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NUCLEAR POWER IN PERSPECTIVE*

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This paper contains the text of a public lecture given in the series "Energy and Australia" at the Australian National University on April 2, 1980. An abbreviated version was given at the 50th ANZAAS Congress in Adelaide on May 14, 1980.

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PROFESSOR RINGWOOD was born in Melbourne in 1930 and attended Melbourne University where he took a Ph.D. in geochemistry in 1956. After a period as research fellow at Harvard, he joined the Australian National University in 1958 and is now Director of the Research School of Earth Sciences at that University.

He was elected to the Australian Academy of Science in 1966 and was Vice-President in 1971-72. He has also been elected Fellow of the Royal Society; Foreign Associate of the National Academy of Sciences, U.S.A.; Fellow of the American Geophysical Union; Commonwealth and Foreign Member of the Geological Society of London, and Honorary Member of the All-Union Mineralogical Society, U.S.S.R.

Among his many honours are the Matthew Flinders Lecture and Medal, Australian Academy of Science; the Bowie Medal, American Geophysical Union; the Brittanica Australia Award for Science; the Arthur L. Day Medal, Geological Society of America; the Rosenstiel Award, Am. Assoc. Adv. Science; the William Smith Lecture, Geological Society of London; the Werner Medaille, German Mineralogical Society; the Vernadsky Lecture, U.S.S.R. Academy of Sciences; Centenary Lecturer and Medallist, Chemical Society of London; the Mueller Medal, Aust. N.Z. Assoc. for Advancement of Science; and the Mineralogical Society of America Award.

His researches have been described in 250 scientific papers dealing mainly with the composition and structure of the earth's interior, phase transformations at high pressures and temperatures, geochemistry and petrology, origin of the earth, moon and planets, and internal structure and composition of the moon. He is also the author of two books, *Composition and Petrology of the Earth's Mantle* (McGraw Hill, 630 pages, 1975) and *Origin of the Earth and Moon* (Springer-Verlag, 295 pages, 1979). During the last 3 years he has applied his geochemical background to the problems of immobilization of nuclear reactor wastes and has been responsible for the development of an advanced waste form, 'SYNROC'.

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ABSTRACT

The nuclear power debate hinges upon three major issues: radioactive waste disposal, reactor safety and proliferation. It is shown that the waste-disposal problem can be solved by optimising both the nature of the waste form itself (immobilization barrier) and by careful selection of a disposal site well-removed from the biosphere. A titanate ceramic waste form, SYNROC, has recently been developed at the Australian National University and has proven to be vastly superior to the borosilicate glass waste forms currently favoured by the nuclear power industry. SYNROC possesses the capacity to accept radioactive waste elements into the crystal lattices of its constituent minerals, thereby immobilizing them. Close structural analogues of SYNROC minerals occur in nature and nave survived for periods up to 2000 million years in geological conditions far more extreme than would be encountered in any radwaste repository. Moreover, individual SYNROC minerals occurring in nature have suffered far more intense radiation damage than any waste form would receive, without experiencing any significant losses of radioactive elements. The SYNROC strategy is thus based directly upon the way in which nature successfully immobilizes radioactive elements on a far larger scale and for much longer periods than will ever be required by the nuclear industry. As such, it provides a readily comprehensible and proven means of radwaste immobilization.

A further independent and redundant barrier preventing radwastes from re-entering the biosphere is provided by the geological setting of the repository. Current plans in many countries favour a large, centralized, mined repository at depths of 500-700 metres, which would accept all wastes from a national nuclear

program over a period of several decades. However, local and state governments in several countries have been understandably reluctant to accept the responsibility of providing a unique site for a national repository. Hence an impasse has arisen which threatens the future of the nuclear industry. An alternative strategy is advocated which involves disposing of the radwaste (immobilized in SYNROC) in deep (4 km) drill-holes widely dispersed throughout the entire country. It is demonstrated that this strategy possesses major technical (safety) advantages over centralized, mined repositories and is more likely to be acceptable to the population at large.

The generation of large quantities of electrical power necessarily involves risks and causes injuries and fatalities. These must be accepted if society wishes to continue its present lifestyle. The comparative risks associated with coal-fired power generation and with the nuclear fuel cycle have been evaluated by many scientists, who conclude that nuclear power is far less hazardous. However, there is no room for complacency. Considerable improvements in reactor design and safety are readily attainable. The nuclear industry should be obliged to meet these higher standards.

The very real threat of proliferation is difficult to combat, although modifications to the nuclear fuel cycle could make it extremely difficult for individual terrorist organisations to obtain access to fissile material. However, there are no obvious technical measures which can prevent a determined small country endowed with modest technology from producing nuclear weapons. These can be produced whether or not the country possesses reactors designed for power production. The most hopeful means of limiting proliferation lies in international agreements, possibly combined with international monitoring and control of key segments of the fuel cycle, such as reprocessing.

A moratorium on the mining and export of Australian uranium is not justified on the basis of a realistic assessment of the issues of radwaste disposal and reactor safety. Moreover, such a policy would be quite ineffectual in view of the current uranium oversupply situation and recent large discoveries of uranium ore in other countries. However, Australia could give the world a lead in the area of anti-proliferation. It is suggested that Australia should establish an enrichment plant and proceed with the manufacture of fuel rods which would be leased to foreign countries. After use, the rods would be returned here for reprocessing and the wastes (derived from Australian uranium) disposed of in this country using a demonstrably safe technology. This would eliminate the possibility that Australian uranium might be used by foreign countries to produce nuclear weapons and would also result in the establishment of major new industries of immense economic benefit to the nation.

1. INTRODUCTION

There are few issues that have caused as much polarisation of society in recent years as the nuclear power debate. This debate has become highly emotional and even irrational. There are several factors involved, of which fear is certainly one. The connection between radiation and cancer strikes a chord in all of us. The fact that nuclear energy was initially exploited in the form of an atomic bomb has left us with the ever-lasting and dreaded threat of nuclear war. There is also an idealogical element manifested by several groups who wish to change the values of society and return to simpler lifestyles involving lower energy consumption. These groups tend to see nuclear power as a symbol of virtually everything that they oppose.

Although these controversies are unlikely to disappear in the short term, I am nevertheless optimistic in the long term. I think that there are many people in the middle of the opinion spectrum who are genuinely and rightly concerned about the problems of nuclear power but are essentially reasonable and responsive if the major issues are fairly presented. I believe that it will be these people who will ultimately decide the outcome of the debate.

In most countries, the principal areas of concern are:

(i) the disposal of high level radioactive wastes produced by nuclear reactors;

(ii) the safety of nuclear reactors;

(iii) the proliferation of fissile material from which nuclear weapons could be made.

I shall consider these issues in sequence and comment on their relevance to the Australian scene.

