Accelerator Driven Subcritical Assemblies

Report to :

Energy Environment and Economy Committee
U.S. Global Strategy Council

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June 20th 1998

Abstract

Recently three groups in Gatchina, Russia, Los Alamos Scientific Laboratory USA, and CERN, Switzerland have proposed to use accelerator driven subcritical assemblies as sources of electricity as an alternate to nuclear fission reactors. By this means the proposers hope to avoid some of the problems that presently plague these reactors and prevent universal acceptance and expansion of the technology. These proposals are discussed and it is shown that there is no appreciable improvement in any real safety parameter, and although there may be an improvement in public acceptance this is very uncertain. An alternate proposal, to use these assemblies to transmute long lived transuranic actinides into other material is also discussed. It is pointed out that such transmutation may well be unnecessary. Nonetheless a modest research program along these lines may well be advisable.

Introduction

Very early in the studies of nuclear physics accelerators have been considered as a source of neutrons. A typical source of neutrons in 1940 was an accelerator of deuterons where the protons were "stripped" by a target. Even after nuclear reactors had been successfully built accelerators were considered to be useful neutron sources. In 1948, there was a fear that the USA had a shortage of uranium and no access to uranium (at that time for military purposes) in other parts of the world. The MTA accelerator project was started to produce fissile material from U238. It produced an average current of 1/4 ampere of deuterons. Goldanskii and other in the Soviet Union wrote several papers on the subject. More recently, about 1975 a large scale project was proposed by Dr Bennett Lewis, of Atomic Energy Of Canada Ltd. He proposed to make a high intensity proton accelerator driving a subcritical assembly of U 238 as a producer of Pu 239 for use in CANDU reactor as a fuel when uranium supplies run out. This was to be an alternate to a fast neutron breeder reactor.

The recent reintroduction of this idea are to produce the heat, and therefore electricity, directly. Three separate groups have considered this in the last 10 years - and it appears that each started from a different direction. A Russian reactor designer, Yuri Petrov of Petersburg Nuclear Physics Institute in Gatchina proposed a subcritical assembly for energy production to avoid the problems of criticality that were so evident at Chernobyl (Petrov 1991, 1992, Daniel and Petrov 1993). Below I call this the GATCHINA group. This idea was independently proposed by Bowman of Los Alamos Scientific Laboratory (LANL) in 1990 (Bowman 1992, Arthur 1995, Krakowski 1995,1996) in 1990 and Rubbia of the European Centre for Nuclear Research (CERN) in 1991, both from the perspective of an elementary particle physicist. (Carminati *et al.* 1993; Rubbia et al. 1994, 1995a, 1995b, 1995c, d, 1996) (hereinafter called the CERN group). It was brought once again to the attention of some government officials in France by Rocherolles (1998) which article stimulated this particular report. The questions have been asked:

(1) has the approach any advantage over light water moderated fission *reactors*? or over other *reactor* systems?

(2) if the answer to question (1) is yes, what is the advantage? and should the approach be pursued? and if so by whom? by an individual government such as the French or an international group?

This paper is a preliminary answer to these questions. Since below I make comparisons with other suggested technology (fusion etc.) that have NOT been shown to work and may never work, it is important to recognize at the outset that few people doubt that accelerator driven subcritical assemblies can be made to work, either for producing energy or for transmutation of waste. The doubts that have been expressed are of the economic viability of the system.

The discussions of GATCHINA, LANL and CERN do not make a clear comparison with what is now being done or could be done with existing light water reactors or fast neutron reactors that exist or could be developed such as Superphenix (Butler 1993, Lanais 1993, Castaing 1996). The advantages possessed by nuclear power with the present light water reactors are among the advantages claimed for the proposed approach. It is not apparent, what if any are the additional advantages (and disadvantages) of using an accelerator. They have tended to assume that other possibilities for overcoming the present impasse of nuclear power in western (OECD) countries do not exist. This applies in particular to the paper by Rocherolles (1998).

All three groups consider an assembly large enough to be an neutron multiplier but too small to be "critical" and sustain a nuclear chain reaction. I try to put the subject (which has been raised from outside the traditional nuclear "industry" as an important approach) into perspective. I ask to what extent, if at all, it resolves any of the problems that presently plague nuclear electric power. I do this by making some comparisons to the existing reactors. None of them are intended to be conclusory, but to ask questions which I would like the proponents of the technologies to answer. I note that each of the three groups above came at the subject from a different direction.

