Review Draft- For Discussion Only

NUCLEAR POWER REPORT

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September 2006

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Financial support for this draft 'evergreen' briefing note has been received from the Government of British Columbia Ministry of Energy, Mines and Petroleum Resources as one of a series of background papers for the Paths to Low Carbon Futures research project.

Updating and amendment of this paper are anticipated as the research project proceeds.

Comment and critique are invited and welcomed, and can be sent c/o Clint Abbott at cabbott@uvic.ca.

Nuclear Power: A Status Report
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1. 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. Th

In summary, nuclear energy is already attractive on economic grounds in some 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.

2. The Current Generation of Nuclear Power Plants

The number of nuclear power plants under construction, in planning, or under discussion is growing rapidly. According to the World Nuclear Association, the International Atomic Energy Agency and the U.S. Energy Information Agency as of January 2006 24 new plants were under construction, 35 more in the active planning stage, and another 115 under discussion.[1]. More have been added since then and Canada has joined the list.

Most of the new construction will be the light water cooled reactors (LWRs) of the type
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3. 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
Switzerland	2.88	-	4.36
Netherlands	3.58	-	6.04
Czech Rep	2.30	2.94	4.97
Slovakia	3.13	4.78	5.59
Romania	3.06	4.55	-
Japan	4.80	4.95	5.21
Korea	2.34	2.16	4.65
USA	3.01	2.71	4.67

Another analysis of relative economics is in a report by the World Nuclear Association entitled, “The New Economics of Nuclear Power”[6]

Component	**Fission Fragments**	**Uranium**	**Long-Lived Component**
Per Cent Of Total	4	95	1
Radioactivity	Intense	Negligible	Medium
Untreated Required Isolation Time (years)	200	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. This solves the repository problem (and the proliferation problem discussed in the next session). If you want to skip the step using the MOX cycle in a LWR there is no problem in doing so. If you do want to use a MOX cycle in LWRs, you have a way to treat the spent MOX fuel. The Global Nuclear Energy Partnership (GNEP) program announced by the U.S. President earlier this year has attracted broad international interests because it gets everyone together on the same fundamental issues.

6. Proliferation Prevention

There is no proliferation proof nuclear fuel cycle. Nevertheless, preventing the proliferation of nuclear weapons must be an important goal of the international community. Achieving this goal becomes more complex in a world with a much expanded nuclear-energy program involving more countries. Opportunities exist for diversion of weapons-usable material at both the front end of the nuclear fuel cycle, U-235 enrichment; and the back end of the nuclear fuel cycle, reprocessing and treatment of spent fuel. The more places this work is done, the harder it is to monitor.

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 cycle using heavy-water-moderated reactors to produce the necessary plutonium.

The level of technical sophistication of these countries ranges from very low to very high, yet all managed to succeed. The science behind nuclear weapons is well known and the technology seems to be not that hard to master through internal development or illicit acquisition. It should be clear to all that the only way to limit proliferation by nation states it through binding international agreements that include incentives, effective inspection as a deterrent, and effective sanctions when the deterrent fails.

The science and technology community can give the diplomats improved tools that may make the monitoring that goes with agreements simpler and less overtly intrusive. These technical safeguards are the heart of the systems used to identify proliferation efforts at the earliest possible stage. They must search out theft and diversion of weapons-usable material as well as identifying clandestine facilities that could be used to make weapons-usable materials.

The development of advanced technical safeguards has not received much funding recently. An internationally-coordinated program for their development needs to be implemented, and proliferation resistance and monitoring technology should be an essential part of the design of all new reactors, enrichment plants, reprocessing facilities and fuel fabrication sites.

Recently IAEA Director General Dr. ElBaradei and United States President Bush have proposed that internationalization of the nuclear fuel cycle begin to be seriously studied. In an internationalization scenario there are countries where enrichment and reprocessing occur. These are the supplier countries. The rest are user countries. Supplier countries make the nuclear fuel and take back spent fuel for reprocessing, separating the components into those that are to be disposed of and those that go back into new fuel. A variant is where some international consortium supplies and takes back the fuel.

If such a scheme were to be satisfactorily implemented there would be enormous benefits to the user countries, particularly the smaller ones. They would not have to build enrichment facilities nor would they have to treat or dispose of spent fuel. Neither is economic on small scales and repository sites with the proper geology for long term storage may not be available in small countries.

Reducing the proliferation risk from the back end of the fuel cycle will be even more complex than from the front end. It is essential to do so because we have seen from the example of North Korea how quickly a country can “break out” from an international agreement and 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.

