by radioactive decay of fission products. Put simply, if you do not cool the reactor sufficiently the heat will cause the nuclear fuel to release radioactivity that cannot be contained. In conventional reactors, heat is removed by active cooling systems (such as pumps), which rely on the presence of coolant such as water. Any such system may fail and therefore they are duplicated in conventional reactors to make sure that there will be support, should the first line of defence fail. Secondly, so-called containment buildings are constructed, which are nothing less than strongly armoured containers to create a barrier to the release of radioactivity. With the PBMR this basic danger of overheating is independent of the state of the reactor coolant. PBMR combines very low power density of the core (1/30th of the power density of a pressurized water reactor), and the resistance to high temperature of fuel in billions of independent particles, which creates an inherent ceiling to temperature control.

However, there are some concerns around the PBMR[16]. In previous experimental reactors of a similar type, it proved difficult to realize the safety and cost benefits. The PBMR's precursor in Germany was closed, as the owners and the German government were unwilling to fund further development. Only time will tell whether PBMR is the appropriate technology for South Africa to pursue.

The PBMR essentially comprises a steel pressure vessel which holds about 450 000 fuel spheres. The fuel consists of low enriched uranium triple-coated isotropic particles contained in a moulded graphite sphere. A coated particle consists of a kernel of uranium dioxide surrounded by four coating layers. The PBMR system is cooled with helium. The heat that is transferred by the helium to the power conversion system, is converted into electricity through a turbine. The plant comprises a module building with the reactor pressure vessel and the power conversion unit (PCU). The vertical steel pressure vessel is 6.2 m in diameter and about 27 m high. It is lined with a 1 m (39 inch) thick layer of graphite bricks, which serves as an outer reflector and a passive heat transfer medium. The graphite brick lining is drilled with vertical holes to house the control elements. The PBMR uses particles of enriched uranium dioxide coated with silicon carbide and pyrolitic carbon. The particles are encased in graphite to form a fuel sphere or pebble about the size of a tennis ball. Helium is used as the coolant and energy transfer medium, to drive a closed cycle gas turbine and generator system. When fully loaded, the core would contain 456 000 fuel spheres. The geometry of the fuel region is annular and located around a central graphite column. The latter serves as an additional nuclear reflector.

To remove the heat generated by the nuclear reaction, helium coolant enters the reactor vessel at a temperature of about 500 ºC and a pressure of 9 MPa. The gas moves down between the hot fuel spheres, after which it leaves the bottom of the vessel, having been heated to a temperature of about 900 ºC. The hot gas then enters the turbine that is mechanically connected to the generator through a speed-reduction gearbox on one side and the gas compressors on the other side. The coolant leaves the turbine at about 500 ºC and 2.6 MPa, after which it is cooled, recompressed, reheated and returned to the reactor vessel.

Although the PBMR technology was originally developed and tested in Germany a consortium of South African and UK companies now owns it.

