NUCLEAR POWER[i]

Issue: What is the status of nuclear power as a future energy source?

Nuclear energy is already attractive on economic grounds in most regions. If carbon emission caps are broadly instituted it will be come even more attractive. Problems of safety and waste disposal can be dealt with through strict regulation and technical systems. Weapons proliferation concerns can only be dealt with through international agreements.

Introduction

Nuclear energy is undergoing a renaissance driven by two very loosely coupled needs; the first for much more energy to support economic growth worldwide, and the second to mitigate global warming driven by the emission of greenhouse gases from fossil fuel. A new generation of power reactors has been developed that are safer, easier to operate, and purported to have lower capital costs. This, coupled with rising costs of fossil fuels and concerns about environmental pollution from fossil fuel power plants, has led to an increase in orders for new plants, mainly from Asia, but beginning to impact North America and Europe as well.

This report first describes the current generation of nuclear reactors known as Generation III. These are mostly Light Water moderated and cooled (LWRs). There are several varieties and new countries are entering the export market. It then gives some estimates of the comparative costs of nuclear generated and fossil fuel generated electricity. Nuclear electricity is elements of spent fuel that create the most problems. This is to be accomplished in reactors using new fuel cycles based on higher neutron energy than is used in LWRs.

Finally, the paper discusses issues related to limiting the potential for the spread of nuclear weapons. Since there is no proliferation proof nuclear fuel cycle, technology can only be an assistant to diplomacy through early detection of attempts to produce material suitable for weapons use. The main burden has to be on diplomacy and there is much discussion of ways to internationalize the fuel cycle, thus limiting the potential for diversion of weapons useable materials.

The Current Generation of Nuclear Power Plants

The number of nuclear power plants under construction, in planning, or under discussion is

The other is a paper by Dr. John Ahearn, former chair of the U.S. Nuclear Regulatory Commission[4]. Both illustrate all the new reactor models being marketed.

Economics of Nuclear Power

The role of nuclear power compared to that from coal or gas-fired plants will depend critically on the comparative economics of these plants. Gen III nuclear plants are expected to supply power at considerably lower costs than their Gen II predecessors. Natural gas prices are much higher today than they were years ago, coal costs are also rising, and coal-fired power plants have to be equipped with evermore sophisticated pollution control equipment.

Table 1 shows the relative costs of electricity per kilowatt hour from these three sources based on an analysis done by the Uranium Information Centre[5]. They used Nuclear Energy Agency and International Energy Agency data. While the discount rate of 5% assumed in this analysis may be too low, nuclear plant life assumption and nuclear load factor are also low. Life extensions for nuclear power plants granted by the U.S. Nuclear Regulatory Commission give a 60-year useful life rather than the 40 years assumed here, while capacity factors in U.S. plants are already above 90% compared to this 85% assumption.

Table 1. Some Comparative Electricity Generating Cost Projections for Year 2010 on

	Nuclear	Coal	Gas
Finland	2.76	3.64	-
France	2.54	3.33	3.92
Germany	2.86	3.52	4.90

Another analysis of relative economics is in a report by the World Nuclear Association entitled, "The New Economics of Nuclear Power"[6]. This report, prepared in 2005 compares seven different analyses done since the year 2003, examining assumptions as well as the sources of the information used. Their conclusion is that nuclear power seems to have a competitive advantage on the average, though the actual advantage will depend somewhat on local circumstances.

All of these analyses assume that uranium fuel costs will not rise unreasonably above today's level and that no carbon emission caps or fees will be imposed. The European Union already has such a cap and trade system in place and as time goes by and the caps tighten the cost of fossil fuel fired power will increase.

One can conclude from this that nuclear power may in fact be less costly than that from fossil fuels, but one will not be sure that this conclusion is correct until we get a considerably more Gen III power plants built and operating.

Resources and Alternate Fuel Cycles

Uranium resources are analyzed regularly by the Organization for Economic Cooperation and Development (OECD) and the International Atomic Energy Agency (IAEA). The most recent estimate is published in the book "Uranium 2005: Resources, Production, and Demand", known as "The Redbook"[7]. This report estimates that there are about 4.7 million metric tons (MMT) of known and easily recovered resources. The percentages of the total in the three largest deposits are in Australia (24%), Kazakhstan (17%), and Canada (9%). Interestingly, the two countries that have the largest rate of growth in energy demand and the largest rate of growth in nuclear energy, China and India, are estimated to each have only 1% of these easily accessible resources.

Standard lore in the mining industry is that resources grow with the price paid for ore and the Redbook estimates that there are about an additional 10 MMT of reserves available at prices up to $130/kg of uranium (U.S. dollars). It the lifetime of the reactors running in 2050. This is one of the drivers toward alternate fuel cycles.

The item in short supply for today's LWRs is the isotope U-235. There are other types of reactors available today, such as the old-style CANDU that can operate with natural uranium, thereby expanding the supply in principle by more than 100 fold. However more emphasis is being placed on other solutions.

