The management of radioactive wastes and the disposal of plutonium

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Date: 2000

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Dr Barnaby is currently working with the Oxford Research Group which has recently been providing advice to the British Government on radioactive waste management.

Dr Barnaby will provide an overview of key policy issues in relation to radioactive waste management and the linkages between the various issues

The management of radioactive wastes

The categories of radioactive wastes

Radioactive wastes are generally divided into three categories according to the concentrations of radioactive isotopes in them and how they are formed - high level waste (HLW), intermediate level waste (ILW) and low level waste (LLW).

HLW contains the greatest concentration of radioactivity, so much radioactivity that substantial amounts of heat are generated by radioactive decay[1]. It arises as a waste liquid stream in reprocessing plants, civil and military. In civil reprocessing plants unused uranium and plutonium are chemically separated from fission products in spent fuel removed from nuclear-power reactors.

If the spent reactor fuel is not reprocessed the spent fuel elements themselves are treated as HLW. If any of the plutonium produced in reprocessing plants is eventually classified as a waste it is treated as HLW.

HLW generates more than 2 kilowatts of heat per cubic metre and a high level of heat dissipation is needed. Heavy shielding is needed during handling, transportation and storage.

ILW is less radioactive than HLW but more radioactive than LLW. It mostly arises from processes in reprocessing plants, including treatment of effluents before they are discharged into the environment, such as the ocean. ILW consists of metals (such as the cladding removed from spent fuel rods), cement, graphite, sledges, and so on. The operation and maintenance of radioactive facilities also produce ILW; it is also produced in substantial quantities when nuclear plants, including submarine and other warship reactors, are dismantled.

Some ILW is relatively short-lived - for example, when it is dominated by radioisotopes like caesium-137 (half-life 30.2 years) and strontium-90 (half-life 28.8 years) and decays to low levels within a few hundred years. Long-lived ILW contains long-lived radioisotopes such as plutonium-239 (half-life 24,000 years), americium-241 (half-life 2.1 million years), and chlorine-36 (half-life 300,000 years).

Long-lived ILW could be hazardous to humans for periods in excess of 100,000 years after its disposal. The heat generated by ILW is usually less than 2 kilowatts per cubic metre but may require dissipation during storage.

LLW contains the least radioactivity. It is produced by the nuclear industry, mostly as metals and organic materials in lightly contaminated scrap (protective clothing, paper towels, plastic wrappings, etc.) The decommissioning of nuclear plant produces large amounts of LLW in the form of building materials, large pieces of plant and equipment.

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[1] The total volume of High Level Liquid Waste in store at the reprocessing plant at Sellafield, for example, in October 1999 was about 1300 cubic metres. Some of the High Level Liquid in the tanks would boil after around 12 hours if there was a total loss of cooling as a result of, for example, a power cut. In the event of the High Level Liquid Waste boiling the amount of fission products released into the environment would depend on a number of factors such as duration of boiling, the number of tanks involved and the extent to which fission products were removed by the ventilation system filters. The consequences would depend on other factors such as wind direction and the weather.

LLW is also produced in hospitals, research establishments, and industries that use radioactive isotopes.

LLW is generally reckoned to contain less than 4,000 million becquerels per tonne of alpha activity or less than 12,000 million becquerels per tonne of beta/gamma activity. It can be handled and transported in normal ways without shielding.

The management of HLW

I will deal mainly with the management of HLW in general and then discuss policies for the disposal of plutonium in particular. It is usually argued that most ILW should be managed in the same way as HLW. Therefore, the following discussion of the management of HLW applies also to the management of ILW.

The disposal of HLW is preceded by a period of interim storage, either at the site, such as the nuclear-power reactor, at which it is created, or at a centralised location. Any movement of HLW is accomplished in special collision- and fire-resistant containers, transported by ship, train or truck. Liquid HLW is solidified ('immobilised') before transport, packaging or disposal.

The disposal of HLW presents special problems because it contains high concentrations of both highly radioactive and extremely long-lived radioisotopes. HLW contains 90 or more per cent of the entire radioactivity in all forms of radioactive waste (almost all the rest is in ILW).