2. THE DISPOSAL OF HIGH LEVEL NUCLEAR WASTES

Let us first consider nuclear waste disposal, with which I have had direct professional involvement. The fission of uranium in nuclear reactors produces a wide range of highly radioactive by-products, particularly cesium 137, strontium 90, and the actinide elements, including plutonium, curium, and americium. These radioactive elements must be isolated from the biosphere for extremely long periods, perhaps up to a million years. This is a very long period in relation to human experience and it is largely because of this extended timescale that there is widespread concern and controversy as to whether isolation can be accomplished safely.

It is generally agreed that, ultimately, nuclear wastes are to be buried deep within the earth. One would expect that the sciences likely to be most concerned with nuclear waste disposal are those of geology and geochemistry, that is, the earth sciences. But, somewhat ironically, most of the individuals who are making very confident statements on either side of the controversy rarely have much background in these relevant sciences. The nuclear power establishment is very largely controlled by nuclear physicists and engineers, and one has to say that the record of their proposals for waste management over the last two and a half decades has been singularly unimpressive. On the other hand, a large proportion of those who are objecting to nuclear power because of the waste disposal problem also lack the expertise to justify many of the statements which they have made. Ill-informed debate of this nature has inevitably led to confusion, much of which has been unnecessary.

My own professional career has been that of a geochemist involved essentially in pure research, studying problems relating to the origin of the earth and the moon, and to the structure and mineralogy of the earth's interior. About three years ago, I cameto realise that much of this previous experience was directly applicable to the problem of high level nuclear waste disposal. Accordingly, I redirected both my own research interests and those of a group of colleagues towards the problem. This has turned out to be a very exciting and satisfying exercise. We have seen a very direct and rapid transfer of knowledge obtained by pure research over two and a half decades to a problem of very considerable practical importance. It is fair to say that we would not have progressed so far, so quickly, on this practical problem without this specific background in pure research.

Let us examine the background to the problem. What we need is a method of waste disposal which, first of all, will satisfy the scientific experts in the relevant fields, and secondly, which will be explicable and readily understandable by laymen. Many scientists working in the field tend to ignore this latter factor. They do not seem to realise that, in the long run, the critical decisions about the use of nuclear power will be made not by experts but by the laymen who constitute the majority of society. The fact that the experts in the various nuclear science establishments have not come to terms with this reality contributes quite measurably to the chaotic situation that we have today.

<u>Waste-disposal barriers</u>

There are two principal strategies involved in safe disposal of high level wastes. Each of these strategies should ideally provide an independent and redundant barrier preventing the entry of radioactive elements into the biosphere. The first is to immobilize the wastes in a highly stable and insoluble form which will not leak or corrode when it is placed in the earth and subjected to the action of groundwaters over a very long period, such as a million years. Thus, we regard the waste-form itself as the primary immobilization barrier. The second strategy is to bury this waste-form in a carefully chosen geological environment which would greatly impede the access of groundwater to the waste and also the subsequent migration towards the surface of any groundwater that had obtained access to the waste. We will call this the geological barrier.

The most popular immobilization barrier that has been advocated by the nuclear power establishment over the last couple of decades has been to incorporate "radwaste" in borosilicate glasses, and then to bury this glass in appropriate geological repositories. The problem with this solution, as all geochemists know, is that borosilicate glasses readily disintegrate if they are placed in the earth and come into contact with groundwaters at quite modest pressures and temperatures (Fig. 1). Indeed, it is very difficult to find a geological environment where one can positively guarantee that groundwater will not gain access to the waste. I made this point in a booklet published two years ago (Ringwood, 1978) and it has been pleasing to see that the same conclusion has since been reached independently by the United States Nuclear Regulatory Commission and the US National Academy of Sciences (NRC-1979). On the other hand, because of the enormous investment they have put into its development, the European nuclear authorities still seem rather reluctant to acknowledge the inadequacies of glass as an immobilization barrier.

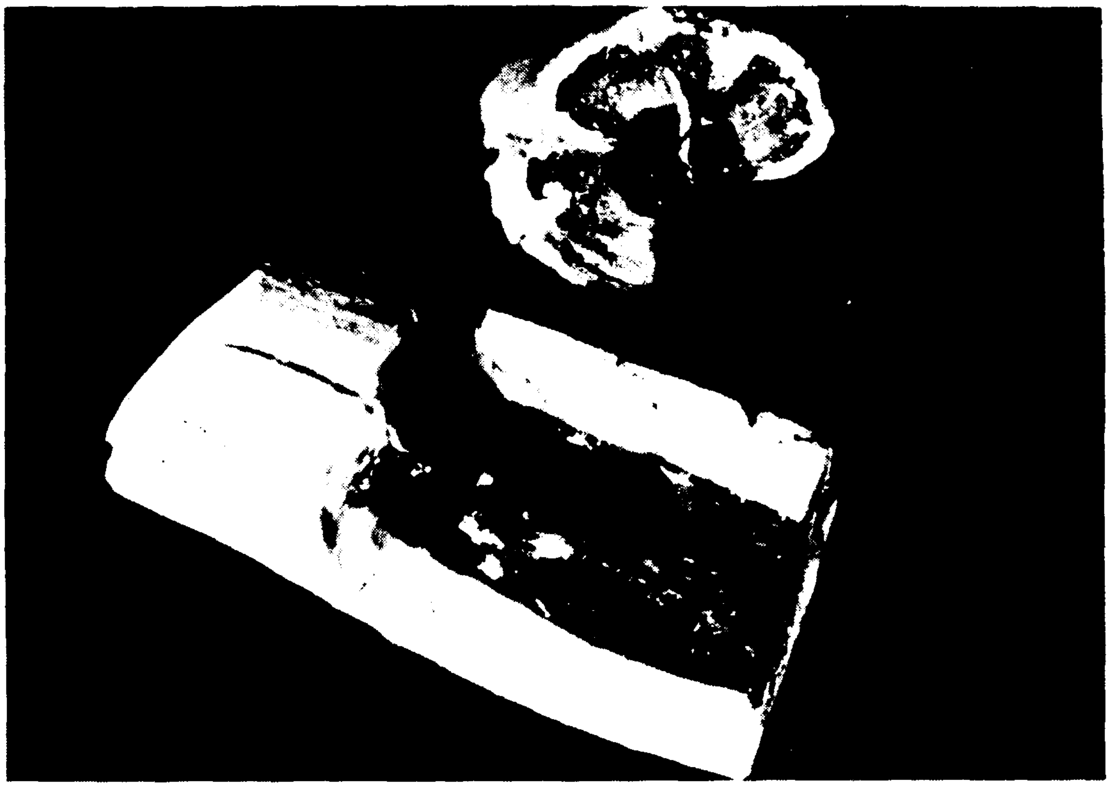


Fig. 1. (a) Cross section and longitudinal view of a 2mm diameter cylinder of borosilicate glass after leaching for 17 hours in 10 wt.% NaCl solution at 400°C and 300 bars. The dark, glassy core, although apparently unaltered, has become embrittled due to hydration. This core is mantled by a soft, crumbling layer of devitrified material, with pronounced fractures. The glass had previously been doped with 1 wt.% each of caesium and uranium. Microprobe analyses of the altered shell showed losses of 50-90% of the original caesium in different regions and 30-90% of uranium as compared to the unaltered glass.