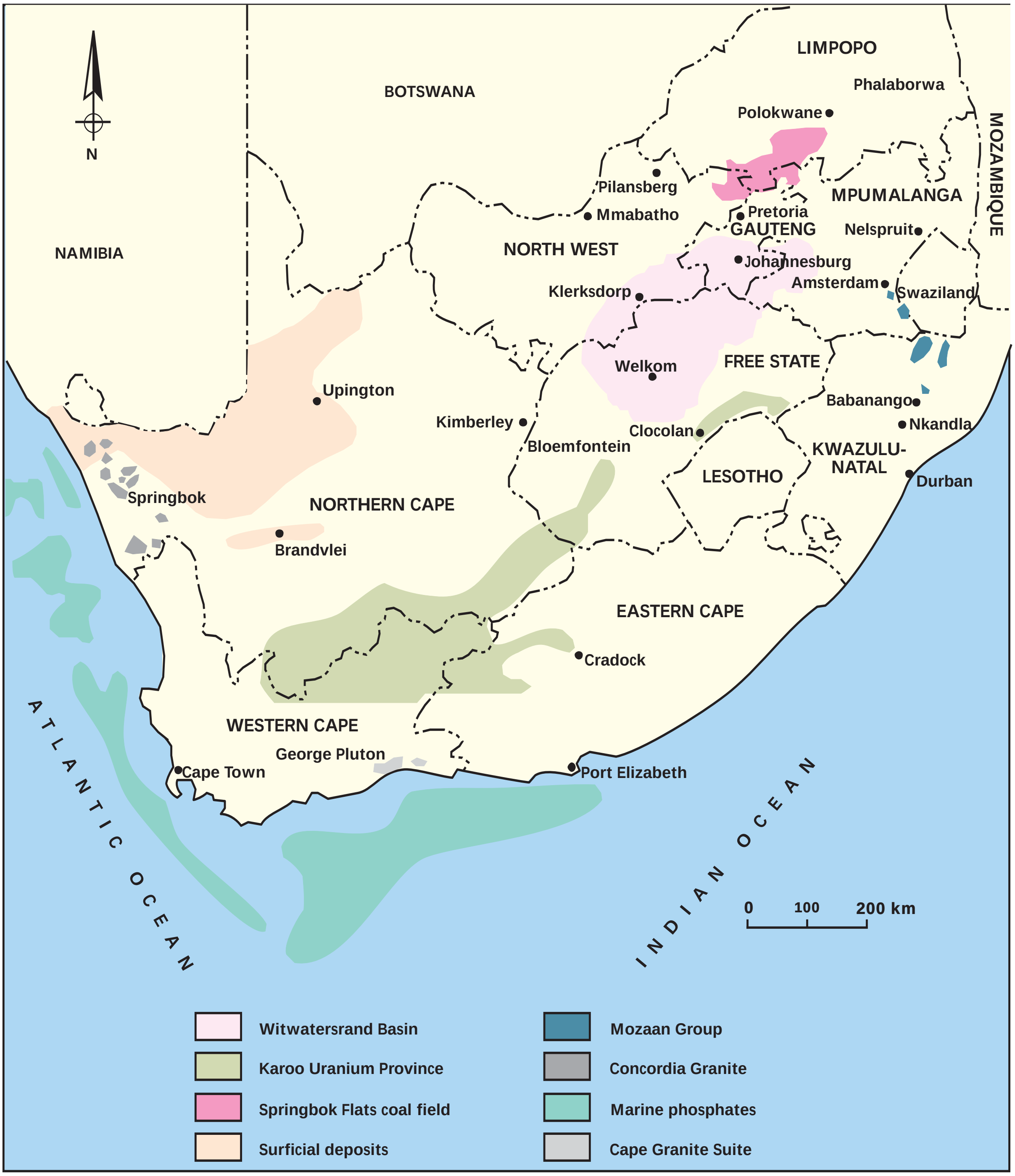

Figure 5—Distribution of uranium deposits in South Africa

Uranium occurrence and production in South Africa

Concentrations of uranium in South Africa have been known for many years. The more important uranium deposits in South Africa are shown in Figure 5[8].

The Witwatersrand Basin is by far the most important uranium deposit, having produced approximately 96 per cent of South Africa's production. The balance was produced from Palabora Mining Company Ltd as a by-product from copper mining. This mine was the only producer of uranium in South Africa outside the Witwatersrand Basin. It holds the distinction of being the lowest grade of any orebody in the world being processed for uranium at only 30 ppm U.

Another notable deposit includes the Karoo Uranium Province. Although never exploited, it was discovered by Union Carbide in 1969 and expensively explored in the 1970s and early 1980s. It is now subject to further prospecting right applications by a number of companies including SXR Uranium One, Uramin and Brinkley Mining. The largest deposit, Ryst Kuil, is 45 km southeast of Beaufort West.

Other deposits include the Springbok Flats coalfield, the surficial and granite deposits in the Northern Cape, the

Mozaan Group conglomerates in KwaZulu-Natal and marine phosphates.

The establishment of the Witwatersrand Basin as a significant low-grade resource had a particular 'cloak and dagger' element and reads like a good detective story.