During the first thousand years after production, the radioactivity of HLW decays to about one-thousandth of its initial value as the shorter-lived radioisotopes, particularly caesium-137 and strontium-90 with half-lives of about 30 years, decay. It takes another 10,000 years until the activity of HLW decreases by another factor of ten, mainly because of the decay of americium-241 that has a half-life of about 430 years. The activity then decays very slowly for about 3 million years when the quantities of very long-lived radioisotopes, such as neptunium-237 and caesium-135 with half-lives of about 2 million years, begin to fall significantly.

When it is first produced HLW generates large amounts of heat - unless cooled, the liquid boils. As the radioactivity decreases so does the heat. It takes 50 or more years before the HLW is cool enough to be disposed of in a geological repository.

As the radioactivity of HLW decays it becomes less hazardous to human health. But it takes about 10,000 years for the radioactivity to decay to the level that would have been generated by the original uranium ore from which the nuclear fuel was produced, should this ore not have been mined. Uranium itself is, of course, itself hazardous and HLW does not become non-hazardous when its radiotoxicity becomes less than that for uranium ore. HLW will remain a health hazard for humans for many hundreds of thousands of years. Because of its radiotoxicity, for all intents and purposes HLW requires permanent isolation from the human environment.

HLW generates such high levels of both radioactivity and heat that massive shielding and effective cooling systems have to be provided during handling and temporary storage. Liquid HLW, usually a nitric acid solution, has to be stored in special cooled stainless steel tanks or vaults for several decades. The liquid is then usually solidified by converting it into a borosilicate glass (pyrex), a process called vitrification, or possibly a ceramic. The vitrified waste is the form in which the HLW will eventually be permanently disposed of.

Complex engineering and technological problems are involved in the management and effective disposal of HLW. These problems have yet to solved in a satisfactory manner. Moreover, the methods finally chosen for the disposal of HLW must meet with political and, more importantly, public acceptance. This may prove a more difficult nut to crack than solving the technical problems.

The amounts of HLW

The amount of civil HLW produced depends mainly on the amount of electricity generated by nuclear-power reactors and hence the amount of spent fuel that is discharged from these reactors. This has grown rapidly over the past two three decades. In 1970, 1,240 tonnes of heavy metal (tHM) (the weight of the spent fuel) was discharged. Currently, about 10,000 tHM are being discharged annually. By 1995, a total of about 170,000 tHM had been discharged; by 2020 the total will have reached nearly 370,000 tHM. After that the total is expected to increase much more slowly. This is because a smaller number of reactors will be operating and the fuel in many of those that are operating will be discharged less frequently because more of the uranium will be 'burnt up'.

Many countries, including all those operating civil nuclear-power reactors to generate electricity, are faced with the problem of disposing of HLW in the form of spent reactor fuel elements and/or as waste fission products from reprocessing plants. Thirty-one countries are currently operating a total of 436 nuclear-power reactors generating a total of about 352,000 megawatts of electricity, about 7 per cent of the electricity generated in the world.

The countries operating nuclear-power rectors are: Argentina, Armenia, Belgium, Brazil, Bulgaria, Canada, China, Czech Republic, Finland, France, Germany, Hungary, India, Japan, Lithuania, Mexico, Netherlands, Pakistan, Romania, Russia, South Africa, South Korea, Slovakia, Slovenia, Spain, Sweden, Switzerland, Taiwan, the United Kingdom, Ukraine, and the United States. Iran is now constructing its first power reactor. The countries with most reactors are the United States (operating 104 power reactors), France (59), Japan (53), United Kingdom (35), Russia (29), Germany (20), Canada (14), South Korea (16), and Ukraine (16).

About one half of the worlds' HLW is produced in countries that currently favour the direct disposal of spent fuel elements rather than reprocessing it. However, reprocessing is going out of favour and consequently the amount of spent fuel directly disposed of is eventually likely to be 75 per cent or more of the total.

The direct disposal of 1 tHM requires roughly 1.5 cubic metres of storage capacity. The direct disposal of the spent fuel accumulated by the years 2020 would require about 550,000 cubic metres of storage capacity, a huge volume of storage space.

