HIGH-POWER ACCELERATORS : KEY PLAYERS IN A POWER-HUNGRY AND PEACE-HUNGRY WORLD DURING THE COMING CENTURY ?

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1. THE GLOBAL ENERGY PROBLEM FOR THE COMING HALF-CENTURY

The energy issue

On the eve of the 3rd millenium, humanity is increasingly faced with the formidable problem not only of achieving an ever-higher standard of living for a continually-increasing world population, but also of doing so without endangering our planet's fragile environment and without exhausting its resources, some of which are limited.

One of the major issues that will dominate the first half of the coming century is the energy problem. At present more than 80% of humanity's energy consumption is covered by burning fossil fuels : coal, oil, natural gas and wood. The rest is mainly hydro and nuclear power, while very little power is derived from renewable sources such as wind, solar power and heat and earth heat for example in the form of hot springs.

Fossil fuels

Within a few decades from now, supplies of some of the main fossil fuels will be dwindling : oil companies predict that by about the middle of the century oil and natural gas will be scarce and far more expensive than today. Coal will last longer, even though it will take over the markets currently occupied by oil and natural gas. But the issue – still not completely clarified – of global warming being caused by the greenhouse gases, mainly CO_2, that are emitted during the burning of fossil fuels, could lead to a requirement of mitigation and consequently result in higher energy costs. For example, existing technology allows the CO_2 in the exhaust of a fossil-fuel-fired turbine to be captured and deposited into an aquifer 1000m below the Earth's surface, where it dissolves due to the high pressure at that depth. Implementing this method increases power cost by about 50% compared to just letting the CO_2 into the atmosphere.

Hydropower

As to hydropower, most of the available sites are already exploited : perhaps 50% more could be built, which is totally insufficient compared to increasing global demand. Furthermore, the ecological problems are far from negligeable and the investment structure is unfavourable to developing countries : low operating costs but very high capital outlay.

Nuclear fission

Nuclear power has for the time being lost momentum in the U.S. and Western Europe (except in France where new plants are being built). One of the reasons for this is deregulation : faster payback is achieved from fossil-fuelled turbines because of their lower capital cost. Another reason is non-fixed interest rates on construction loans. A third is scepticism among a certain portion of the population with regard to safety and waste disposal aspects of nuclear reactors. A fourth is the complex bureaucratic procedure to be gone through in order to obtain a construction licence. In East and South-East Asia, on the other hand, a considerable nuclear power programme is planned, with projects in China, the Koreas, Japan, etc.

Why is public opinion in many countries so sceptical about nuclear power ? During the decades in which Western-type light water reactors have been in use, not a single person has been killed within their containment buildings, whereas tens of thousands have been killed in car accidents without people changing their driving habits. Perhaps because of the Chernobyl accident ? Chernobyl uses a totally different different graphite-moderated reactor and does not have any containment building. Or because of the unsolved waste problem ? Whatever the motivation behind public antagonism, it undoubtedly exists.

For all the above reasons, nuclear power in its present form is not a promising candidate for covering humanity's future energy needs.

Nuclear fusion

Rather large budgets have been devoted to international research on fusion reactors, but the problem has proved to be more complex than expected, so we do not know when a real breakthrough may come.

Solar power

How about solar energy, photoelectricity or simply solar heat ? Space projects have been needing solar electric panels for several decades, and obtained them. Important developments have been accomplished in this field and financed thanks to space needs. The resulting technology however is not competitive in ordinary commercial applications on Earth, except at some distant spots where demand is so very small that power lines or microwave transmission are uneconomical and diesel-generated power is impractical – for example at desert vacation cottages in California and certain parts of Africa. In order for solar energy to supply basic power, very large areas are needed for the photoelectric panels. That land is expensive, as are the panels themselves and also their supports, which must be strong enough to resist violent storms. One way to decrease the cost of the panels is to integrate them into the buildings' walls and roofs, but this surface area is insufficient. Furthermore, the panels must be regularly cleaned of dust and sand and sometimes, in the higher latitudes, snow and ice. It is not known when solar power will become commercially competitive.