The Neutron Multiplication Process

When neutrons fall upon uranium or other fissile material, they can produce fission of the atomic nucleus which releases more neutrons. This is described by the neutron multiplication coefficient, k the number of neutrons released from the fission of uranium minus the number of neutrons absorbed by the reactor construction and shielding materials. If $k > 1$ the rate of the fission reaction increases with time; In a stable reactor, the fuel assembly must be have $k = 1$. This value is called the "critical" value. One of the important features of reactor design is to limit the value of k. In a normal reactor this is controlled by negative feedback mechanisms or insertion of neutron-absorbing control rods. If the value is uncontrolled, the value is limited only by disassembly (explosion) of the reactor. A release of even a small fraction of the energy stored in nuclear fuel can cause a Chernobyl-scale accident.

Control and Delayed Neutrons

The control of a subcritical assembly is appreciably different from the control of a reactor. A subcritical assembly would be controlled by adjusting the accelerator power to achieve the desired output heat. Since it is only a multiplicative assembly (indeed the CERN group call it an energy amplifier) there is little chance of a runaway. For a critical reactor any random increase in power generation must be controlled by a rapid feedback mechanism through mechanical control of neutron absorbing rods (it is an energy amplifier with infinite gain). Fortunately there is a scientific fact that aids in this control. About (1/2)% of all neutrons in fission are delayed by periods varying from 20 milliseconds to 20 seconds. These arise because some fission products are produced after beta decay of a parent, in state sufficiently excited that they will promptly decay hadronically and emit neutrons. The apparent half life is that of the parent and is controlled by the weak beta decay interaction. These neutrons are sufficiently important that Fermi declared that "without delayed neutrons we could not have a nuclear power program". I would modify this today to read "without delayed neutrons we would have to have an accelerator driven subcritical assembly". But delayed neutrons exist - so the necessity is unclear.

If there were no delayed neutrons, the time constant for power changes in a nuclear reactor would be of the order of the slowing down time of the neutrons which is 100 microseconds in a light water reactor. No mechanical control system can work that fast. However, since delayed neutrons exist, the time constant is much longer IF changes in reactivity are limited to less than the fraction of delayed neutrons. Then, as demonstrated repeatedly in the many operating reactors, a power reactor can be easily controlled. But if a larger change is made then the reactor can become "prompt critical" and a rapid power excursion can take place as happened at Chernobyl with disastrous results.

Does reactivity (k) change with time?

I pose the question, implicit in the work of the above three groups: "can one have a design where we can state with absolute assurance that the reactor can never become critical yet have a large value of k?" If so there might be a safety advantage over a reactor. Then the sub-critical assembly can act (as emphasized by the CERN group) as an energy AMPLIFIER. The energy contained in an external source of neutrons will be multiplied, or amplified by the factor of 1/(1-k).

At first sight it might be thought that a subcritical system has the considerable advantage that if anything goes wrong, the initial source of neutrons, the accelerator, stops. A large number of possible accident situations would be eliminated from consideration. For Petrov, living in a country that designed the RBMK reactor which is very susceptible to accidents where the reactor can go prompt critical (as happened at Chernobyl) there is both a strong technical and a strong psychological advantage to avoid criticality. While the accelerator would stop in a power failure it is possible to imagine other failure scenarios where the accelerator keeps going. For those who live in western countries or Japan where the Light Water Reactor (LWR) is dominant, the advantage is less clear. It is very hard for the light water reactor to go prompt critical and only the psychological advantage remains.

Moreover the system would be much less attractive if we cannot be sure that k is less than unity under ALL conditions; as the fuel moves for example, or as the uranium (or thorium) is burned up and some of it is transmuted to plutonium (or uranium 233). Rapid reactivity excursions that can occur in a critical reactor can also occur in a subcritical assembly and must be considered almost as carefully. Since we are here addressing the perceptions of the public rather than those of experts, this must be done in a credible manner. Although k did increase with time in the first design of Carminati et al, this was corrected in later designs. It is important to be sure that k does NOT change over the burn up of the fuel; otherwise it would be impossible to have a large amplification and at the same time have stability under all conditions. Clearly, these possibilities should be explored further.