Options for HLW disposal

Currently, HLW is stored (normally as spent reactor fuel elements stored in pools of water at reactor sites) either at sites where it is produced, in a centralised store, or at the sites of reprocessing plants. Such surface storage is an acceptable waste management policy but is not a permanent solution to the HLW disposal problem. In the long term, surface storage will prove unfeasible and unsafe. A satisfactory and publicly acceptable method of isolating HLW permanently from the human environment will have to be found.

A number of options for the permanent disposal of HLW have been considered. These include disposal on land, in the oceans and in space. The main options are: disposal in deep geological repositories on land; disposal on the ocean floor (now banned by international agreement); disposal in geological formations under the deep ocean floor (called sub-seabed disposal, now banned by international agreement); disposal in glaciated areas, in Antarctica, for example (this would require modifications of international treaties); using rockets to fire into the sun (the danger of accident, reinforced by the Challenger accident makes this unacceptable); and nuclear transmutation (the conversion of long-lived radioisotopes into shorter-lived or even stable isotopes, the technology for which is unlikely to be available for a long time if at all and prove to be expensive). Of these options, virtually all countries operating nuclear-power reactors believe that the most appropriate one is disposal in deep geological repositories on land.

Permanent disposal of HLW in deep geological repositories on land

The effective disposal of HLW in a geological formation must contain and isolate the HLW from the human environment until its radiotoxicity is reduced to a level that is no longer hazardous to human health. The main threat to isolation is the corrosion of the containers of the HLW. It is, therefore, crucial that the geological formation chosen as the disposal site contain as little water as possible.

In current concepts, the isolation of the HLW is achieved by a series of independent barriers to the movement of radioisotopes out of the waste containers. The main barriers are the geological formation itself and the use of a waste form that is as leach resistant as possible. Currently, the favoured leach-resistant material is borosilicate glass (pyrex). Additional barriers are corrosion-resistant containers in which the HLW is contained and materials placed around the waste containers that retard groundwater and any leaching of the radioisotopes in the HLW, called backfill.

Deep geological repositories on land is argued to be the optimum option for the permanent disposal of HLW because: it requires no further human involvement to ensure its safety; burial at depths of a few (say 3 or 4) kilometres makes human intrusion, intentional or accidental, extremely unlikely; there are a number of geological environments possibly suitable for permanent disposal including rock salt, clays, and granite, basalt and other types of crystalline rock; the technology for deep geological disposal exists.

Plans for a permanent repository for spent nuclear reactor fuel and the HLW arising from reprocessing are most advanced in the USA. A repository is being actively investigated at the Yucca Mountain in Nevada, about 145 kilometres north-west of Las Vegas. The site has been chosen because of its long distance from centres of population, its exceptionally dry climate, its deep water table, and the geochemical and hydrolic properties of its rock.

The US department of Energy has so far spent about $7,000 million assessing the properties of arid terrain for its use as a deep repository, an operation involving more than a thousand experts, including geologists, materials scientists, engineers and computer scientists, who are investigating the site's geology, testing materials for constructing storage containers suitable for burying waste in underground tunnels, and defining the environment that the barrier system will experience over time and the effects of heat on that environment. The size of these resources is indicative of the scale of the problems to solved in finding a suitable way of permanently disposing of HLW.

Yucca mountain consists of tuff (volcanic rock) that is mainly silicon dioxide. Even though it is in a very arid area, about 10 per cent of the volume of the tuff is water. The development of highly corrosion-resistant containers is, therefore, a major requirement for the permanent disposal of HLW in Yucca mountain (or for that matter anywhere else).

The proposal is that HLW is contained in cylindrical containers, between 3 and 6 metres long, each weighing about 50 tonnes. The containers would be placed lengthwise along 50 horizontal tunnels, each about 1 kilometre long.

In December 1998, the US Department of Energy issued a Viability Assessment stating that Yucca Mountain is a promising site for a geological repository, although many uncertainties remain. If the Secretary of Energy recommends the site to the President, adequate resources are made available, and the considerable local and national opposition to the construction of the repository can be the overcome, the first HLW could be placed in a repository in Yucca Mountain by 2010. If it is opened, the decision about when to close and seal the repository will be left to future generations.