Solar power produced outside Earth and transmitted by microwave or laser beams to Earth's surface may become competitive enough to be implemented but probably not until rather late in the next century.

2. TOWARDS SOLVING THE ENERGY PROBLEM : ACCELERATOR-DRIVEN, SUBCRITICAL NUCLEAR POWER

It has been seen above that the problem of energy for the next half-century is characterized by the problems and insufficiencies of existing sources of power. What then can be envisaged for that period and a long time thereafter ?

A very promising solution is offered by a machine type which combines a high-power accelerator with a subcritical nuclear reactor. Why is it so promising ? This is because subcriticality enhances safety and the extra neutrons supplied by the accelerator mean superior flexibility.

Protons, accelerated to 1 – 2.5 GeV, hit a metal target in the centre of the subcritical reactor causing so-called nuclear spallation in the target nuclei. Each beam proton liberates about two dozen neutrons, which diffuse into the reactor blanket, replacing those neutrons which are missing due to subcriticality. The proton current has to be several 10:s of mA.

The idea is far from new, having been considered as early as the 1950's, but sufficiently powerful accelerators could not be built until the 1980's. Linacs of the required strength are today's technology. They can be either normal-conducting or super-conducting. Cyclotrons are also being considered for the same purpose (by Rubbia and his group at CERN). A development project is planned.

The choice of the subcritical reactor blanket has its own history. It was shown early on that light water was not feasible : its properties for neutron diffusion required many proton beams. Heavy water was studied by LANL with the Russians. D_2O was abandoned and the work was concentrated on molten salt. Now both the American and European development groups have chosen liquid metal, namely liquid lead / bismuth. This material is the beam target ; it serves as an ideal moderator and also as a coolant. The Russians have the most know-how in the world about using these metals as coolant thanks to their long experience from a separate class of their submarines.

Now, what is it that this system is expected to achieve in the energy sector in the not-too-distant future ?

1. It can efficiently incinerate the bomb material plutonium and the other transuranium elements in spent fuel, eliminating them almost completely. This it can do better than any other method.

2. It can transmute the most dangerous fission products in the spent fuel – technetium, iodine and cosium – to stable isotopes. These are the most dangerous fission products because they cause specific biological damage to the human body and are moreover soluble in water, so that if a leak occurs in the copper canning of the fuel assemblies in terminal repository, they may end up in the ground water.

This dual capability eliminates two of the greatest disadvantages of nuclear power as currently implemented. Furthermore, subcriticality makes it impossible for the reactor to "run amok".

3. WHY IS INCINERATION OF CIVILIAN PLUTONIUM IN SPENT FUEL IMPORTANT ?

Because any rogue country, mafia, terrorist organization or even wealthy individual can make nuclear bombs from civilian plutonium relatively easily and cheaply. Such bombs present one disadvantage in that it cannot be known before they are actually ignited what explosive power they will provide, but it will be somewhere between 10% and 70% of the power of the Hiroshima bomb for a bomb containing 10 kg of plutonium. And terrorism on that scale can have devastating effects and lead to war.

The scale of the risk of nuclear bombs made from civilian plutonium is certainly not small. The amount of spent fuel in the world is over 100,000 tons, spread in cooling ponds in over 30 countries, and not always well guarded against theft or coup. These 100.000 tons will have become 200.000 tons within a decade or so. Most of this is uranium-238 but 1%, or 2,000 tons, is plutonium. And since less than 10 kg of civilian plutonium is needed to make a bomb, this material is enough to produce 200,000 bombs. This is the scale of the problem.

This risk must of course be kept under best possible control. Thus the United Nations International Atomic Energy Agency (IAEA) in Vienna has been entrusted with checking that this widely disseminated plutonium is not misused to make bombs. Because the half-life of plutonium is 24,000 years, this IAEA control must be maintained for about 100,000 years. If this international agreement concerned any less serious problem, it would have to be regarded as totally absurd : no human institution lasts that long, and particularly no international agreement. No wonder some people have doubts about nuclear power !