(b) Reflected-light photograph of polished cross-section of the same sample of borosilicate glass. Unaltered core is visible lower centre (note that a fracture originating in the altered zone also penetrates the core). The altered shell displays a variety of textural features indicative of several diverse devitrification and recrystallization mechanisms. Strong fracturing is obvious in the inner regions, and exfoliation of thin outermost layers has also occurred. Field of view is approximately 2mm across.

The SYNROC strategy

During the last three years, my colleagues and I at the ANU have developed a geochemical approach to radwaste immobilization. The process involves incorporation of the radwaste elements in the crystal lattices of the minerals of a synthetic rock which we call SYNROC. Our experiments have shown that SYNROC possesses an extreme degree of stability and leach-resistance compared to glass (Ringwood et al., 1979a,b). Because of its crystallinity, it cannot decompose in the way that glasses do. SYNROC is composed of a particular mixture of titanium, aluminium, zirconium, calcium, and barium oxides (Table 1). When this mixture is heated to 1200 or 1300 degrees centigrade, it recrystallizes to form a mechanically strong rock. It is very much analogous to a natural rock like granite which consists of three common minerals: feldspar, quartz, and mica. However, for our purpose, we produce a synthetic rock consisting of three very rare minerals: hollandite, perovskite and zirconolite (Fig. 2). We have shown that these titanate minerals have a truly exceptional capacity to withstand corrosion under geological conditions. Moreover, we have demonstrated that these particular titanate minerals have the capacity to accept virtually all the elements which occur in nuclear waste into stable sites in their crystal lattices (Ringwood et al., 1979a,b). It is because of this particular characteristic that the radionuclides become very tightly bound and thereby immobilized.

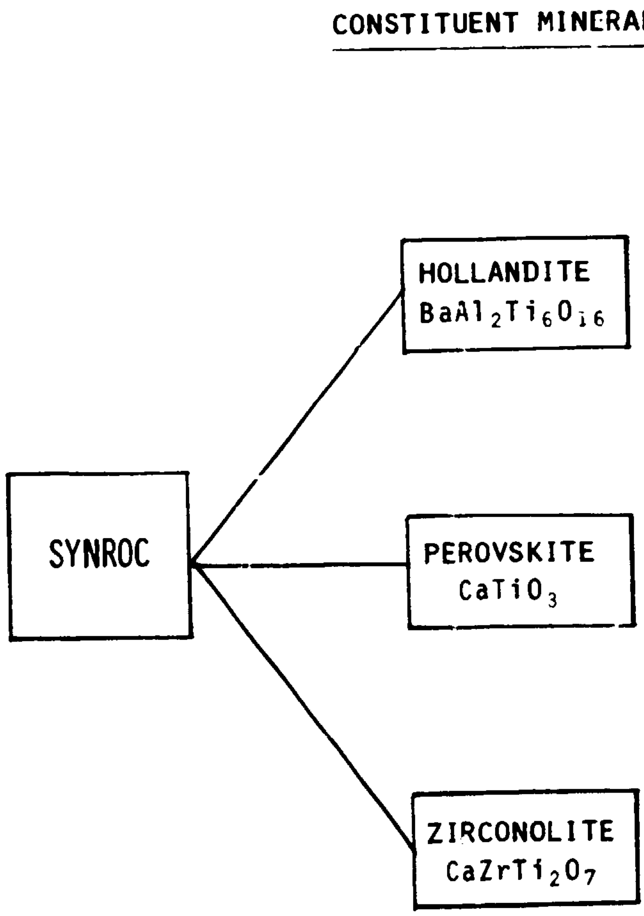
Although the chemical composition of SYNROC does not resemble that of any naturally-occurring rock, the three minerals of SYNROC are found separately and rarely in certain natural igneous rocks which range up to two thousand million years in age. These three minerals have survived in geological and geochemical

Table 1. Composition of SYNROC *

wt%	Bulk	Hollandite 40	Zirconolite 35	Perovskite 25
TiO_2	59.5	70.0	48.5	58.1
ZrO_2	11.4	-	32.1	0.5
Al_2O_3	6.0	12.0	3.3	0.3
BaO	7.0	18.0	-	-
CaO	15.9	-	16.1	41.1

* 90wt.% of SYNROC can readily accommodate 10wt.% of calcined high-level radioactive waste.

Figure 2. Mineralogy of SYNROC



environments where the pressures, temperatures, and leaching conditions have been far more severe than are ever likely to be encountered in a geological repository. It is these characteristics which strongly suggest to us that they possess the long-term stability required for radwaste immobilization. Moreover, some of these ancient natural minerals actually contain substantial amounts of uranium and therefore we can examine the effects of radiation damage upon them. We have demonstrated that these minerals have experienced over 10 times more intense radiation damage than they would receive in SYNROC containing 10% of radwaste and aged for a safe period ($\sim 10^6$ years), without <u>any</u> appreciable leakage of radioactive elements (Ringwood et al., 1980).

Thus, it is nature which provides the key evidence that, despite very intense radiation damage, these particular SYNROC minerals possess the ability to immobilize the long-lived actinide elements for enormous periods. A key factor to remember is that the SYNROC process is based on a detailed geochemical understanding of how nature immobilizes dangerous radioactive elements on a vastly greater scale than is ever contemplated by the nuclear industry. Moreover, nature demonstrates that it is possible to immobilize high concentrations of radioactive elements for periods up to a thousand times longer than are needed for the decay of radwaste to safe levels. It is for these reasons, reinforced by experimental studies on leaching of these materials at very high pressures and temperatures, that we are confident that SYNROC has the capacity to lock up radwaste for the required period and prevent its entry into the biosphere.

When one considers that SYNROC as an immobilization barrier would also be backed up by an independent geological barrier (discussed below). I believe that we have every reason to conclude that the radioactive waste disposal problem can be solved. Moreover, not only is it a solution that is likely to be acceptable to experts, it is the kind of solution which is likely to be readily understandable by laymen. There are now at least six major United States laboratories which have research programs on SYNROC and there is also a major programme underway at the Australian Atomic Energy Commission. There is now a definite policy in the United States to develop alternative waste forms to glass, and more effort is currently going into research on SYNROC than into any of the other six or seven alternative waste forms which are under consideration.