France is also actively studying the problems of the permanent disposal of its HLW, which includes spent reactor fuel, and HLW from its reprocess plants and nuclear-weapon programme. In December 1998, the French government announced that an underground laboratory is to be built at the Est clay site at Bure to investigate the possibility of constructing a deep repository there; a search for a site for an underground laboratory in granite is underway. The French plan to make a decision on a site for a deep repository for HLW by 2006. Because of political opposition this deadline is, to say the least, not likely to be met.

Other countries - including Belgium, Canada, Germany, Sweden and Switzerland - have established underground research laboratories in various geological environments to investigate the option of permanent disposal in geological repositories.

Australia has produced no HLW. Australia has LLW arising from uranium mining and the use of radioisotopes in medicine, industry and research. LLW from uranium mining is managed and disposed of near the mine in accordance with a Code of Practice. LLW from medical, industrial and research uses is held in about 50 temporary storage site across the country until a national repository is commissioned. Western Australia has established its own surface disposal facility for LLW.

Pangea's proposal

A proposal to construct an international repository for the disposal of HLW is being pursued by a company called Pangea Resources. Pangea Resources Australia, based in Perth, was created specifically to explore the possibility of creating a global repository in Australia. The companies involved in Pangea are BNFL (UK, 70%), NAGRA (Switzerland), and EHL (Canada), the holding company of Golder Associates. It is planned that it would be a commercial undertaking and would have dedicated port and rail infrastructures. It would take spent fuel and other wastes from commercial reactors, and possibly also material from weapons disposal programs.

At present there is clear and unequivocal understanding that each country is ethically and legally responsible for its own wastes. Therefore, it is argued that all nuclear wastes will be disposed of in each country concerned.

Nevertheless, Pangea argues that: "By taking a fresh look at the reasons for the difficulties which have faced most national repository programs, and discarding the preconception that each country must develop its own disposal facilities, it is possible to define a class of simple, superior high-isolation sites which may provide a multinational basis for solving the nuclear waste disposal problem. The relatively small (sic) volumes of high-level wastes or spent fuel that arise from nuclear power production make shared repositories a feasible proposition. For small countries, the economies of scale that can be achieved make the concept attractive. For all countries, objective consideration of the relative merits of national and multi-national solutions is a prudent part of planning the management of long-lived radioactive wastes."

A major research program by Pangea has identified Australia, southern Africa, Argentina and western China as having the appropriate geological credentials for a deep geologic repository, with Australia being favoured on economic, technological, legal and grounds and because it is a stable democracy. Pangea has identified a large area of outback Australia, focused on the extensive contiguous sedimentary basins extending from central Western Australia into northern South Australia.

The Pangea concept envisages a dedicated port and rail link to an inland repository site covering perhaps 5 sq km on the surface and 20 sq km underground (500 metres down). There would be a fleet of 35 dedicated and purpose-built ships at any one time. Pangea's business plan is based on taking 75,000 tonnes of spent fuel and high-level waste from reprocessing spent fuel, plus some intermediate-level wastes from decommissioning nuclear facilities, over some 40 years.

Spent fuel would be shipped to the facility at a rate of about 2,000 to 3,000 tonnes per year once it was fully operational. This rate is about 20% of the spent fuel generated annually by commercial reactors around the world, or to put it another way, the repository is designed to take 25% of the world's civil waste inventory at the time it opens. The projected size of the repository is thus similar to that proposed at Yucca Mountain, Nevada.

The capital cost is estimated at A$ 10 billion, with some $700 million per year operating cost. The project envisages establishment of a shipyard and foundry for the manufacture of 70 specialised ships and some 3000 large stainless steel transport casks as well as port and fleet maintenance facilities. Direct employment would be about 2000, indirect about 6000 people.

The project is aimed at nuclear waste generated by countries other than the USA, though that country would need to be closely involved because through Non-Proliferation Treaty provisions it controls some 60% of the nuclear fuel worldwide and would have to authorise any international movement of it. Similarly, Australia, as a supplier of uranium, is involved.

The Pangea proposal is quite distinct from the proposed National Radioactive Waste Repository in South Australia for Australia's own low-level wastes. The Western Australian parliament, however, passed a Bill to make it illegal to dispose of foreign high-level waste in the state without specific parliamentary approval.