7. 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 of reactors are currently running in France, Japan, and Russia, and one has been running in the United States until recently.

A second is cooled with a mixture of lead and bismuth. Experience here is with reactors in Russian submarines of the Alpha class. Two of these submarines have been lost at sea and there is concern that there may be an un-understood problem of some type.

The third variant uses a molten-salt mixture in which the fuel is dissolved. The salt continuously circulates and fuel is added and spent fuel is taken out continuously. It has operational attractiveness, but the molten salt is quite corrosive making for a difficult materials problem.

Two of the Gen IV types are cooled with helium gas. Both are “passively safe” in that a loss of gas flow does not raise fuel temperatures high enough to release radioactive materials. Pressures in these reactors are high and so are temperatures. One is designed to have a fast neutron spectrum and to operate above 800.C giving high electrical efficiency. The other has a thermal neutron spectrum and runs at about 1000.C. The very high temperature is supposed to allow efficient production of hydrogen. However the very high temperature does generate difficult materials problems.

Finally, there is super-critical water-cooled reactor that can be designed with either a fast or a thermal neutron energy spectrum. Operational pressures are very high but temperature is also considerably above ordinary water-cooled reactors improving electrical efficiency.

My personal opinion is that the nearest to deployment of all of these is the sodium-cooled reactor. The others will need considerably more R&D. It is not clear now which of the FSRs is the best solution for the long term.

B. INPRO

The 26 member International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was created by the IAEA in the year 2000[10]. It stated objectives are:

> To help assure that nuclear energy is available to contribute, in a sustainable manner, to the energy needs of the 21st century.
>
> To bring together technology holders and users so that they can consider jointly the international and national actions required for achieving desired innovations in nuclear reactors and fuel cycles.

It has a phased agenda and to date has been developing an evaluation methodology for the use of nuclear power in a variety of countries and for a variety of uses. It has looked at applications including electricity generation, hydrogen production, process heat, and desalinization. Its output has been mainly focused on developing tools that countries not now major users of nuclear energy can use to determine the infrastructure and support systems 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.

8. 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 cost's 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 economically attractive everywhere.

Set against these positive factors are concerns about safety, waste disposal and weapons proliferation. Safety is mainly a technical, regulatory and operational issue. The new generation of nuclear plants is inherently safer than the old because of their greater use of passive safety systems. Strong regulatory systems are a must, however. A serious nuclear accident anywhere in the world will deal a blow to nuclear energy everywhere.

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spent fuel is leading to world wide collaboration on the development of the necessary technology. It will take of the order of twenty years to fully demonstrate the system, but that is more a matter of selecting the best option rather than proving the principle.

Weapons proliferation concerns are real and the science and technology communities cannot, even in principle, deliver a proliferation free nuclear fuel cycle. This has to be a job for the international community, and ideas are arising for internationalizing the fuel cycle. If this can be done successfully, proliferation opportunities will be much reduced. It will not be easy to develop a system where users of nuclear energy can be assured of security of supply of the necessary fuels. This is a problem for the diplomats.

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 Japan since 1996-7. In US: NRC certified 1997, FOAKE.	• Evolutionary design • More efficient, less waste • Simplified construction (48 months) and operation
USA (Westinghouse)	AP-600 AP-1000 (PWR)	600 1100	AP-600: NRC certified 1999, FOAKE. AP-1000 NRC design approval 2004.	• Simplified 48 48 48 600

Country and developer	**Reactor**	**Size MWe**	**Design Progress**	**Main Features (improved safety in all)**
Russia (Gidropress)	V-448 (PWR)	1500	Replacement for Leningrad and Kursk plants.	• High fuel efficiency
Russia (Gidropress)	V-392 (PWR)	950	Two being built in India, Bid for China in 2005.	• Evolutionary design • 60-year plant life
Canada (AECL)	CANDU-6 CANDU-9	750 925+	Enhanced model. Licensing approval 1997.	• Evolutionary design • Flexible fuel requirements • C-9: Single stand-alone unit
Canada (AECL)	ACR	700 1000	ACR-1000 proposed for UK. Undergoing certification in Canada.	• Evolutionary design • Light water cooling • Low-enriched fuel
South Africa (Eskom, Westinghouse)	PBMR	165 (module)	Prototype due to start building 2006.	• Modular plant, low cost • Direct cycle gas turbine • High fuel efficiency
USA-Russia et al (General Atomics - OKBM)	GT-MHR	285 (module)	Under development in Russia by multinational joint venture.	• Modular plant, low cost • Direct cycle gas turbine • High fuel efficiency

REFERENCES

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[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]