Drill-hole disposal

Having created a waste form of high integrity the next step is to complement it with an independent and redundant barrier, the geological barrier. The solution envisaged in virtually all countries is to deposit the waste in a mined repository. This would consist of a central vertical shaft excavated for perhaps 500 to 700 metres in a favourable geological environment. Ideally, this would be chosen so that the time-scale for migration to the biosphere of radionuclides dissolved from the waste, would be long compared to the time required for decay of these radioactive elements to safe levels. At the bottom of the shaft would be a series of horizontal drives, and, in these, short vertical holes in which the waste would be emplaced (Fig. 3). After radwaste had been emplaced, the holes and drives would be back-filled. It is planned that repositories of this type would be very large structures, capable of receiving all of the waste of a country the size of the United States for several decades.

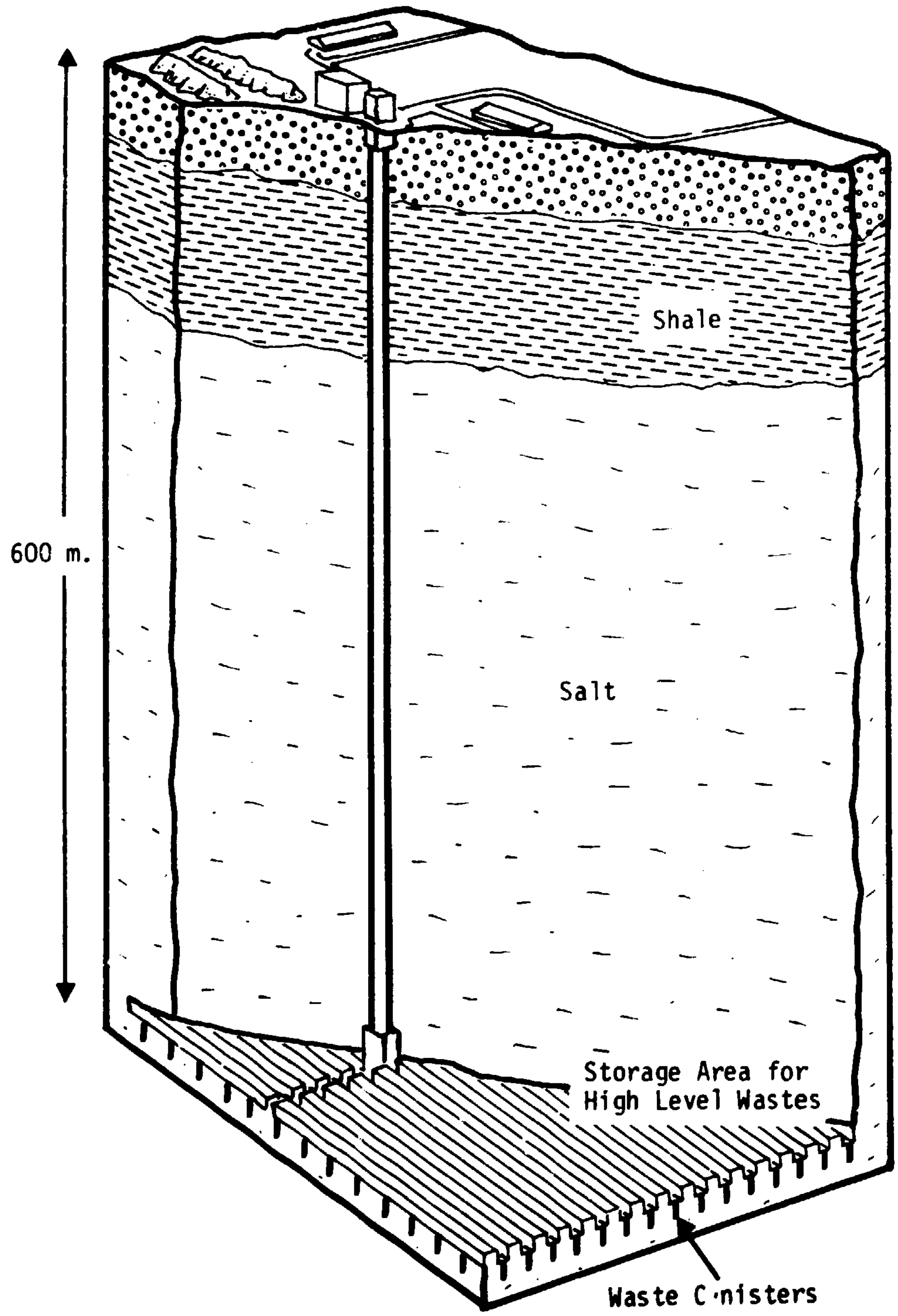


Fig. 3. Design for large mined repository in salt (after Cohen, 1977).

Despite the widespread official acceptance of this concept, it has encountered tremendous public resistance, particularly in the United States and Germany (and increasingly in England and France). This resistance is creating an impasse for nuclear power. The first major problem concerns the issue of perceived safety. The safety analysis of a mined repository is a very complicated technical problem, and although the scientists and technologists may convince themselves that they can design a repository which is safe, it is difficult, because of the complexity of the issue, to convince a layman. My own view is that it should be possible to design a mined repository possessing an acceptable degree of safety. But I despair of being able to explain in any simple terms to the general public why they should accept that such a disposal strategy is really safe.

The second problem relates to the size of the repository and the implicit centralization policy. Because we are dealing with a repository which will be operated for perhaps 40 or 50 years and which will eventually contain a tremendous amount of lethal material, it is obvious that the consequences of repository failure would be very serious. Understandably, local communities are very reluctant to be chosen for the dubious honour of providing the nuclear garbage tip for the remainder of the country. As experience in Germany and the USA shows, no individual county, state or province is likely to be willing to provide the site for a very large mined repository serving the entire country. Partly because of this human and political problem, and partly because of technical considerations, I prefer an alternative strategy - the disposal of waste in widely dispersed deep drill holes (Ringwood, 1980).

The technology to drill very deep holes - as deep as four kilometres or more, with diameters of one to three metres - has recently become available. A series of deep single holes of this particular type offers very considerable possibilities for nuclear waste disposal. I would propose initially immobilizing waste in SYNROC, then depositing the SYNROC cylinders in the bottom 2.5 kilometres of such a hole, and finally sealing the upper 1500 metres. One single hole of these dimensions is capable of accepting the waste from a hundred very large nuclear power stations operating for a year. This is clearly a very considerable capacity. The cost of drilling such a hole amounts to about 0.1% of the cost of the electrical power that would be produced.

I propose to bury the SYNROC encapsulated in metal canisters, and to surround the canisters with magnesium oxide, as shown in Figure 4. The rationale is that any water gaining access to the hole would react with the powdered magnesium oxide to produce magnesium hydroxide, thereby causing an expansion in volume by a factor of two and producing a self-sealing effect. All pore space is thereby closed up and the expansion of the magnesium hydroxide prevents any further access of water. In addition, magnesium hydroxide (which is the natural mineral brucite) is very ductile and would seal any cracks in the wall of the drill hole. If per chance an earthquake subsequently caused a fault to transect the drill hole, it would be sealed off by the brucite.