As enriched uranium is being burned in today's LWRs the amount of U-235 in the fuel decreases while the amount of plutonium increases. Some nations, France and Japan for example, separate the plutonium from spent fuel, blend it with uranium from the same spent fuel, and use this "mixed oxide fuel" or MOX in their LWRs. This can increase the energy for the given amount of enriched uranium fuel by about 30%.

For the long run, the expectation is that reactors with a higher neutron energy than today's, the so-called Fast Spectrum Reactors (FSRs) can be used as breeders to make new fuel as well as producing energy. For example, an FSR fueled with a mixture of natural uranium and plutonium can be designed to produce energy and also more plutonium fuel from the uranium in that fuel. A slightly more complex variant is the thorium cycle breeder. Here the first stage uses thorium and plutonium to produce electricity and uranium-233 from the thorium. The U-233 is then used with the thorium to produce energy and more uranium-233. This last is the route favored by India which has a much larger supply of thorium than uranium.

The Spent Fuel Problem

Spent fuel has three main components (table 2). Fission fragments make up about 4%, are intensely radioactive, and need to be isolated for only 500 hundred years until their radioactivity decays to below the level of concerns. Uranium makes up 95% and is negligibly radioactive. The difficult problem comes from the remaining 1%. This is composed of the actinides: plutonium, americium, neptunium, and curium (collectively called the transuranics or TRU), plus two fission fragments present in small amounts. These are long-lived and have to be kept from the biosphere for hundreds of thousands of years, or treated somehow to decrease the required isolation time.

There is little problem with two of the three components. There is no scientific or engineering difficulty with fission fragments because they have to be stored for only a relatively short time, and there is little argument about the engineering of such repositories. There is no difficulty with the uranium for it is not radioactive enough to be of concern and could even be put back in the mines from which it came.

Table 2. Components of Spent Reactor Fuel

Component	Fission Fragments	Uranium	Long-Lived Component
Per Cent Of Total	4	95	1
Radioactivity	Intense	Negligible	Medium
Untreated Required Isolation Time (years)	500	0	300,000

There has, until recently, been a difference of opinion in how to handle the long-lived part. The differences were however less than they appeared to be. The U.S. advocated the "Once Through" fuel cycle in which the spent fuel from LWRs was kept intact and disposed of untreated in a geological repository. Others, typified by the French, advocated reprocessing the spent fuel to separate the plutonium for use as MOX fuel while sending the rest to a repository. The spent MOX fuel would then also go to a repository. There has been much heat and a little light in the discussion of the relative proliferation resistance between the two approaches.

Recently the two views have converged. The new approach is to destroy or "transmute" the long-live component in an FSR. The higher neutron energies of an FSR can cause all of the long-lived parts to fission and become just another source of fission fragments that need to be stored for several hundred years[8]. In this model all the long-lived elements are separated and fashioned into the fuel elements of an FSR for transmutation. In a continuous recycle fashion the output of the FSR is reprocessed again and the remainder of the long-live part is sent through once more as fuel, and so forth. Th88fash03 0 1.1kipact antep us-0.0001 TDs was kepay the tw(T

Clandestine weapons development programs have already come from both ends of the fuel cycle. South Africa, which voluntarily gave up its weapons in an IAEA-supervised program, and Pakistan made their weapons from the front end of the fuel cycle. Libya was headed that way until it recently abandoned the attempt. There is uncertainty about the intentions of Iran.

India, Israel, and North Korea obtained their weapons material from the back end of the fuel develop weapons if the material is available. North Korea withdrew from the Non-Proliferation Treaty at short notice, expelled the IAEA inspectors, and reprocessed the spent fuel from their Yongbyon reactor, thus acquiring the plutonium needed for bomb fabrication in a very short time.

However, the supplier countries that should take back the spent fuel for treatment are not likely to do so without a solution to the waste-disposal problem. In a world with a greatly expanded nuclear power program there will be a huge amount of spent fuel generated worldwide. The projections mentioned earlier predict more than a terawatt (electric) of nuclear capacity by 2050 producing more than 200,000 tons of spent fuel per year. This spent fuel contains about 2,000 tons of plutonium and minor actinides and 8,000 tons of fission fragments. The once-through fuel cycle cannot handle it without requiring a new repository on the scale of United States' Yucca Mountain every two or three years.

Reprocessing with continuous recycle in fast reactors can handle this scenario since only the fission fragments have to go to a repository and that repository need only contain them for a few hundred years rather than a few hundreds of thousands of years. The supplier-user scenario might develop as follows. First, every one uses LWRs and all of the enrichment is done by the supplier countries. Then the supplier countries begin to install fast-spectrum systems as burners. These would be used to supply their electricity needs as well as to burn down the actinides in their own and the returned spent fuel. Eventually, when uranium supplies begin to run short, the user countries would go over to fast-burner systems, while the supplier countries would have a combination of breeders and burners as required.

The diplomatic problems in instituting such a regime are formidable. The user nations will sign on only if they feel comfortable with the supply guarantees that are included. The situation is no different in principle with what we all live with today, for oil and gas supply.