The Thorium Cycle

In all three of the proposals discussed above a Thorium Cycle was proposed. Although the existing light water reactors are designed so that they can use thorium (Lanais 1965), and was used in the first Shippingport reactor, all of them at the present time operate on a uranium fuel chain. (It is sometimes called a fuel cycle but closure has not been achieved in practice so that it is not presently a fuel cycle) The reactor burns up U 235, and transmuting some of the U 238 to Pu 239. Eventually Fermi and others conceived of using the Pu 239 in a reactor. But plutonium 239 is often used as the fuel in an atomic bomb, so that has raised both a legitimate fear, and a larger psychological fear, of the possible availability of this plutonium for proliferation of nuclear weapons. A thorium cycle, it is sometimes argued can avoid this fear by avoiding any production of plutonium 239. But the thorium cycle does produce U 233, and bomb experts assure us that a bomb can easily be made from U 233, and since there are no neutrons from spontaneous fission of U 233, U 233 can also be used easily in a gun-type nuclear bomb. The advantages of a thorium cycle are not therefore as large as often claimed.

However a thorium cycle could, if one wished, be used in a light water reactor system about as easily as in a subcritical assembly. The number of neutrons per fission is smaller for thorium than for plutonium 239 or uranium 238, and a thorium loaded reactor must therefore be larger than the minimum size uranium reactor. The reasons that thorium is not presently used as a fuel is that initial fuel fabrication and chemical processing are somewhat more complex than for a uranium cycle, and until the fuel chain is closed into a cycle there seems no advantage. Thus many of the advantages claimed for the subcritical assembly raised by the above three groups are really advantages of a thorium cycle which has been considered before for a light water reactor and never found important enough to be implemented.

Before leaving the discussion of the thorium cycle, I note that a crucial issue is WHICH thorium cycle. If the start of the process is a fuel load of plutonium and thorium (as suggested by some to destroy weapons plutonium) uranium 233 will be produced which can be separated from the spent fuel mix as easily as plutonium can be separated. Although U 233 has a nasty gamma ray, it is only a little more difficult to use in a bomb than plutonium. Thus this cycle is almost as proliferation prone as the plutonium cycle.

A good discussion of the various fuel cycle possibilities, written in the context of a heavy water moderated (CANDU) reactor may be found in Veeder and Didsbury (1985).

A more sophisticated thorium cycle would include a little U 238 - enough to make the resultant U 233/U 238 mixture less than 20% and therefor unsuitable for a bomb without (expensive and tedious) isotope separation. But then Pu 239 would be produced from the U 238 and the problems of the plutonium cycle would reappear. But the LANL group argues that although the problems of plutonium would reappear, they would be less serious because the mix would include a large fraction of the isotope Pu 238 (produced from the thorium) which generates a lot of heat and makes the mixture impossible to use in present designs and difficult to use in other designs. This was raised with considerable optimism by Coops (1995) and was discussed at an IAEA meeting (Altshuler, Janouch and Wilson 1997), but some scientists who are knowledgeable about bomb design insist that a bomb can be made with any amount of Pu 238. But to the extent that it is more difficult, this may be a non-proliferation advantage.

In passing I note a proposal to use thorium in a fuel chain that is deliberately never closed but that the whole reactor stays buried (Teller et al 1996,1997)

Radioactive debris.

It is clear also that the distribution of radioactive isotopes in fission cannot and does not vary fast with the regeneration constant k. The difference between k = 0.95 and k = 1.0 is not and cannot be important. A small residual effect might remain. If a higher burn up can be achieved, fewer short lived radionuclides would be around at the (hopefully less frequent) time of fuel change.

Severe accidents

In a Russian RBMK reactor a major problem is that under some circumstances, such as those at Chernobyl unit 4, and perhaps an Anticipated Transient Without Scram (ATWS) can lead to prompt criticality which cannot be controlled. A subcritical assembly can avoid this if indeed the mechanical configuration makes k = 1 impossible. Although prompt criticality was a concern in some early designs of fast neutron reactors cooled with liquid sodium or lead, this does NOT apply to the more modern designs, especially those with metal fuel. The major cause of potential accidents in a light water reactor, and probably in modern designs of liquid metal reactors remains in a subcritical assembly. That is a failure of Post Accident Heat Removal (PAHR). Although a subcritical assembly cannot explode like a Chernobyl reactor did, accidents such as that at Three Mile Island, could still occur as the amplifying assembly overheats during a Loss Of Coolant Accident (LOCA). The overheating is dependent ONLY upon the energy production in the system and not on the value of k, and therefore is the same whether the system is a reactor or a subcritical assembly.

The above is a general statement and it is well recognized that safety depends upon details. Some of the proponents of sub-critical assemblies argue that the cooling of the subcritical assemblies can be safer than in a critical assembly. The drawings in some of the reports include "passive" safety features that are attractive. But these features could also, probably at much less expense, be added to a critical reactor system. The important question, unanswered by the proposals of the three groups is "will the avoidance of control rod mechanisms enable a simpler, and more effective heat removal system, or will the presence of the accelerator beam tube make such a system more complicated and less reliable?"