There are major technical and socio-political advantages in this policy of deep drill-hole disposal. The most obvious benefit is that with a single 4 km drill hole, the waste is deposited much further from the biosphere than in the case of a mined

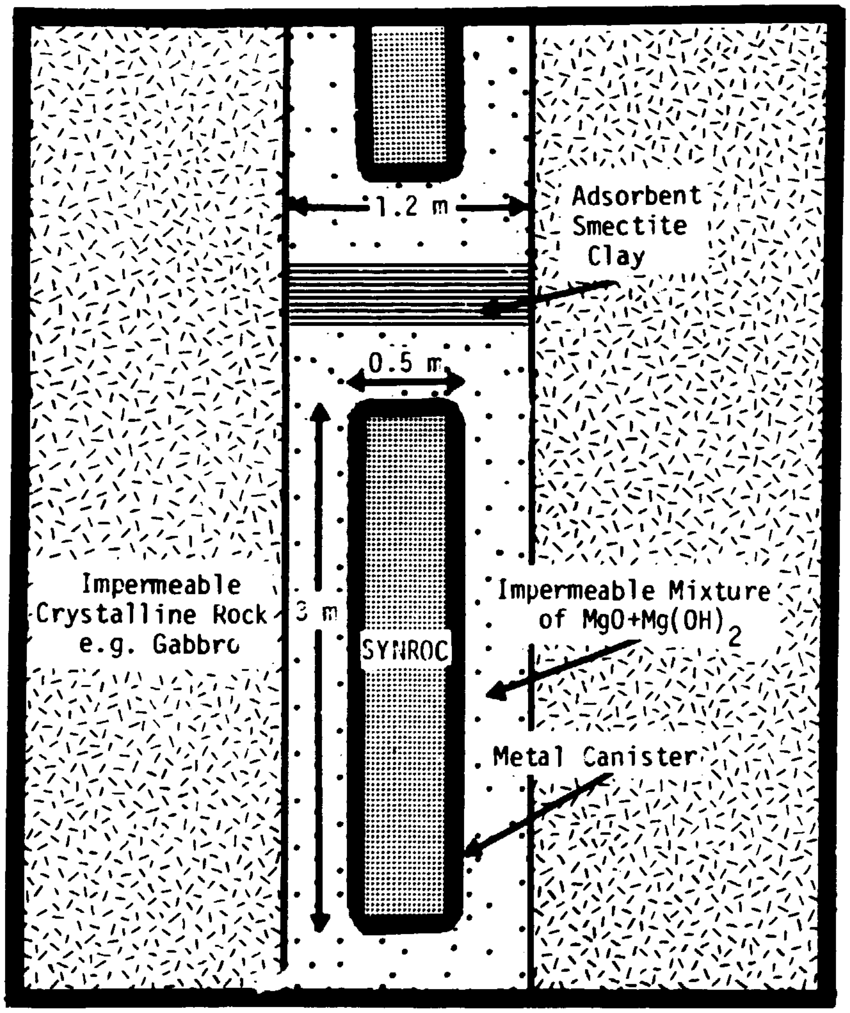


Fig. 4. Disposal of high-level waste (immobilized in SYNROC) within a hole drilled in impermeable crystalline rock eg. gabbro. Canisters are mechanically supported and fully sealed within the hole by an impermeable, pore-free mantle consisting of a mixture of periclase (MgO) and brucite ($Mg(OH)_2$). Each unit is separated by a further barrier consisting of impermeable and adsorbent clay.

repository (typically 500-700 metres deep - Fig. 5). In simple terms, the further away from the biosphere the waste is deposited, the safer it is and the longer it would take for diffusion and transport by circulating groundwaters to return radionuclides to the biosphere.

There is another important factor. The permeability of rock systems, particularly crystalline rocks, decreases drastically with increasing depth. There are areas in the Canadian shield where crystalline rocks are virtually dry at depths below one kilometre. This implies that by disposing of waste at depths below 1500 metres in carefully-chosen crystalline rocks, there is a high probability that environments can be found where there is little or no groundwater, and where the permeability of the rocks is so low that the timescales for any upward diffusion of groundwater to the biosphere are extremely long compared to the decay rate of the waste. On the other hand, with a mined repository at a depth of about 600 metres, the problem is of a different order (Fig. 5). At this depth, permeability is usually high and groundwater abundantly present. In most areas, even in salt mines, the access and circulation of groundwater causes problems.

There is yet another technical disadvantage with a mined repository. The deposition of such a large amount of waste in a planar configuration within a relatively small area causes a serious thermal problem. The waste generates a considerable amount of heat and this in turn causes thermal stresses in the rocks which may lead to cracking. Fracturing in the rock system may allow the return of groundwater to the biosphere. Much of the research currently directed into mined repositories concerns