4. THE SOLUTION TO THE PLUTONIUM THREAT

If a nuclear waste treatment system of accelerator-supported subcritical reactors is set up, however, the situation becomes totally different. For every 10,000 MWE (30,000 MWTh) of first-generation nuclear power in a given country, a subcritical capacity of 25% i.e. of 2,500 MWE (7,500 MWTh) is sufficient to clean up both the waste of the first-generation reactors and the waste of the subcritical clean-up reactors themselves. And the need for IAEA safeguard is restricted to the actual lifespan of the clean-up reactors, i.e. 35 to 40 years (instead of 10,000 to 100,000 years under the current configuration).

Before implementation, normal technological development must be carried out, mainly with regard to materials properties and chemistry, and some pilot plants must be financed, designed, constructed and put into operation. This phase takes about seven years. If these pilot operations work as expected, one or two full-scale plants must then be built and tested before widespread implementation can begin. This second phase would take some time, perhaps 12 to 15 years.

For the time being two pilot plant projects seem to have a chance of receiving funding in the relatively near future, one in the U.S. and one in Europe. In a month or two we will know more about how close to being financed they are.

What are the economic aspects of a full-scale clean-up plant ? The thermodynamical efficiency of a plant of say 3,000 MWTh is similar to that of a light water power reactor, if not a little higher, so it produces the same electric power. But the accelerator "steals" almost 10% of the power produced and also adds somewhat to the total capital cost of the plant. This increases the cost of the power to be sold to the net. However, cost-reducing factors are also present. While the reactor tank and other tanks, pipes, valves, heat exchangers and so on are all built to resist high pressure in a light water power reactor, no high-pressure designs are needed in a liquid-metal-cooled plant, the regulation system is simpler and the final repository for fission products not to be treated is simpler and cheaper.

Even if the power available for the net from the clean-up plant turned out to be slightly more expensive than power from critical LWR:s, the cost differential would be further reduced by the fact that only one LWR-sized clean-up reactor is needed to handle the waste from four LWR:s (and itself).

5. THE NON-PROLIFERATION ISSUE

One of the important properties of an accelerator-assisted subcritical reactor system is its capacity to burn the bomb material civilian plutonium almost completely. But it is a fact that high energy accelerators can be used to produce the bomb materials plutonium or uranium 233 if the beam is (clandestinely) diverted to a different target. Can this threat be avoided ? The answer is yes. First of all, IAEA personnel and instruments would discover the vacuum line to the clandestine target, on condition that the personnel were allowed to make routine visits and that their measuring instruments were not manipulated. Manipulation of the instruments would immediately be apparent to IAEA, and refusal to allow access to a country or plant would clearly signal unauthorized activity. IAEA could do nothing about it except alert the UN. But the UN could decide to stop the system by bombing the accelerator, an action that would not release any significant amount of radioactivity. In contrast, the UN cannot bomb a reactor which has already been or is in operation because of the huge amounts of radioactivity it contains.

6. CONCLUSION

Looking forward to the coming century and humanity's growing energy needs, accelerator-assisted subcritical reactors seem to hold good potential. Nuclear fusion and solar power, in principle promising, appear still to need long research and development times and may not be commercially available until later into the century, by which time fossil fuels will already have become scarce and very expensive. Nuclear power, in the form of the currently-exploited light water reactors, leaves plutonium in the spent fuel, plutonium which can be used to make bombs and which, if stored (as it is today), needs to be guarded for about 100,000 years.

The technology to construct accelerator-assisted subcritical reactors exists today and the pilot-plant phase could get under way as soon as financing is supplied. Accelerator-assisted subcritical reactors present certain advantages compared to light water reactors : they cannot run amok, do not produce plutonium that has to be stored, and can clean up the existing waste from the first generation of nuclear reactors (as well as their own). And in terms of cost, any slight differential in the cost of the electricity supplied to the net compared to current light water reactors would be many times compensated for by the benefit in terms of their superior safety, their plutonium clean-up and their transmutation capability.

With accelerator-assisted subcritical reactors, nations and utilities which, under the pressure of increasing fossil fuel costs during the coming century, want to invest in nuclear power may have the opportunity to do so with a significantly improved nuclear system. And all current nuclear-power nations could have the means to clean up waste which has hitherto been stored with its plutonium and other biologically damaging isotopes intact.