After the success of the American atomic project and the production of the first atom bomb, uranium became a 'strategic product' that would be required in large quantities. It was a matter of urgency not only to increase production, but also to survey the world's resources and to make certain that the control of uranium deposits should be in the 'right' hands. The governments of the United States and Great Britain jointly sponsored worldwide prospecting programmes for the discovery of new sources of supply. Weston Bourret, a geologist from the United States, visited South Africa in 1944 and sampled operational properties on the Witwatersrand. His report was a top-secret document—supposedly nobody in South Africa was aware of the true purpose of his visit. Over a hundred product and ore specimens were collected for preliminary radiometric assessment, chemical analysis and mineralogical studies in the USA.

The results were regarded as sufficiently important for the then prime minister, General Jan Smuts, to be approached about the possibilities of extracting and recovering uranium from the large tonnages treated. The British Geological Survey and the Atomic Energy Division, using a portable Geiger counter, did underground examinations of several mines. Small hand samples were also collected and taken back to the USA and Great Britain. Larger samples were taken from the Blyvooruitsicht, Vogelstruisbult, Western Reefs and the East Daggafontein Mines. The findings concluded the following:

'Present evidence appears to indicate that the Rand may be one of the largest low-grade uranium fields in the world.'

It was recommended that intensive research should be done into the extraction of uranium from the ores of the Witwatersrand. This led to a remarkable period of scientific co-operation between scientists in South Africa, Great Britain and the USA to find an answer to the complex problem of how to extract the uranium without interfering with the production of gold[9].

The South African Uranium Research Committee was established and the first uranium plant was set up at West Rand Consolidated Mines Ltd in September 1952. Four other South African mines became uranium producers shortly after, namely Blyvooruitsicht, Vogelstruisbult, Western Reefs and the East Daggafontein Mines. However, the USA and Great Britain increased the atomic weapons and nuclear programme. Consequently, in 1960, there were already seventeen uranium extraction plants in South Africa, treating slimes from 26 mines and producing over 6 200 tons of uranium oxide.

In the early years of local uranium production, South Africa's entire output was committed to supplying the Western world's nuclear armaments programmes. After 1959 the needs of these programmes declined and uranium production in South Africa followed suit, reaching a nadir of 2 262 tons of uranium in 1965. In 1961 a scaling down of the South African production plan was implemented, so that 17 mines would be feeding only 13 treatment plants by the end of 1963. After that, in 1964 and 1965, the number of plants would be reduced to 11.

However, in the 1970s the world's oil crisis led to a higher demand for uranium. The steep rise in prices stimulated the uranium industry and trebled its production to 6 143 tons of uranium. The marked increase in the price of uranium in the late 1970s brought the mineral into greater prominence.

The boom in the nuclear power industry received a severe blow in 1979 when the Three Mile Island incident triggered an anti-nuclear backlash. The nuclear industry declined, and a number of plans for nuclear plants were cancelled in various parts of the world. Demand for uranium dropped and consequently so did its price, which by the end of 1984 had fallen to about a third of its peak level attained in 1978.

Rationalization of the South African uranium industry followed. At the end of 1985, a total of 14 uranium plants were in production and had produced 4 880 tons of uranium during that year. By the end of 1984, a total of 136 000 tons of uranium had been produced by the Witwatersrand gold mines, with a minor contribution from Palabora Mining Company, amounting to 2 000 tons. All of South Africa's uranium is produced as a by-product; the majority from the Witwatersrand gold mines and historically a small proportion from the open-cast copper mine at Phalaborwa.

Currently, the only Southern African producers are AngloGold Ashanti's Vaal River Mine and the Rossing Mine in Namibia. However, a number of new mines are close to production including SXR Uranium One's Dominion Reefs Uranium Mine[10] near Klerksdorp and the Paladin's Langer Heinrich Mine in Namibia. A number of exploration companies, such as Uramin and Brinkley Mining, have recently listed on London's AIM exchange with the express objective of raising money to fund uranium exploration activities in Africa.