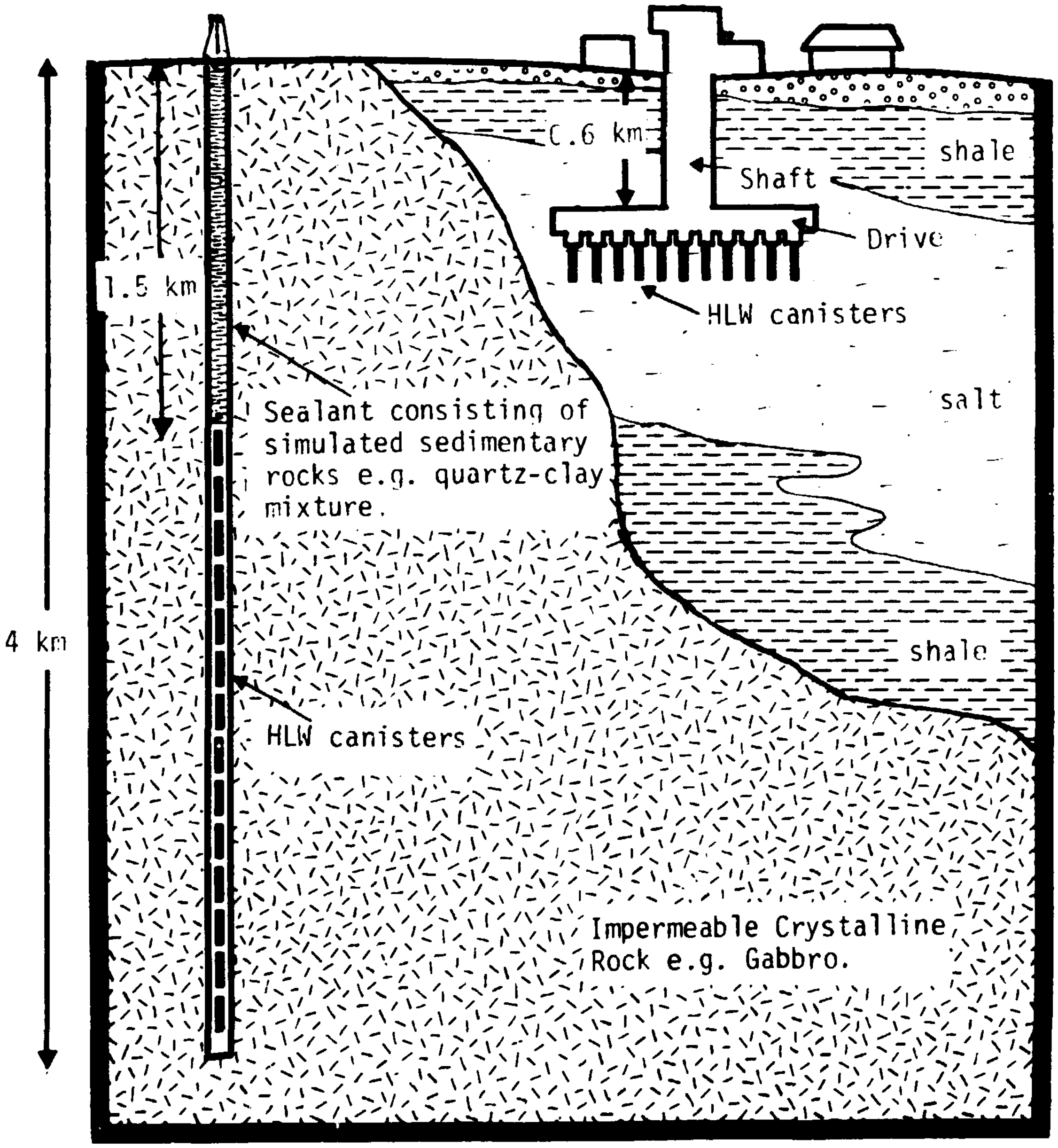


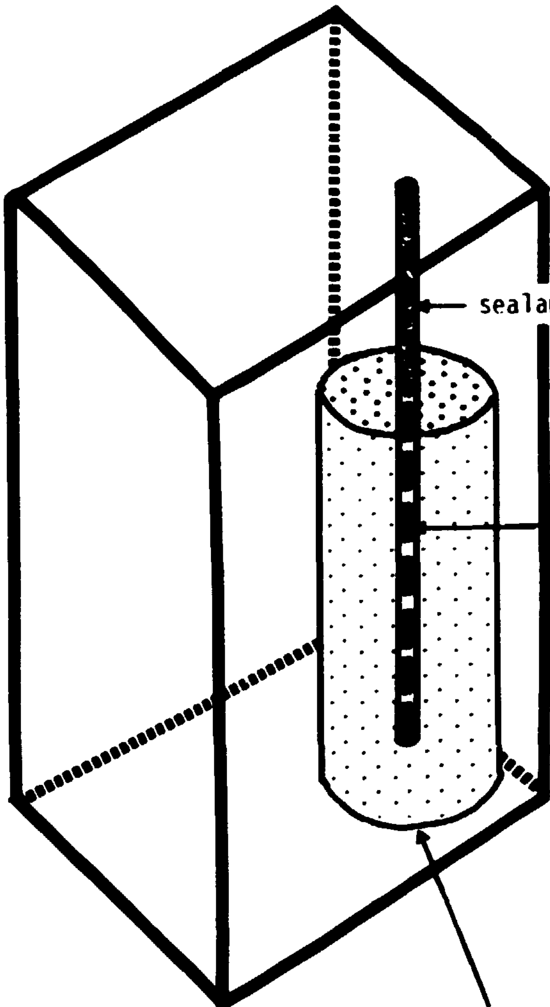
Fig. 5. Notional comparison of drill hole disposal concept with mined geologic repository.

this issue. On the other hand, isolated deep drill holes can be placed as far apart as is desired, although they need be only a few hundred metres apart in order to avoid the thermal problem mentioned above.

Drill holes also produce a much smaller environmental impact than mined repositories. A single hole would remain open only for a few years while it is filled and can then be permanently sealed. On the other hand, the strategy for a mined repository is to keep it open for 40 or 50 years while it is being filled. In terms of environmental impact this presents a much more serious problem. Local governments, states and provinces are more likely to accept a strategy based on wide dispersal of radwaste in relatively small repositories scattered through a country than a single large repository which makes one area the sole unlucky recipient. These, and other related topics are discussed in greater detail by Ringwood (1980).

Evaluation of radiological hazardsassociated with deep hole disposal

It is also possible to demonstrate that in any single drill-hole, the radwaste hazard is not excessive compared to the natural radiation hazard that forms an inescapable part of our environment. Imagine a drill-hole containing waste and surrounded by a concentric cylindrical space as in Figure 6. That cylinder could consist either of low grade (e.g. 0.2%) uranium ore, or it could consist of ordinary country rock. (The average rock occurring near the earth's surface contains about 2.7 parts per million of uranium and 10 parts per million of thorium). The radius of the imaginary concentric cylinier of either country rock or uranium ore in Figure 6 is chosen so that the cylinder would contain the



"Equivalent cylinder" may be comprised of either typical country rock, 2.7 ppm U, 10 ppm Th or 0.2% U ore-body. In the latter case, the "equivalent cylinder" has a smaller radius.

Fig. 6. Comparison of (alpha) radioactivity for SYNROC deposited in drill-hole, with radioactivity of natural sources contained within "equivalent cylinder" of surrounding rock (cf. Table 2).

same net amount of alpha radioactivity as the waste which has been inserted in the drill hole. With time, the activity of the waste in the drill hole decays so that the radius of the imaginary cylinder will decrease.

The quantities involved are given in Table 2. Consider a single hole containing the waste from a hundred power stations generated throughout an entire year. After only a thousand years (a very short time geologically) the total equivalent amount of uranium ore within the cylinder would be about 136,000 tons, which is comparable to a large uranium orebody. The radius of the concentric cylinder containing this grade of uranium ore (0.2%U) is only about 60 metres (Fig. 6). At an age of 10,000 years the activity of the waste would have declined to that of a medium-sized orebody containing 30,000 tons of uranium, whilst the radius of the imaginary cylinder would decline to 27 metres. At 100,000 years it reduces to a 3000 ton orebody with a radius of 9 metres.