I therefore reiterate that the ONLY advantage of a subcritical assembly for producing power using either a uranium or thorium cycle seems to me to be the possible psychological advantage of avoiding prompt criticality. This psychological advantage might manifest itself in different ways. It might for example result in less draconian regulation than is now the case in the USA and therefore may lead to a cost advantage. Since the main reason that nuclear power in the USA is not now being pursued is that the cost has risen in real, inflation corrected terms, this advantage could, in principle be very considerable.

The cost estimates in the reports of the different groups are on similar bases, but this basis differs from the cost estimates for anyone now proposing a commercial nuclear power reactor. I would like to see a realistic comparison. My suspicion (which I would be delighted to have proved wrong) is that there is NO cost advantage other than the possible one of less regulation. The reason is that the costs of a nuclear reactor are NOT connected with the reactivity control, but with the heat removal - and the heat removal problems are almost the same for a reactor and a subcritical assembly.

If regulation were logical, which of course it rarely is, I would see little advantage there also. But if accelerators are regulated sensibly and reactors regulated in a draconian manner, it might be necessary to use accelerators.

There seems a clear cost disadvantage to the subcritical systems. The control rods which are relatively simple devices, are replaced by an accelerator which is expensive. And an accelerator is not merely expensive in its high capital cost, but it will take 20-25% of the power output of the assembly.

I thus come to the conclusion - a conclusion shared by some advocates of using accelerators and subcritical assemblies - that there is no reason to use them *solely for producing power.*

Transmutation of Waste (ATW)

But there may be an advantage not mentioned in the first of these papers - in the transmutation of waste. This is the present focus of the LANL group (Venneri et al. 1998). Again there are two possible advantages: a technical advantage, and a psychological advantage. Again however, one must be careful not to overstate; a large part of the claimed advantage can be gained by reprocessing and use of MOX or similar fuel, a bit more by the use of a fast neutron reactor. But there remains some advantage in accelerator transmutation, and it remains to be seen whether that is important enough to justify large expenditures.

The issues are closely intertwined with the technical, political and psychological issues connected with nuclear waste disposal (McCracken 1982, Fenn 1991, McKinley 1992). It is therefore necessary to understand these to a considerable extent. They are also very complex and there is a considerable divergence of views. I endeavor below to discuss two alternate views although neither is at the extreme of expert opinion.

The Waste Problems

The waste products which dominate both the heat generation and the toxic hazard in the 10 - 100 year time frame are Cs 137 and Sr 90. (Cohen 1977, Hebel et al. 1978, Bodansky 1997, Rasmussen et al. 1997) There seems no option but to wait for the decay of these isotopes. The problem MAY be mitigated in future by use of the isotopes in a major way for other purposes: sterilization of medical supplies and irradiation of foodstuffs. But it is hard to see how irradiations, important though they may be, could use more than a small fraction of the total inventory of radionuclides. Therefore one must plan to allow these wastes to decay in a secure storage facility.

At 100 years after cessation of fission the transuranics cause two thirds of the decay heat and the decay radioactivity. They last for periods of time from 1000 to 1,000,000 years. But opinion varies about whether the heat or the radioactivity are large enough to be a problem or whether it is worth transmuting them by fission or spallation. Even if it is accepted that transmutation is ultimately desirable, opinion varies on whether this should be done at once, or whether, for example, it might be done AFTER the cesium and strontium have decayed.

I maintain that there are three very questionable assumptions in most discussions of nuclear waste (Jakimo et al. 1978). It is important not to make these assumptions, or at least to be aware that one is making them for some political reason and not for a technical reason.

(1) A common misconception is that nuclear waste poses an unusually dangerous hazard in society. I agree that it is certainly unusual. I disagree that it is unusually hazardous. Indeed a former Chairman of the United States Atomic Energy Commission, the honorable Dixy Lee Ray declared that it was the biggest non problem they had. I sometimes say that it is the only major waste problem in society for which we have a

good technical solution. Normally waste is diluted but still released to the environment - and now there are arguments and evidence that low dose linearity is usual rather than unusual in society (Crawford and Wilson 1995) dilution does not completely avoid the problem. Nuclear waste can be kept concentrated and kept out of the environment. This is an advantage - NOT a disadvantage.

(2) A common assumption is that we must bury waste in such a way that it does not come into contact with people for a million years - and do so without any human attention. Moreover that this should be done with prior proof of almost complete certainty. This demand is made for no other waste in society. An alternate demand is that modest human attention - not much more than a night watchman be allowed. Since the time constant for something going wrong in a repository is of the order of years (compared to microseconds for a bomb; seconds for an RBMK reactor and hours for a LWR) this should be possible.