The current uranium market

The demands for uranium for military purposes reached a peak during the Cold War between the West and the East, but subsequently declined after the Nuclear Non-Proliferation Treaty was signed by the great powers of the world, banning the manufacturing of nuclear arms. The decline in uranium production for military purposes gradually gave way to the use of uranium for saner purposes, such as radiation for the treatment of cancer and generating heat to drive turbines and generators in nuclear power stations.

The international uranium market is in transition from being inventory driven to being production driven. Demand is set to outstrip supply by a considerable margin, the inventories (stockpiles) built up during the period of excess (effectively from 1945 to 1986) will not be sufficient to supply the developing shortfall and the uncertainty over potential uranium supply through to 2010 suggests future shortages[11].

International shortages of uranium supply along with escalating nuclear programmes in countries such as India and China have caused the spot price of uranium to more than double in the past two years. According to the World Nuclear Association, India and China have official plans in place to construct 64 new reactors between them.

Market analysts are predicting another doubling of the price of uranium in the short term. Secondary uranium sources (decommissioned atomic bombs) are rapidly declining, notably the US-Russian highly enriched uranium programme, which has been delivering uranium to the market at the rate of 24 m lb per annum, and this level is not thought to be viable for the future. In addition, China is in transition from being a uranium exporter to importer. And critically, of course, the collapse in market prices through the 1980s and 1990s following record levels at the end of the 1970s (reminiscent of another highly-priced metal) has meant that there was a dearth of exploration during the 1980s and the first half of the 1990s.

As a consequence of market developments, uranium mine production dropped significantly in the first half of the 1980s from approximately 150 m lb at the start of the 1980s, when it just exceeded demand, to below 100 m lb per annum during the 1990s, while consumption was rising from roughly 150 m lb towards 175 m lb per annum, as shown in Figure 6. The gap between production and requirements has until now been met from the secondary sources mentioned above, which are now rapidly being depleted.

Nuclear power generation has been on the increase over the past decade although during the 1990s there was little freshly commissioned greenfield capacity. This has been due to improved reactor performance, increased fuel burn-up (i.e. the amount of energy recovered from the fuel bundles), extended fuel cycles, and capacity increases of between 5 and 15 per cent at existing plants. The average load factor in the United States has risen from approximately 65 per cent in 1990 to roughly 90 per cent by 2000, while the extension of the fuel cycle now means that the period between refuelling the core in the reactors has extended significantly and now runs at between 18 and 24 months, whereas in the 1970s it could be as short as 12 months. In addition, the average capacity factor for nuclear plants stood in 2003 at 89.6%, compared with 70.6% for coal, while the natural gas-fired plants were operating at only approximately 40% of the time—and renewable, wind-powered plants operated only for one-third of the time.

These increases in efficiency have resulted in considerable cost reduction, and in the USA, nuclear power is now competitive with coal and natural gas ($31–46/MWh post absorption of early plant costs, against $33–41/MWh for coal and $35–45/MWh for natural gas). This is one of the factors that has led to a renaissance of the industry. The present picture shows increases in capacity underway internationally.

China has plans to increase its nuclear capacity and India has several reactors, either planned or under construction. Russia is now completing plants whose construction was halted when the old Soviet regime was disbanded. Finland has just ordered its fifth nuclear reactor, while France, which uses nuclear sources for 78% of its energy supplies, has agreed to build the prototype for the European pressurized water reactor. Over and above this, a number of plants are receiving 20-year extensions to their licences. Between March 2000 and October 2004, 30 reactors were granted 20-year extensions to their original licences of 40 years; a further 16 renewal applications have been filed, with another 22 expected, meaning that just under half of the installed reactors are expected to receive licence extensions.

In 2003, only 55% of the uranium consumed had been mined that year. The depletion of uranium reserves in this way has continued for many years and has largely gone unnoticed. Low-grade uranium sources are plentiful and readily accessible, but uneconomical at current prices. High-grade uranium deposits such as those found in Saskatchewan's Athabasca Basin are scarce, involve substantial drilling, are located at great depths and require expensive radiation protection measures for mineworkers.