In terms of the other analogy in which the radioactivity within the drill hole is equated to that in a concentric cylinder of average "country-rock", the radius of the equivalent cylinder after a thousand years is about one kilometre. In other words, there is as much radioactivity within a kilometre of country rock around the hole after a thousand years as there is in radwaste buried in the hole. When the radwaste is buried in the drill hole, it is already immobilized in an extremely resistant waste form (SYNROC) which is not soluble in groundwater. Moreover, it has been buried sufficiently deeply (>1500 metres) so that it is in an impermeable region where there is virtually no groundwater. Contrast this situation with uranium orebodies, which typically occur within a couple of hundred metres of the surface where active circulation of groundwater occurs, and where oxidising conditions

Table 2. Comparison of (alpha) radioactivity from SYNROC containing 10 percent of radwaste with radioactivity of natural sources (rocks and orebodies) as a function of time*.

SYNROC AGE	RADIUS OF EQUIVALENT CYLINDER		MASS OF U IN ORE BODY
	Low grade ore 0.2% U	Country rock 2.7ppm U, 10.8ppm Th	
Years	Meters	Meters	Tonnes
1,000	57	1080	136,000
10,000	27	517	31,000
100,000	8.7	167	3,200
1,000,000	10.6	203	4,800
10,000,000	2.8	53	330
100,000,000	0.8	16	29

*Cylinders of SYNROC (0.5 meter diameter) are emplaced axially in deep drill-hole. The "equivalent cylinder" of rock or ore contains the same total alpha-activity as the radwaste at the time indicated.

exist so that the uranium is readily soluble and migratory. Likewise, a large proportion of the uranium in natural country rocks is present at grain-boundaries and is very easily leachable and transportable.

The hazard posed by radwaste immobilized in SYNROC and buried deeply in a single drill hole as shown in Figure 5 is actually quite trivial after a thousand years, compared to the ubiquitous levels of radioactivity that are present in the surrounding country rock. Mankind has evolved in an environment where significant levels of background radiation from natural rocks and orebodies are inescapable.

On the basis of these considerations presented above, and also from other evidence documented elsewhere (Ringwood et al., 1979b, 1980; Ringwood, 1980), I conclude that the combination of an advanced waste-form, such as SYNROC, combined with deep drill hole burial, is capable of providing a completely safe system of high level waste disposal, a system capable of withstanding assessment by experts, yet also readily understandable by laymen. The problem of high level waste disposal therefore does not justify claims by many people in the community that nuclear power should be abandoned. Nor does the disposal problem justify the refusal to export Australian uranium.

3. REACTOR SAFETY

Modern societies require large amounts of electrical power to sustain their lifestyles, and this situation is unlikely to change despite the idealism of the advocates of low energy-consumption lifestyles. One respects that approach, but realistically, I do not think it is going to prevail, at least for a long time. Whatever technology is used to generate power must inevitably involve risks and consequent casualties. This situation, unfortunately, is inescapable. There are only two realistic options for producing base-load electricity during the next few decades - coal-fired power stations and nuclear reactors.

There have been many independent studies of the total hazards from the entire fuel cycle, including the mining of the raw material, be it uranium or coal, its transport from the mine to the place where it is to be used, the operation of the power plant, the emissions from the power plant, and the pollution that is caused by those emissions, including both radioactive and chemical emissions. These studies have shown that, on the basis of the production of a unit amount of electrical power, the coal fuel cycle is far more hazardous than the nuclear fuel cycle (see summary by Newcombe, 1978; also Mole, 1979; Inhaber, 1979a,b). For example, in the United Kingdom, where there are many underground coal mines, there were 9000 accidental deaths caused by coal mining between 1945 and 1978. In addition, there were 40,000 serious reportable injuries and an unknown but possibly very large number of casualties resulting from chemical and dust pollution (Mole, 1979). It is not widely known that the burning of coal also introduces radioactivity into the atmosphere. Coal contains a significant amount of radon and the amount of radioactivity introduced into the atmosphere by burning coal exceeds that produced during the normal operation of a nuclear power station (Okamoto, 1979). Moreover, there are many power stations both in this country and overseas, which burn coal in a manner which introduces large amounts of poisonous chemicals and heavy metals into the environment. Unlike radioactive materials, these remain toxic indefinitely.

Let me make it clear that I am not in any sense advocating abandoning coal as a raw material to generate power! Some of the problems of coal-fired power can be overcome by the implementation of more advanced, but highly expensive technologies. We must be prepared to balance the benefits against the costs for both fuel cycles on a comparative basis. It is not reasonable to evaluate the nuclear power cycle in isolation and very critically, whilst applying entirely different standards from those applied to the coal cycle. In this respect, the media cannot escape criticism. Unless there is a major mining accident, the media tend not to record the numerous individual deaths and injuries resulting from the coal-based power cycle. Like road accidents, they have been with us for too long; they are not news. However, the media regularly report the most trivial emissions from nuclear plants even when only comparable to small fractions of the natural background radiation and posing negligible hazards. Cases where an individual worker has received a radiation dose equivalent to a fraction of a chest X-ray have been reported on a world-wide basis. In its lack of balance and perspective, sensationalist reporting of this kind is irresponsible and contributes greatly to the present climate of fear and misunderstanding.

Much of the concern regarding nuclear power also relates to the fear of catastrophic accidents to a nuclear plant which might cause the deaths of some hundreds or in a "worst-case" scenario, even thousands of people. This is, of course, a very unpleasant prospect and these fears have increased greatly since the Harrisburg incident. It is fair to note, however, that numerous catastrophic accidents have actually occurred with underground coal mining. There are also other kinds of catastrophic man-made accidents such as dam failures which have killed hundreds of people at a time and which, according to risk-assessment analyses, have the capacity to kill thousands in future disasters. We should try to view these issues in perspective. The fact is that, to date, the safety record of nuclear power has been very good. There have been no significant accidents involving substantial loss of life. On the other hand, we should never pretend that serious accidents cannot happen. We should accept that they can, and probably will. However, the experience of nuclear technology to date leads us to expect that they will be extremely rare.

It should nevertheless be pointed out that prior to Harrisburg, the nuclear industry had been remarkably complacent, even to the extent of irresponsibility. The industry claimed that serious accidents were virtually impossible and repeated this claim so often that it was lulled into a false sense of security. Once an adequate degree of safety had been achieved (as perceived by the industry) there was little incentive to strive for further improvement. As a result, during the last two decades the efforts devoted to the further improvement of reactor safety have been decidedly inadequate.

Although the safety of reactors is already very high, there is still room for substantial improvements. An obvious step is to site reactors further away from large cities. It is usually quite unnecessary to place reactors in centres of high population density. Another obvious improvement is better design of the control rooms of nuclear reactors. The design of the control room at Three Mile Island left much to be desired. For example, I am informed that green indicating lights signified the malfunction of a system whereas red lights were meant to indicate that a system was functioning satisfactorily! We know now that there are far better ways of designing control systems for highly complex equipment and for displaying information in a manner which enlightens rather than confuses the operator. The mission control centre for the Apollo lunar voyages provides an object lesson in this area. We also know how to train people to operate complex equipment. It seems ludicrous that the operators of a billion dollar investment in a nuclear reactor should be much less well trained than a pilot of a Boeing 747. Yet the fact is that the operators of nuclear power stations are often quite inadequately trained for their jobs. There is no excuse for this.