Responding to Pangea's proposal early in 1999 for a repository in Australia Industry Minister Senator Minchin said that Australia has a long-standing and bipartisan policy of not importing nuclear wastes, adding that he had no immediate intention of considering such a proposal. Nevertheless, Pangea is continuing its geological investigations in Australia while extending its feasibility study to other potential host regions.

Australia is a major supplier of uranium, under international safeguards, to fuel nuclear reactors. With the International Atomic Energy Agency (IAEA), the Australian Safeguards & Non-Proliferation Office tracks "Australian Obligated Nuclear Materials" all the way through to spent fuel, reprocessing (if undertaken), and recycling of plutonium (if separated) in mixed oxide fuels. The question arises: is there a moral obligation on uranium suppliers in respect to the wastes, other than that involved in safeguards procedures?

Pressure has been put on Australia to accept Pangea's proposal. For example, a US Administration official, Robert Gallucci, has appealed to Australia to consider seriously Pangea's proposal for the international disposal of "nuclear waste and plutonium from bombs dismantled at the end of the Cold War. If Australia could appreciate the concept and decide it was in the national interest, there would be enormous benefits for the world." There is also some support in Australia for the proposal. For example, Sir Gustav Nossal, talked of "the opportunity to offer the world an Australian solution to a global problem", giving Australia a "leadership role in solving the problems of nuclear weapons and waste".

Synroc

The synroc process, invented more than 20 years ago by Ted Ringwood of the ANU, mixes radioactive waste constituents with minerals to produce a solid in which the radionuclides are held within the lattice of crystals. Synroc immobilises radioactive waste and is an alternative waste form to borosilicate glass and ceramics.

British Nuclear Fuels Limited is currently examining the technology. The process has not been demonstrated on a commercial scale but the US Department of Energy is interested in applying the process to immobilise military plutonium before it is permanently disposed of.

The Pangea concept can be traced to the Synroc Study Group, consisting of four Australian resource companies, ANSTO and the Research School of Earth Sciences at ANU, set up by the Australian government to study the commercial potential for Synroc.

The Disposal of Plutonium: The Need for a Policy

Three main ways have been proposed to reduce the world's stock piles of plutonium:

- plutonium oxide could be mixed with uranium oxide to produce MOX fuel for nuclear-power reactors;
- the plutonium could be stored indefinitely;
- and the plutonium could be immobilised by incorporating into glass blocks (vitrified) or ceramics and permanently disposed of in deep (4 kilometres or so deep) geological repositories. In the latter case, the plutonium could be mixed with, or surrounded by, HLW to provide a radiological barrier to prevent access to it.

The management of plutonium is a crucial issue, with ramifications for nuclear-weapon proliferation and nuclear terrorism. Plutonium is dangerous for two main reasons: it can be used to manufacture nuclear weapons; and, as described below, it is highly toxic mainly because its atoms decay by emitting alpha particles which are very ionising and particularly harmful to human cells.

Inadequate control of plutonium will frustrate efforts to prevent the spread of nuclear weapons, particularly to countries that do not now have them. It will also make it easier for terrorist groups to acquire some plutonium and use it to construct their own nuclear explosives.

The most common plutonium isotopes, moreover, stay radioactive for extremely long periods of time. Plutonium-239, for example, has a half-life of about 24,000 years. To all intents and purposes, once it is in the environment, it stays there permanently. Because of its radiotoxicity and long half-life the disposal of plutonium presents particularly difficult problems.

The world would, therefore, be a much safer place if the governments of countries with stocks of plutonium would adopt effective policies for reducing, managing and disposing of them.

Global plutonium stocks

Plutonium was first discovered in 1941 and first produced in significant amounts as part of the Manhattan project, set up by the Americans in the Second World War to manufacture nuclear weapons. Since 1945, the world has produced a huge amount of plutonium - a total of about 1,500 tonnes.

About 250 tonnes of this plutonium were produced for use in nuclear weapons. The other 1,250 tonnes are civilian plutonium produced as an inevitable by-product by civilian nuclear-power reactors while they are generating electricity. By 2020 the amount of civil plutonium is likely to increase to about 3,000 tonnes.

China, France, the USA, and the UK have now stopped producing military plutonium. A small amount of military plutonium is still being produced in Russia in three reactors that are also used for domestic heating purposes; they will be shut down when their heating function can be replaced, probably before the end of the 1990s. India and Israel are probably still producing plutonium but in relatively small amounts.