In South Africa, electricity consumption has been growing rapidly since 1980. Eskom supplies about 95% of South Africa's electricity and more than 60% of Africa's requirements, predominantly from coal-fired stations. Eskom expects that by 2008, regional electricity demand will exceed supply capacity and has already started to curtail the export of electricity. Moving electricity over long distances is inefficient, so the Koeberg nuclear power station near Cape Town was introduced in the mid-1980s. Koeberg is the only

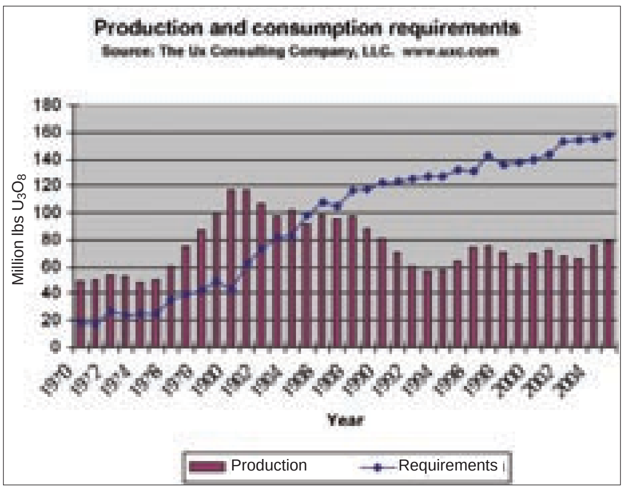

Figure 6—Production and consumption requirements

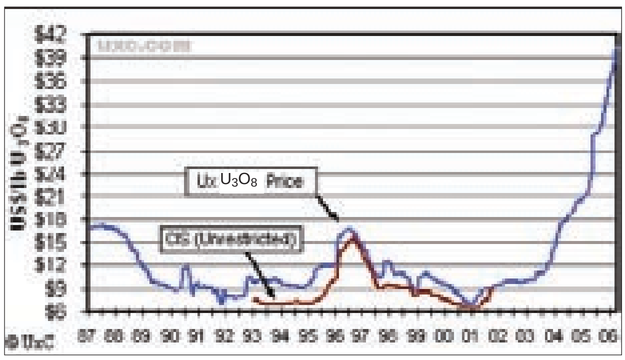

Figure 7—U_3O_8 price over the last 20 years

nuclear power station in Africa and the largest turbine generator in the Southern hemisphere, although some sources argue that it was built as a smokescreen for South Africa's weapons programme[12].

Governments worldwide struggle for solutions to control greenhouse gas emissions and produce affordable energy. It is claimed that nuclear power is the cleanest, least expensive and most secure form of electricity. The US Department of Energy is actively providing incentives encouraging power corporations to apply for licences to build new reactors in an attempt to stave off an imminent energy shortage. Fearful of lack of availability and elevated prices, utility companies have been mostly responsible for the high level of spot demand for uranium. Figure 7 shows the U_3O_8 price over the last 20 years, highlighting the recent increase in price. Figure 8 shows the U_3O_8 price since 1969, which clearly illustrates that the current price increases are likely to be sustainable, especially when compared to the prices achieved in the mid-70s in real 2005 money terms[13].

All of this points to a sustained shortfall in supply and clear scope for fresh mine production. Given that uranium comprises only 1% of nuclear reactors' costs, the fundamentals of the market point to sustainable higher prices with current (June 2006) spot prices well over US$40/lb. Clearly there are other issues at stake given that the market remembers Three Mile Island and Chernobyl, but the political will appears to be strong enough for the market to support fresh mine production.

Future use and trends

Mainly driven by fears of global warming (with impetus provided by the recent rise in oil prices), at a political level nuclear power is now seen as an acceptable and the only solution to wide-scale reduction in greenhouse gasses. As recently as 24 May 2006 George Bush made the comment[17]:

'For the sake of economic security, the USA must aggressively move forward with the construction of nuclear power plants'. He went on to say, 'Nuclear power helps us protect the environment and nuclear power is safe.'