A third area where improvements could be made is in the choice and design of reactors. The United States commercial light water reactor was based upon the type of reactor developed by the US Navy for the propulsion of submarines. This technology was handed over to the nuclear industry, which was thereby saved from the expenditure of enormous funds which otherwise would have been required for research and development. Yet it is far from certain that if one was starting from first principles to design a reactor exclusively for civilian power generation, the light water pressurized reactor concept would be chosen. The extraordinary success of these reactors in capturing most of the world market has been due largely to very generous government-backed credit facilities combined with over-optimistic cost projections (Bupp and Derian, 1978). The promotion of these reactors has been accomplished so effectively that the system has even been emulated by the Soviet Union.

It should be acknowledged that these reactors are thermally more efficient than most other current types of reactors and therefore generate power slightly more cheaply (when they are operating). Yet there are other reactor types, such as the Canadian heavy water reactor (CANDU) (McIntyre, 1975) and the British gas-cooled reactors which are believed to be intrinsically safer than the US light water reactor. In the trade-off between power costs and safety issues, it is not altogether obvious that potential marginal economic benefits of the light water reactor should always prevail over the safety issue. In my opinion the design and construction of nuclear reactors is too important an enterprise to be entrusted to competing large private companies, as in the United States. A national effort analogous to the Apollo programme, aimed at producing the safest and most effective reactor for the purpose of civilian power generation, would surely yield a superior product.

In conclusion, I believe we ought to recognise that all technologies involve learning processes, and that nuclear power is still a very young technology. It seems rather short-sighted to press for the abandonment of nuclear power when, to date, its record is very good. Instead, we should be putting much more pressure on the nuclear industry to improve its product. I am sure that this objective could be achieved.

4. PROLIFERATION

A major concern shared by many people is that the general application of nuclear power is likely to lead to widespread dissemination of fissile material, i.e. plutonium and uranium highly enriched in the ^{235}U isotope. This material could be used for the manufacture of atomic bombs, either by nations or terrorist organisations. There is no doubt that the problem of nuclear proliferation is extremely serious and that this concern is entirely justified. Regrettably, there are no easy answers to this problem. It seems likely that the nuclear fuel cycle could be modified so that terrorism could be combatted by suitable modifications to the chemical and isotopic composition of fissile materials which are produced during reprocessing. Unfortunately, however, it is too late to prevent a sovereign nation from developing its own atomic weapons. The development of atomic weapons by any nation that really wants them is essentially independent of whether it proceeds to develop nuclear power. Any determined small country with modest technology could make atomic bombs, irrespective of the availability of large nuclear power stations. The fact is that the required knowledge and technology have been too widely disseminated. Twenty-five years ago the proliferation issue might have justified a moratorium on nuclear power; today it is too late. Proliferation can only be regulated by international agreements, combined with pressure applied by major powers. We must do our utmost to see that meaningful international safeguards and anti-proliferation agreements are negotiated. As a start, one would like to see reprocessing under United Nations supervision and internationally controlled banks for fissile material.

5. THE AUSTRALIAN SCENE

There has been considerable controversy here about uranium mining and export. We should be realistic about these issues.

Australia possesses quite large reserves of uranium - perhaps about 20% of the total world reserves presently known. However, we tend to over-estimate the importance of Australian uranium on the world scene. Uranium is not a rare element, geochemically speaking. In the last few years there have been major discoveries in Africa, Canada and Brazil; and I am certain that with intensive exploration, there will be many more major discoveries. We do not have anything like a monopoly of this particular commodity. Indeed, it is quite clear that, with the likelihood of future discoveries of large reserves in other countries, combined with the falling demand for uranium that is occurring at the moment, it really does not matter very much to other nations whether or not Australia withholds her uranium from the world market. The principal consequence of such a policy is that we would lose any influence that we might otherwise have had at international levels. On the other hand, if Australia markets uranium responsibly as a member of the international community and becomes a trusted trading partner, there is a real chance that we could influence the nuclear policies of other countries in desirable directions.

Australia is a large exporter of coal as well as being a potentially large exporter of uranium. If considered on the basis of total energy content of the fuel, we stand to make much more money from exporting coal than we would from uranium. If we refuse to export uranium, we are implicitly attempting to induce other countries to use coal (preferably Australian coal) from which we will profit more. In view of the comparatively higher health risks of the coal cycle (Newcombe, 1978; Mole, 1979; Inhaber, 1979a,b), it seems to me that this position is extremely equivocal from an ethical point of view. I would conclude that in view of the demonstrable hazards of the coal fuel cyc.e, Australia should not justify a refusal to sell uranium to other countries on grounds connected with our perceptions of reactor safety or waste disposal. I believe that the choice of the fuel cycle to be adopted is the responsibility of the country that requires the power, and that we have neither the expertise nor the right to influence that choice.

There is, however, an important area where Australia could give the world a lead. I have attempted to demonstrate that the radwaste disposal problem can be solved and that the issue of reactor safety is tractable. If, after detailed examination, these conclusions became widely accepted within Australia, it would then be reasonable to consider establishing a major new nuclear enterprise in the country. This enterprise would consist firstly of uranium enrichment. We could then combine uranium enrichment with the manufacture of fuel rods. The fuel rods would not be sold to other countries; they would be <u>leased</u> under highly specific conditions, as previously suggested by Crook (1977). After the use of Australian fuel rods in foreign reactors, the lease conditions would require that the fuel rods be returned to Australia. In parallel, we would establish a reprocessing plant where the rods would be treated to remove the highly radioactive fission products and actinide elements - the high level wastes. The wastes would be solidified into a stable waste-form as discussed earlier. We would then accept the responsibility for disposing of waste generated from Australian uranium in deep drill holes located in suitable geological environments (of which there are many) within this country.

As I have shown earlier, this would be an entirely feasible policy from the technological point of view. It would also solve the very serious ethical issue which concerns most Australians, namely the possibility that exported Australian uranium might be used by foreign countries to produce nuclear weapons. We could thus contribute very materially towards the solution of the proliferation problem. If adopted, these policies would result in the establishment of major new industries which would be of immense economic benefit to Australia. They would also provide an example of world leadership by this country in an area where leadership is desperately needed. It is exciting to consider that it might be possible to arrive at a national policy which is both ethically responsible and at the same time of great economic benefit. I need hardly add that such combinations are indeed very rare. To get the best of both worlds we must begin by setting aside our prejudices and examining these issues with the responsibility that they deserve.

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