(3) An American assumption, not shared by all countries and in particular not shared by France, is that "final" waste disposal must be decided "now".

(4) The United States Environmental Protection Agency has set a limiting standard for radionuclides that could be allowed to be released to the environment (Standard 40CFR191). While it is clearly desirable to keep releases low, some critics (falsely) imply that exceedance os the standard would be a disaster comparable, for example to the arsenic problems in Bangladesh drinking water.

Indeed calculations of the integrated dose for the waste disposal part (back end) of the nuclear fuel chain are always less than those for the mining and milling part (back end). Examples are given in Tables 6-2 and 6-3 of Rasmussen (1997) based on NCRPM (1987) and Oak Ridge (Michaels 1992) studies. The change due to transmutation by any method only a small reduction (about 1.5 person-Sv or 150 person-Rem per plant year). Therefore even if one assumes the linear dose response at low doses of radiation, the change in the already small health risks from the waste disposal is small (0.02 cancers per plant year). Using the 1975 NRC guideline in RM-30-2 that risks should be reduced if they cost less than $1,000 per man rem (updated to $2,000) the estimated expenditures for transmutation of waste are excessive by over a factor of 100. The risk would be even smaller (and the cost exceedance even bigger) if the risks are discounted (as economists and public policy analysts suggest that they should be) at the usual discount rate. But the public preoccupation with these minute health risks which manifests itself in political opposition to waste disposal facilities[(1)] is not in accord with these professionally made calculations. This makes it difficult to use them as a basis for public policy.

Nonetheless if one rejects these common assumptions, a simple approach to waste disposal might be as follows:

(i) keep all fuel rods in a reactor spent fuel pit under water for 10 years and then when that pit is full:

(ii) move the fuel rods intact to dry spent fuel storage (above ground or easily retrievable aerated storage) after 10 years for a time UP TO 100 years.

This procedure has been demonstrated and seems safe. Aircraft, meteorite or atomic bomb hits could disperse the waste, but these have low probability and subsequent clean up is possible. This storage could be at a reactor site or central storage depending upon security requirements and economic and political constraints.

(iii) after 100 years (or earlier if desired) either:

(a) retrieve the waste, extract the plutonium for use to generate electricity (and with precautions to discourage use for bombs) and bury the rest. It would be easier to meet any requirement to limit the release to the environment. Heating problems would no longer be important. One of the more imaginative proposals is that of Watters and Chandra (1985).

Or:

(b) bury the whole spent fuel rods in a way that would ensure that they would not become a "plutonium mine" (Pedersen 1998) for would be bomb makers.

According to this view, the radioactivity in the transuranic material is NOT a problem. According to this view therefore transmutation of waste is unnecessary. This view has the merit of being close to the "conventional wisdom" before 1975 (since which date the USA and perhaps the world, have had no coherent plans for nuclear power development).

I characterize (or perhaps my detractors would say - parody) the pre-1975 "conventional wisdom" as follows:

(i) after 10 years in storage extract the plutonium from the fuel for use in fast breeder reactors or perhaps in LWRs - the choice between these two to be made by economics.

(ii) transmute other transuranics in fast neutron reactors, used for this purpose as "burners" (Lanais et al 1993, Castaing et al 1996).

(iii) bury the rest.

I note that this "conventional wisdom" automatically got rid of most of the transuranics and might easily get rid of all in the fast neutron reactors (although so long as nuclear power were used there would always be an inventory): I suspect it was this pre-1975 way of considering a logical nuclear fuel cycle that led to the common misconceptions about nuclear waste that I noted above.

Another extreme view might be that all fissionable material, including the long lived fission products Iodine 129 and Technicium 99, should be transmuted BEFORE burial, and preferably as soon as possible. It seem to be this view that drives the suggestion that accelerators be used for transmutation of waste. The various technologies for transmutation is discussed in some detail by Rasmussen et al. (1996).

Even if the first view has the most likelihood of being "proven" or eventually accepted as correct, some research on the alternate possibility of the second view could well be considered a worthwhile task, roughly in the way that most people are willing to accept that the world should spend money on fusion research even though most of the scientists who support such research have grave doubts that fusion will actually work in the sense of being economically competitive with alternates.

