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NUCLEAR POWER REPORT

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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. This, coupled with rising costs of fossil fuels and concerns about environmental pollution from fossil fuel power plants, has lead to an increase in orders for new plants, mainly from Asia, but beginning to impact North America and Europe as well.

Section 2 of this report 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.

Section 3 gives some estimates of the comparative costs of nuclear generated and fossil fuel generated electricity. Nuclear electricity is becoming more competitive and in many places is projected to be the low cost option.

There is considerable R&D going on to develop the next generation of reactors that might use fuel cycles different from those used today. Before describing this effort (section 7), it is worth spending some time on the potential problems that lead to the search for new types of reactors and new fuel cycles.

Section 4 discusses when we might run out of the natural Uranium-235 needed for today's LWRs. Estimates of natural uranium availability are necessarily crude since very little exploration has been done in the past several decades. Also, this section introduces alternate fuel cycles that can increase resources by 100 fold.

Section 5 analyses the problem of how to deal with spent fuel. There seems to be a convergence of views focusing on destroying the 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.

Section 6 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.

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 known as Generation III (Gen III). Compared to the previous generation of reactors these are characterized by simplified design, more emphasis on passive safety systems and modularity in construction where feasible. Capital cost targets are around $1200-1400 per kilowatt of electric power (KWe) for a new reactor built in the United States. Costs per kilowatt depend of course on where the reactor is to be built and some places would be more expensive, Japan for example, and some would be less costly, China for example. Both the purchasers and the suppliers of nuclear power plants now recognize the advantages of standardized design and we will not see the situation of the last round of construction in the 70s and 80s where nearly all power plants were of unique characteristics. What we will probably see instead is a few manufacturers dominating the market with their standardized designs. The choices will be based, as usual, on a combination of costs and national interests.

The first of these Gen III reactors, the GE ABWR, has been operating in Japan since 1996 and received design certification from the U.S. Nuclear Regulatory Commission in 1997. Since then other designs have evolved and today Gen III LWRs are available based on GE, Westinghouse, and Framatome designs. There are also Russian designs.

The situation of the Canadian CANDU design is unclear. The newest CANDU is a kind of hybrid; heavy water moderated and light water cooled, using low enriched uranium (2% U-235). This combination is said to allow considerable simplification in the design and to bring down the cost per KWe, but it does require enrichment which was not needed in the previous generation of CANDUs.

India is building heavy water moderated reactors as well, and also developing breeder reactors based on the thorium – U-233 cycle.

Two excellent sources of more detail on activities are available. One of these is the Uranium Information Centre in Australia[2]. Appendix A is a summary table from one of their reports[3]. 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.

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
Canada	2.60	3.11	4.00

US 2003 cents/kWh, Discount rate 5%, 40 year lifetime, 85% load factor.
Source: OECD/IEA NEA 2005.

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.

4. 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 has been pointed out by many that this is a highly uncertain number. There has been little exploration for uranium ore for many years and the true number may be much larger. Also, there are about 4000 MMT of uranium in sea water. If cost effective extraction systems can be devised, supply will be hugely expanded.

However, the price of uranium is only a minor part of the cost of reactor fuel for today's LWRs. U-235 represents only about 0.7% of natural uranium, so to reach the 4% enrichment level used in fuel today, nearly 6 kg of uranium are required per kg of fuel. Added to that are costs of enrichment and fuel fabrication. The total is about $1600/kg of fuel. At today's fuel burn-up levels this represents about 0.5¢/kwh in the cost of electricity. If uranium prices went to $300/kg the cost of nuclear electricity would only increase by about another 0.5¢/kwh.

Today's reactors use about 68,000 tonnes of fuel per year. Energy demand is expected to increase by a factor of 2-3 between now and 2050 and, if nuclear electricity increases by the same amount, all of the roughly 15 MMT now thought to be available would be needed for 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.

5. 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)	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. In return for these benefits, user countries would give up potential access to weapons-usable material from both the front end and the back ends of the fuel cycle. If this is to work, an international regime has to be created that will give the user nations guaranteed access to the fuel that they require. This is not going to be easy and needs a geographically and politically diverse set of suppliers.

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.

The technology of waste treatment and disposition is in good shape, though the political acceptability of any system is an issue in some countries. What appears now to be a convergence of opinion on the merits of transmutation of the long lasting components of 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 construction and operation • 3 years to build • 60-year plant life
France-Germany (Framatome ANP)	EPR (PWR)	1600	Future French standard. French design approval. Being built in Finland. US version being developed.	• Evolutionary design • High fuel efficiency • Low cost electricity
USA (GE)	ESBWR	1550	Developed from ABWR, under certification in USA	• Evolutionary design • Short construction time
Japan (utilities, Westinghouse, Mitsubishi)	APWR	1500	Basic design in progress, planned at Tsuruga	• Hybrid safety features • Simplified Construction and operation
South Korea (KHNP, derived from Westinghouse)	APR-1400 (PWR)	1450	Design certification 2003, First units expected to be operating c 2012.	• Evolutionary design • Increased reliability • Simplified construction and operation
Germany (Framatome ANP)	SWR-1000 (BWR)	1200	Under development, pre-certification in USA.	• Innovative design • High fuel efficiency

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

Appendix B: Generation IV Advanced Reactors Selected for further R&D[12].

	Neutron Spectrum (fast/ thermal)	Coolant	Temp. (°C)	Pressure*	Fuel	Fuel Cycle	Size(s) (MWe)	Uses
Gas-cooled fast reactors	fast	helium	850	high	U-238+	Closed, on site	288	electricity & hydrogen
Lead-cooled fast reactors	fast	Pb-Bi	550-800	low	U-238+	Closed, regional	50-150** 300-400 1200	electricity & hydrogen
Molten salt reactors	epithermal	fluoride salts	700-800	low	UF in salt	Closed	1000	electricity & hydrogen
Sodium-cooled fast reactors	fast	sodium	550	low	U-238 & MOX	Closed	150-500 500-1500	electricity
Supercritical water-cooled reactors	thermal or fast	water	510-550	very high	UO_2	Open (thermal) Closed (fast)	1500	electricity
Very high temperature gas reactors	thermal	helium	1000	high	UO_2 prism or pebbles	Open	250	hydrogen & electricity

* high = 7-15 Mpa
\+ = with some U-235 or Pu-239 ** 'battery' model with long cassette core life (15-20 yr) or replaceable reactor module.

Sources:
DOE 19/9/02.
DOE EIA 2003 New Reactor Designs

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

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[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/).

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