The amount of military plutonium in the USA is about 100 tonnes and the amount in Russia is about 130 tonnes. China, France, and the UK each have less than 10 tonnes of military plutonium. Israel and India have each produced a few hundred kilograms. Whereas the amount of military plutonium in the world is not increasing very much, the amount of civil plutonium is increasing significantly. The world's nuclear-power reactors are producing an additional 75 tonnes of plutonium a year.

About 300 tonnes of civil plutonium have been separated from spent nuclear-power reactor fuel elements in reprocessing plants; if current reprocessing plans go ahead, by the year 2010 there will be about 550 tonnes of separated civil plutonium.

About 80 tonnes of civil plutonium are now in France, about 60 tonnes in the UK, about 50 tonnes in Japan, and about 40 tonnes in each of Germany and Russia. Smaller amount (less than 8 tonnes) are in each of Belgium, India, Italy, the Netherlands, Spain, Switzerland, and the USA.

The nuclear-weapon proliferation issue

There are various grades of plutonium, each with different isotopic compositions depending on the way in which the reactor producing it is operated[2]. Plutonium produced in commercial or civil nuclear-power reactors operated for the most economical production of electricity is called reactor-grade plutonium. Plutonium produced in military plutonium production reactors, specifically for use in nuclear weapons, is called weapons-grade plutonium.

Some recent official statements imply that plutonium produced in nuclear-power reactors - and therefore that which could be obtained from MOX - cannot be used in nuclear weapons or nuclear explosive devices. For example, Ryukichi Imai, former Japanese Ambassador for Non-Proliferation, stated that:

> *"Reactor-grade plutonium is of a nature quite different from what goes into the making of weapons... Whatever the details of this plutonium, it is quite unfit to make a bomb."*

This statement is incorrect, as Robert Seldon of Lawrence Livermore Laboratory explains:

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[2] The production of plutonium Nuclear reactors are fuelled with uranium. Uranium has two important isotopes - uranium-235 and uranium-238. Uranium-235 is a fissile isotope. When a nucleus of an atom of a fissile isotope captures a neutron travelling at any speed, fast or slow, it undergoes fission. When fission occurs, the fissioned nucleus splits into two nuclei - called fission products. During this process, two or three neutrons are also emitted. If one of these neutrons is captured by the nucleus of an atom of uranium-238 it will only cause fission if it is travelling at a very high speed. If it does not have this speed, a nucleus of the radioactive isotope neptunium-239 will be produced which will decay into plutonium-239, another fissile isotope. Therefore, as the uranium fuel is used up in the reactor an increasing amount of plutonium-239 is inevitably produced.

But plutonium-239 can also capture neutrons to become plutonium-240, which in turn can capture neutrons to become plutonium-241, and so on. Consequently, as time goes on a mixture of plutonium isotopes is produced. There are various grades of plutonium, having different isotopic compositions, according to the way in which the plutonium is produced. Plutonium produced in commercial nuclear-power reactors operated for the most economical production of electricity is called reactor-grade plutonium. Plutonium produced in military plutonium-production reactors, specifically for use in nuclear weapons, is called weapons-grade plutonium.

> *"All plutonium can be used directly in nuclear explosives. The concept of... plutonium which is not suitable for explosives is fallacious. A high content of the plutonium 240 isotope (reactor-grade plutonium) is a complication, but not a preventative."*

And at a conference in Vienna in June 1997, Matthew Bunn, who chaired the US National Academy of Sciences analysis of options for the disposal of plutonium removed from nuclear weapons, made a crucially important statement based on recently declassified material "of unprecedented detail on this subject":

> *"For an unsophisticated proliferator, making a crude bomb with a reliable, assured yield of a kiloton or more -- and hence a destructive radius about one-third to one-half that of the Hiroshima bomb -- from reactor-grade plutonium would require no more sophistication than making a bomb from weapon-grade plutonium. And major weapon states like the United States and Russia could, if they chose to do so, make bombs with reactor-grade plutonium with yield, weight, and reliability characteristics similar to those made from weapon-grade plutonium. That they have not chosen to do so in the past has to do with convenience and a desire to avoid radiation doses to workers and military personnel, not the difficulty of accomplishing the job. Indeed, one Russian weapon-designer who has focused on this issue in detail criticized the information declassified by the US Department of Energy for failing to point out that in some respects if would actually be easier for an unsophisticated proliferator to make a bomb from reactor-grade plutonium (as no neutron generator would be required)."*

That reactor-grade plutonium can be used to fabricate nuclear weapons was proved by the British who exploded such a device in Australia in 1956 and by the Americans who exploded at least one such device in the 1960s.