In the UK, although the debate is far from over, Blair has firmly put nuclear power back on the agenda[18].

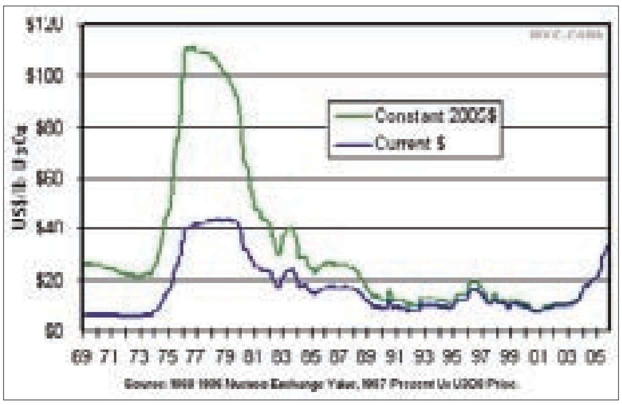

Figure 8—U_3O_8 price since 1969

Rapidly developing countries like China and India are relying on nuclear power for their growing energy requirements.

In summary, the reasons for nuclear rehabilitation are simple[19]. Many scientists say global warming, blamed in large part on the burning of fossil fuels, could herald catastrophic climate changes such as more droughts. Turmoil in the Middle East, declining reserves of oil elsewhere and the rising power of energy-rich Russia have pushed security of supply up the political agenda. The nuclear fuel cycle and nuclear energy cannot boast zero CO_2 emissions, as the cycle does rely on other human activity, which results in CO_2 emissions, but does result in approximately 10% of the emissions of a coal fired power station. As it can be stored for decades, it is not at the mercy of supply chains.

The only deaths associated with Koeberg, opened in 1984, were when two nuclear inspectors died in a car accident on the way to the Vaalputs nuclear waste repository in the Northern Cape[20]. This compares to around 1 000 people being killed in South African coalmines since then. Such is the caution around nuclear power that anyone working in a nuclear environment is continually monitored, including some 50 000 people in England and the US who have been involved in 'nuclear work' such as dismantling of nuclear submarines. None of them has been found to be suffering any out-of-normal health effects.

However, there are still some challenges to be met. Over the next 10 years, nuclear power cannot contribute either to the need for more generating capacity or to carbon reductions as it simply cannot be built in time. Clean coal technologies, energy efficiency and renewables such as solar and wind will need to play a significant part in managing cleaner energy supply in the short term. However, for long-term sustainable clean energy, nuclear seems to offer the only alternative.

However, there are some concerns that could provide some resistance to the rapid expansion in nuclear energy. These include:

- Public acceptability and perception
- Long-term waste disposal
- High capital cost
- Questions of safety (brought to the fore by Chernobyl and to a lesser extent by Three Mine Island)
- Risk of terrorist attacks
- Risk of nuclear proliferation.

It could, however, be argued that nuclear power represents our best shot at replacing the burning of fossil fuels. Should South Africa use its supply of cheap coal on electricity generation when electricity can be generated from uranium? The reasoning behind the last question is that we should be hoarding our precious supply of cheap coal so that it can be turned into liquid fuel, and Sasol has the technology to do it. Given the world's oil crisis, when supplies dwindle, South Africa can make a financial windfall by providing the rest of the world with fuel from our coal.

If for argument's sake, carbon dioxide from vehicle emissions does prove to be a significant contribution to global warming, hydrogen or battery-powered electric cars could certainly work well for high-density inner cities. But if hydrogen is being generated or batteries are being charged via coal-fired power stations, we are back to square one with fossil fuel emissions.

In summary, in the short term the current supply shortage of uranium is likely to result in continued high prices, which in turn is already triggering increased exploration activity and new mine production. In the longer term, new power generating capacity is likely to sustain the demand for uranium and, despite some challenges, nuclear energy is likely to be the dominant power source into the next century.