Specific Comments upon the Present Proposals

I will take as a guide the present proposal of the LANL group (Venneri et al. 1998). The CERN group has variants of this. They combine the following four technologies (1-4) below:

(1) A high intensity accelerator - LANL chose a superconducting proton linear accelerator but CERN was at one time considering a sector focussed cyclotron (Rubbia et al. 1995c)(figure 1). I note that either choice is already the most advanced of the technological developments needed for the Accelerator Transmutation of Waste and needs the least research.

At Los Alamos about $200 million a year is already being spent on developing such an accelerator to produce tritium for weapons. Parenthetically I note that technically this is unnecessary for 80 years at least because:

(i) the purpose is to keep the US weapons stockpile at a level 10,000 weapons whereas the 50 odd nuclear weapons available at the Cuban missile crisis were demonstrably enough to scare the country and create effective deterrence. A reduction by a factor of 100 (over 7 half lives) would allow the present tritium stocks to last for 80 years.

(ii) tritium is produced in surplus in Canadian heavy water reactors. Although Canada will not sell this tritium for military purposes, this could change if there develops a proper international regime for control of nuclear weapons.

(iii) Russia has a large surplus of tritium and this could be available for a price less than that of building another production source.

(iv) An existing reactor such as FFTF in Hanford might be modified to produce tritium (Lanais et al 1993)

(v) If the government of the USA can overcome its distaste of reactors, another special reactor such as that at Savannah River or Hanford seems a choice which is more logical than an accelerator.

(vi) A light water reactor could be modified to produce tritium if there were no objection to the use of civilian facilities for that military purpose (note that tritium is not presently a Strategic Nuclear Material.)

Although if any one of the items (i) to (vi) were correct the development of superconducting accelerators for military purposes might cease, this technology is far enough advanced that it is still the most advanced of the technologies needed for a viable subcritical assembly.

It follows that although an accelerator is the easiest of the technologies to work on, and might well be the one that actually would show progress, it is not the limiting factor in the ATW technology. Accordingly I believe research on accelerators should have a LOW priority for the overall ATW program. This would especially apply in China where there has not yet been enough nuclear power produced to justify a program at all.

(2) A subcritical assembly. This would be a fast neutron facility. The mechanical designs suggested by both CERN and LOS ALAMOS use a vertical beam pipe bringing the proton beam down onto the target. (figure 2) This seems to be based upon the (paper) designs for Liquid Metal fast neutron Reactors (LMR) of Westinghouse and General Electric. This has important inherent safety devices as shown in the attached figure 3 from Westinghouse. The assembly is likely to use U 233/Th as fuel. Subcritical assemblies analogous to Pebble Bed reactors an Molten Salt Reactors (Arthur et al. 1995) have also been considered but are not in the present designs.

(3) The choice of coolant for a fast neutron assembly is interesting. The main choices are:

(i) Helium gas

(ii) liquid sodium

(iii Lead-bismuth eutectic (LBE)

LANL are choosing to work on (iii) the lead bismuth eutectic (LBE). Many starry eyed individuals, of which I used to be one, like (i) helium gas as a coolant. One reason is that such a system would have been a natural development from the High Temperature Gas Cooled (graphite moderated) Reactor (HTGR). But the HTGR has been abandoned by every country that has started work on it (USA[(2)], England[(3)] and Germany[(4)]) and this would then be a big extrapolation in technology.

Number (ii), liquid sodium has a lot of advantages. It is non-corrosive (except to such comparatively unimportant materials as human skin) and has a low neutron capture cross section. It has been widely used in test reactors for 40 years. Minor problems have developed but the expert engineers assure us that these are soluble. But psychologically the public fear of a runaway sodium fire is important. Without this fear the fast neutron reactor at MONJU would not have been shut down for 2 years.

Number (iii) - LBE - is attractive superficially. As a heavy element it is excellent as a target for the initial production of neutrons. As shown by the phase diagram between lead and bismuth shown in figure 4 there is a liquid eutectic at moderate temperatures. Neither bismuth nor lead burn as readily as sodium does, but it is heavy. It is corrosive at high temperatures - unlike liquid sodium. Work in the USA failed in the past to overcome this. But Russian work succeeded. Several of their latest submarines have reactors cooled by liquid lBE (figure 5). It is self shielding and this makes a compact assembly, keeps the weight down and enables the submarine to go faster. I do not know whether that will be a good alternate to liquid sodium, and solve the public perception problems. LANL think it is worth the research. But I note that the Russian BN 600 fast neutron breeder/burner reactors, designed at the same place, Obninsk, use liquid sodium, and there are no plans for using LED for any but submarine reactors.

However, I believe that understanding in the west (OECD countries) of how to use LBE will have implications beyond the ATW program and is well worth pursuing.