The toxicity of plutonium

The radiological hazard of plutonium arises mainly from the ionising radiation delivered to various internal organs of the body when plutonium is ingested or inhaled into the body. Plutonium delivers a negligible external radiation dose to the skin because it emits mainly alpha particles, which do not generally have sufficient energy to penetrate the skin.

Generally speaking, for the intake of a given amount of plutonium, that which is inhaled is much more hazardous than that which is ingested. Plutonium is more easily absorbed into the blood stream through the lungs than through the gastrointestinal (GI) tract. Inhaled plutonium will irradiate the lung; ingested plutonium will irradiate the walls of the GI tract. Ingested and inhaled plutonium may migrate via the blood stream to concentrate selectively in the liver and bones.

The health effects of plutonium may be short-term (acute) or long-term (chronic). Inhalation, for example, may lead to acute pulmonary oedema. Long-term effects include an increased risk of cancer. Inhalation of plutonium will expose the lung tissue to irradiation by alpha particles, increasing the risk of lung cancer. Some plutonium may eventually be carried from the lung to other organs (mainly the liver and the skeleton) where the radiation will increase the risk of cancer at these new sites.

The best estimates made by the International Committee for Radiological Protection of the fatal cancer risks arising from the inhalation and ingestion of plutonium suggest that reactor-grade (i.e., civil) plutonium is much more toxic that weapons-grade (i.e., military) plutonium. For weapons-grade plutonium, the inhalation of about 430 micrograms will have a very high probability of causing a fatal cancer and the ingestion of about 30 milligrams will have a very high probability of causing a fatal cancer. For typical reactor-grade plutonium, the inhalation of about 60 micrograms will have a very high probability of causing a fatal cancer and the ingestion of about 3 milligrams of will have a very high probability of causing a fatal cancer.

These figures suggest that if the individuals in a population inhale a total of a gram of typical reactor-grade plutonium, there will be about 20,000 extra deaths in the population. The ingestion of a gram of this type of plutonium would result in nearly 400 extra deaths from cancer.

To put these figures into perspective, a spherical piece of plutonium oxide containing 1 gram of plutonium has a diameter of 5.5 millimetres (0.22 inch). The increased risk of cancer mortality from the inhalation and ingestion of plutonium isotopes is a long-term health effect - the cancers may take some years (up to 25 or so) to appear.

Acute effects are possible after the inhalation or ingestion of larger amounts of plutonium. Evidence for these effects is mainly based on experiments with beagle dogs. These suggest that the inhalation of a total of between 10 and 20 milligrams of reactor-grade plutonium may cause death in humans from acute respiratory failure within a week and the inhalation of 2 to 4 milligrams of this reactor-grade plutonium may cause death within about a month from pulmonary fibrosis or pulmonary oedema.

Mixed-oxide nuclear fuel

The reason given for producing MOX is to dispose of the embarrassing surplus of plutonium produced by reprocessing plants. This situation is, of course, idiotic because the use of MOX as fuel in reactors produces more plutonium***.

The production of MOX is illogical. And there are a number of important arguments against using MOX:

- the cost of MOX fuel is much higher than that of normal uranium-oxide fuel;
- technical considerations may make reactors fuelled by MOX less safe;
- the need to protect MOX fuel elements kept at nuclear reactors will involve reactor operators in new physical security problems;
- the use of MOX increases the risk of serious accidents during its transportation;
- international safeguards designed to prevent nuclear proliferation are difficult to enforce at facilities associated with MOX;
- the use of MOX will increase rather than reduce the stock of plutonium[3];

[3] The following figures explain why the MOX route would increase stocks of plutonium. A typical MOX fuel assembly - about 289 fuel rods arranged geometrically - contains about 435 kilogrammes of uranium and 25 kilogrammes of plutonium. The MOX fuel remains in the reactor for three years. The spent MOX fuel assembly contains about 19 kilogrammes of plutonium. There are 48 MOX assemblies in, for example, a typical pressurized water reactor (PWR) generating 900

- and the use of MOX increases the risk of nuclear-weapon proliferation by countries and, perhaps more seriously, by terrorist organisations.