References

1. FORD, M.A. Uranium in South Africa. *Journal of SAIMM*. vol. 93, no. 2, Feb 1993, pp. 37–58.
2. Website of the World Nuclear Association: www.world-nuclear.org/education/uran.htm.
3. Website of Mesa Uranium Corp.: www.mesauranium.com.
4. Website of the World Nuclear Association: www.world-nuclear.org/education/ral.htm.
5. ROSE, H.J.M. Chapter 27 – Radiation in Mines. *Environmental Engineering in South African Mines*. The Mine Ventilation Society, 1982, pp. 741–761.
6. Website of the International Atomic Energy Agency (IAEA): www.iaea.org.
7. TARJANNE, R. AND RISSANEN, S. *The Uranium Institute 25th International Symposium*, Aug 2000, London.
8. COLE, D.I., Uranium. *The Mineral Resources of South Africa*. Council for Geoscience. 1998. pp. 642–658.
9. TAVERNER, L. An Historical Review of the Events and Developments Culminating in the Construction of Plants for the Recovery of Uranium from Gold Ore Residues. *Journal of SAIMM*. November 1956, pp. 125–143.
10. Website of SXR Uranium One: www.uranium1.com.
11. NORTIER, J. Chief Financial Officer. SXR Uranium One. Personal Communication. May 2006.
12. FIG, D. *Uranium Road – Questioning South Africa's Nuclear Direction*. Jacana, Johannesburg, p. 15.
13. Website of Ux Consulting Company: www.uxc.com.
14. PLANTING, S. Surge of Effort to Shift Patterns of Power Use. *Financial Mail*. 3 December 2004.
15. Web site of Pebble Bed Modular Reactor Ltd. www.pbmr.co.za
16. FIG, D. *Uranium Road – Questioning South Africa's Nuclear Direction*. Jacana, Johannesburg, p. 97.
17. LOVEN, J. Bush Pitches Plan to Expand Nuclear Power. Associated Press. 24 July 2005.
18. PORTILLO, M. If we don't want to depend on oil, we must go nuclear. *The Sunday Times* (UK). 18 September 2005.
19. Lovell, J. Is nuclear power worth the waste? *The Sunday Independent – Business Report*, 23 April 2006, p. 3.
20. DUGMOR E, H. Shooting sacred cows. *The Sunday Independent – Sunday Dispatches*. 11 June 2006.

Appendix—Types of ionizing radiation

X-rays and gamma rays, like light, represent energy transmitted in a wave without the movement of material, just as heat and light from a fire or the sun travels through space. X-rays and gamma rays are virtually identical except that X-rays are generally produced artificially rather than coming from the atomic nucleus. Unlike light, X-rays and gamma rays have great penetrating power and can pass through the human body. Thick barriers of concrete, lead or water are used as protection from them.

Alpha particles consist of two protons and two neutrons, in the form of atomic nuclei. They thus have a positive electrical charge and are emitted from naturally occurring heavy elements such as uranium and radium, as well as from some man-made elements. Because of their relatively large size, alpha particles collide readily with matter and lose their energy quickly. They therefore have little penetrating power and can be stopped by the first layer of skin or a sheet of paper. However, if alpha sources are taken into the body, for example by breathing or swallowing radioactive dust, alpha particles can affect the body's cells. Inside the body, because they give up their energy over a relatively short distance, alpha particles can inflict more severe biological damage than other radiations.

Beta particles are fast-moving electrons ejected from the nuclei of atoms. These particles are much smaller than alpha particles and can penetrate up to 1 to 2 centimetres of water or human flesh. Beta particles are emitted from many radioactive elements. A sheet of aluminium a few millimetres thick can stop them.

Cosmic radiation consists of very energetic particles including protons that bombard the earth from outer space. It is more intense at higher altitudes than at sea level where the earth's atmosphere is most dense and gives the greatest protection.

Neutrons are particles that are also very penetrating. On earth they mostly come from the splitting, or fissioning, of certain atoms inside a nuclear reactor. Water and concrete are the most commonly used shields against neutron radiation from the core of the nuclear reactor. ◆