Reactors for the Future

A. Generation-IV International Forum (GIF).

In the year 2000 the United States proposed that a group of nations, all of which had nuclear reactors and were interested in nuclear power for the long term, get together to examine options for the reactor of the future. Initial members of the GIF[9] were Argentina, Brazil, Canada, France, Japan, South Korea, South Africa, Switzerland, United Kingdom, and the United States. China, the European Union, and Russia joined in the year 2006. The consortium examined options and selected six as the most promising for further development (appendix B). In 2005 five of the GIF members, Canada, France, Japan, U.K., and U.S.A., agreed to a coordinated program of R&D on these six.

Three of the designs have a fast neutron spectrum which allows a closed fuel cycle where all of the very long lived components in the spent fuel can be continuously recycled in the reactor. In this way, only components that need isolation for hundreds of years need go to a waste repository, considerably simplifying the design of repositories. All three operate at moderately high temperature with improved electrical efficiency and with low pressure simplifying reactor vessel design.

The liquid sodium-cooled version is the one where there is the most experience. These kinds they would need for nuclear use. For example, countries that do not now have nuclear energy would need to set up regulatory systems to oversee such development. The INPRO methodology tells them the requirements. This is particularly important in the areas of safety, environmental impact and spent fuel handling. Reports on work to date are available from their website[9].

INPRO plans to begin sponsoring cooperative R&D programs in its next phase which is scheduled to begin this year.

C. Small Reactors

Small reactors have been proposed for many uses including supplying energy to places far from national electrical grids, supplying process heat, producing hydrogen, making better and inherently safer units, getting manufacturing economies through mass production, etc. It seems as if nearly every country involved in nuclear power programs has some effort in this area. There is far too much activity to describe in a brief paper. If interested in the details of world wide activity, the reader should look at a recently produced summary by the Uranium Information Center[11].

In the past, a multiplicity of small reactors has not proved to be economical for power production. Every time a manufacturer has started with a small unit, the economies of scale have driven the size up to reduce the cost per unit energy. There clearly are cases where small unit can be economical (ship propulsion, for example) and we will have to wait and see how this technology works out and what its costs will be.

Conclusion

This paper provides a snapshot of the nuclear power situation as of today. Nuclear energy is attractive in a world where fossil fuel energy sources costs are rising, and where there is a real worry about security of supply. In addition, concerns about global warming make the greenhouse-gas free nuclear option attractive. Nuclear energy is already the low cost option for electricity production in some areas of the world and if carbon caps or taxes are implemented broadly, nuclear will be more
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Weapons proliferation concerns are real and the science and technology communities cannot, even in principle, deliver a proliferation free nuclear fuel cycle. Ideas exist for multilateral guarantees of supply of fuel for civilian power reactors and for long term storage of nuclear waste materials. If internationalizing the fuel cycle can be done successfully, proliferation

Appendix A: ADVANCED THERMAL REACTORS Being Marketed[3].

Country and developer	Reactor	Size MWe	Design Progress	Main Features (improved safety in all)
US-Japan (GE-Toshiba)	ABWR	1300	Commercial operation in	

Country and developer	**Reactor**	**Size MWe**	**Design Progress**	**Main Features (improved safety in all)**
Germany (Framatome ANP)	SWR-1000 (BWR)	1200	Under development, pre-certification in USA.	Innovative design High fuel efficiency
Russia (Gidropress)	V-448 (PWR)	1500	Replacement for Leningrad and Kursk plants.	High fuel PWR)

REFERENCES

[1] The data is courtesy of the U.S. Department of Energy's Office of Nuclear Energy.

[2] The Uranium Information Center (UIC) in Australia (http://www.uic.com.au) is one of the most accessible sites for information about almost everything related to nuclear energy.

[3] UIC, Nuclear Issues Briefing Paper # 16, December 2005.

[4] John F. Ahearne, American Physical Society Forum on Physics and Society, April 2006, (http://www.aps.org/units/fps/newsletters/2006/april/article1.cfm).

[5] UIC, The Economics of Nuclear Power, Briefing Paper # 8, April 2006.

[6] The New Economics of Nuclear Power, World Nuclear Association, December 2005, (http://www.world-nuclear.org/economics.pdf).

[7] The New Economics of Nuclear Power, World Nuclear Association, December 2005, (http://www.world-nuclear.org/economics.pdf).

[8] The required isolation time in this system depends on the efficiency with which the long lived material can be separated from the fission fragments. For example for 99.9% separation efficiency, the isolation time would need to be about 500 years while for 99.5% it would be about 1000 years. It is more likely that 1000 years is the right number to plan for at this stage.

[9] Generation IV International forum, (http://gif.inel.gov/).

[10] (http://www.iaea.org/OurWork/ST/NE/NENP/NPTDS/Projects/INPRO/index.html).

[11] UIC Small Nuclear Power Reactors, Briefing Paper # 60, February 2006.

[12] GIF Roadmap, (http://gif.inel.gov/roadmap/).