(4) The subcritical assembly does not avoid the need for chemical separation of the different parts of the spent fuel. It must be remembered that it was the concern about chemical separation that led to the end of the pre-1975 "conventional wisdom" (Keeney et al 1975). In the USA it was felt that to have chemical separation plants that isolated pure plutonium was highly dangerous from the point of view of weapons proliferation, and ceased activities to "set an example", an example that has NOT been followed by France, Germany or Japan. LANL propose to use electroprocessing whereby chemicals are separated by their electrochemical potential and pure plutonium is not separated (it comes with higher actinides). (figure 6) This technology has been sponsored during the last 20 years by Argonne National Laboratory. It is attractive from the point of view of non-proliferation because:

(i) plutonium is never separated from the higher actinides nor separated from all the fission products so that it is unusable except in a fast reactor

(ii) unlike the PUREX (solvent extraction) chemical separation processes pyroprocessing is viable in small sizes so that it is feasible to have a separate facility for each reactor. Then even impure plutonium need never leave the reactor site. Although an independent review (Basolo et al 1995) was not sure of all the claims of proliferation resistance, it was generally supportive of the research. However I note that the Integral Fast Reactor (IFR) program at Argonne National Laboratory (which was developing this concept) was terminated by the US administration and congress (using rhetoric that shows that they failed to understand the important nonproliferation features) in 1994 and only a waste processing program remains. Whether LANL can successfully reinstate such a program is uncertain.

However, I believe that research in electroprocessing is important. It shows great potential for being a proliferation resistant technology and may therefore overcome one of the legitimate public concerns about nuclear energy.

The Shippingport reactor used thorium as a fuel. The use of thorium has been abandoned since then. However, use of thorium as a fuel shows promise of being able to extend the time when light water reactors will be the "nuclear workhorses" of the electric utility industry and delay the time when breeder reactors may be needed. Research on the thorium cycle would seem to be appropriate but I believe it would best be associated with light water reactors rather than accelerator driven subcritical assemblies.

Both CERN and LOS ALAMOS groups claim that it will be faster to use up all the fissionable material in a subcritical assembly than in a liquid metal reactor as shown in figure 6. The overall mass balance for 65 years of operation with the principal purpose of getting rid of fissionable material is shown in figure 7. This depends critically upon details and is in any case only relevant if it is desired to get rid of all traces of nuclear fission as soon as possible.

A Possible Program

My opinion should be clear from the above: the Accelerator Transmutation of Waste (ATW) must be considered in the context of a complete nuclear power program. What such a program could or should be in the USA becomes more uncertain as time proceeds. But I presently envisage the following (in addition to the monitored waste storage mentioned earlier):

(1) Continue to use light water reactors, and heavy water reactors (CANDU) in Canada, with uranium fuel of appropriate (including zero enrichment for the CANDU) enrichment. Elsewhere (Wilson 1997) I have pointed out that the present impediment is COST, The cost of nuclear produced electricity has increased a factor of at least 2.5 over earlier costs in the 1970-1975 period primarily by overregulation.

(2) Study the use of thorium as a fuel in light and heavy water reactors to extend the availability of fuels.

(3) For those countries that wish to do so, chemically separate plutonium fuel, *with stringent safeguards against non-proliferation,* and burn it as MOX fuel.

(4) Endeavor to develop an economic fast neutron system. Probably a reactor but perhaps an accelerator driven assembly.

(5) Develop the chemical and target facilities for either reactor or accelerator transmutation of waste but build large facilities only if the waste disposal system demands it (probably only due to public perception).

Parallel Developments

There is a large field, or set of fields, of scientific endeavor that use neutrons for basic scientific studies - including studies in physics, chemistry, biology and medicine. Since reactors are now politically difficult to build, spallation sources of neutrons are now preferred. Early facilities used pulsed electron accelerators but nowadays pulsed proton accelerators are preferred. There are basic facilities at the Rutherford laboratory (ISIS) at Los Alamos (LANCE) at Argonne National Laboratory (IPNS) and proposed for Oak Ridge (SNS) and a new European facility (ESS).

One set of uses of spallation sources demands accurate timing. This is to separate the neutron energies by time of flight especially in the multi electron volt energy region. But there are others for which timing is not so crucial and the maximum number of neutrons is needed. One estimate is that these latter uses comprise 75% of all uses (Greene 1998).