The use of MOX in a nuclear-power reactor cannot, therefore, be said to be a solution to the problem of excess plutonium stocks, at least for the foreseeable future. A more rational solution would be to stop reprocessing of spent nuclear fuel rods to separate out the plutonium in the first place and to store existing stocks of plutonium as safely as possible until they can be permanently disposed of. Many argue, however, that the storage and disposal of plutonium cannot be made safe.

It should be emphasized that 75 or 80 per cent of the plutonium still contained in spent civilian reactor fuel elements will have to be disposed of without reprocessing the elements. Only about 20 per cent of the plutonium contained in the 180,000 tonnes of spent fuel rods discharged by civilian reactors has been separated in reprocessing plants, and, according to global plans for civil reprocessing, this percentage is unlikely to increase significantly in the foreseeable future.

If governments are serious about their commitment to reduce the risk of nuclear-weapon proliferation and nuclear terrorism, they should stop separating plutonium from spent reactor fuel elements by closing their reprocessing plants, stop producing MOX nuclear fuel and dispose permanently of existing plutonium stocks.

Conclusions

The bulk of radioactive waste that exists now and that will be produced in the future arises from military and civil nuclear programmes. Much ILW and all HLW must be disposed of in a way that permanently isolates it from the human environment. This problem has not yet been solved.

And many believe that the problem of the permanent disposal of HLW in a way acceptable to the public is insoluble and is likely to remain so for at least the foreseeable future, particularly because of the need to isolate the wastes for a period of many hundreds of thousands of years.

The international community is faced with the problem because it was decided to develop and maintain nuclear-weapon programmes without any thought being given to the problems raised by the production of large amounts of highly radioactive waste. Years went by before the problems were seriously considered. By then large amounts of highly radioactive waste had been produced.

The reprocessing of spent nuclear fuel to separate the plutonium from it produces large amount of liquid HLW, exacerbating the problem of disposal. The only rational use for

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megawatts of electricity - three refuellings of 16 assemblies. A 900-megawatt PWR will, therefore, dispose of about 96 kilograms of plutonium per year, [(25 - 19) times 16 kilograms per year] or about 1 tonne of plutonium per decade.

Meanwhile, the non-MOX fuel assemblies in the remaining 70 per cent of the reactor core will produce plutonium as the uranium oxide fuel is burnt up. Overall, the typical ratio of plutonium "out" to plutonium "in" would be about 1.17 for a 900-megawatt PWR using MOX and uranium fuel assemblies and containing 5.2 per cent of plutonium in 30 per cent of the core. Thus if current plans for reprocessing and for MOX use are enacted, the world's stock of plutonium will grow. Plutonium stocks could decrease only if MOX fuel were used in a very much larger proportion of the reactor cores. Yet this is not possible for reactor safety reasons.

plutonium is to produce nuclear weapons. It is, therefore, argued that all reprocessing plants should be closed and existing stocks of separated plutonium should be immobilised and permanently disposed of. Nevertheless, because of existing stocks the problem of disposing of HLW and ILW will not be avoided if nuclear power and reprocessing are abandoned.

The policy of the governments of many of the 32 countries faced with the problem of disposing of HLW is to eventually dispose of it in deep underground repositories. That deep disposal is the best option is also the view of the international agencies, such as the International Atomic Energy Agency, dealing with nuclear waste.

However, no country is at present permanently disposing of HLW. Nor is one likely to for the next two or three decades.

Existing storage arrangements are usually said to have a limited life. However, some argue that HLW and ILW should be kept in surface stores for as long as possible and that, when they are eventually permanently disposed of, any deep repository should not be sealed so that the waste can be retrieved if more satisfactory methods of disposal are developed in the future.

There is no precedent for the problem of disposing of highly radioactive waste. No publicly and politically acceptable solution that protects the human environment and future generations is in sight. Such is the legacy of the nuclear age.