Some of the early electron accelerators and the ISIS accelerator used a subcritical fissionable assembly of uranium as a neutron multiplier to increase the yield. The multiplication was a factor of 1.6 in ISIS far less than the factor of 20 - 100 proposed in the ATW and related programs. But the target size had to be small to obtain a high brightness, and this would not be necessary if sheer numbers of fissions were the goal. This is not now done (Appleton and Bauer 1996). The reason stated for the abandonment is that the target lifetime (6 weeks) was too small due to anisotropic growth of the uranium crystallites - probably associated with hydrogen and helium embrittlement. (Taylor 1998). A desire to keep the pulse structure of the neutron beam short to satisfy those "users" who need the short pulse does not enter the balancing of issues till the multiplication factor is much larger.

Another reason (consistent with what I noted above) is that getting more power in an accelerator is easier than coping with a multiplying target. Whatever the reason, there is an obvious inference and an obvious simple plan for immediate study.

(i) the inference is that my belief that the multiplying target is difficult is confirmed, and

(ii) research on a multiplying target (subcritical assembly) could begin IMMEDIATELY at any one of the spallation neutron facilities. Indeed research on the spallation process itself is under way (Boudard, Leray and Volant 1998)(Rubbia et al. 1994).

The negative approach of this paragraph can be replaced by a positive approach if the proponents desire. There exist accelerators where parts of the program can be tested NOW at moderate expense. These include ISIS, LANCE and also the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory. It is noteworthy that a liquid lead target for the LANCE spallation source is being built by the scientists at OBNINSK (Venneri 1998). This could be a beginning of Americans learning how to use the Russian technology of lead coolant.

A renewal of the program to understand multiplying targets at these spallation sources could also allow an immediate start of understanding this potentially limiting part of the technology. A more urgent approach to the Argonne National Laboratory program on electron and pyroprocessing can bring this technology too to the stage where the whole ATW approach can be more seriously evaluated.

Conclusion

I can envisage a nuclear power future with a waste management program that would satisfy me *without* a program either for accelerator transmutation of waste (ATW) or any fast neutron program for transmutation of waste. It seems likely to me that a program *without* transmutation would be cheaper than one with transmutation but maybe not appreciably so.

However, a modest program aimed at opening up possibilities is probably in order. In my view it should have a higher priority than a fusion program, but a lower priority than a nuclear research program on reducing costs of the existing light water reactor and related programs to the 1973 levels. Although much of the impetus for the present proposals comes from people knowledgeable about accelerators, I believe that the best approach to such a modest program is to enhance research in the problems of targets, coolant, and electroprocessing at existing facilities. Since the purpose is to aid in coping with waste disposal and clean up problems, any funds from the USA should come from these ample budgets rather than from the nonexistent (in FY 1988) or minuscule (in FY 1999) nuclear research budget, and certainly not from the basic energy research budget.

The major conclusion in the above is consistent with the conclusion in the monumental study of Rasmussen et al (1997). "The committee found no evidence that applications of advanced Separation and Transmutation (S & T) have sufficient benefit for the U.S. High Level Waste (HLW) program to delay development of the first permanent repository for commercial spent fuel." and "over the next decade the United States should undertake a sustained but modest and carefully focussed research and development program on selected Separation and Transmutation (S & T) technologies with emphasis on improved processes for separating LWR and transmuter fuels..."

I note that some of these conclusions were also reached independently by a committee of the European Commission (Pooley 1997), and by Panofsky (1998)

Acknowledgements

The ideas herein were developed during conversations with many people. I particularly want to thank Dr Yuri Petrov for his personal hospitality on several occasions and Los Alamos National Laboratory for being my host for 2 weeks in March 1998. I would also like to thank A. Birkhofer, Robert Budnitz and W.K.H. Panofsky for useful comments upon a draft.

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1. The refusal of the Unites States Senate in June 1998 to vote on high level waste storage facilities in Nevada is an example of this trend.

2. The first electricity producing reactor at Peach Bottom was a gas cooled graphite reactor. A larger reactor at Fort St Vrain in Colorado was built and operated (intermittently) for a while. However it proved difficult to keep in operation for a variety of engineering reasons. Several still larger reactors in the 1000 MWe range were ordered in the 1970s but these orders were canceled by Gulf General Atomic in 1978 (and $500 million in penalties paid) and G.A. then got out of the business. Attempts to start again have always been conditional on large subsidies.

3. England had a number of gas cooled graphite moderated reactors, the MAGNOX type and the Advanced Gas Cooled Reactors (AGR). Many still operate. However England made a decision to switch to the Pressurized Water Reactors around 1982 and also abandoned the experimental helium cooled reactors at Winfrith Heath.

4. Experimental work on a helium cooled reactor continued in Julich for some time after it was abandoned in USA and UK but has ceased by now.