Nuclear Energy:
Current Status and Future Prospects

Professor Burton Richter
Stanford University
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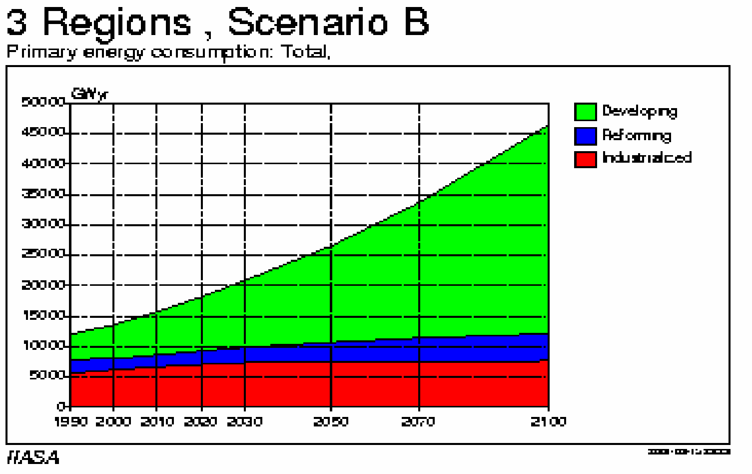
1. Introduction

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. With the current mix of fuels, growing the economy increases emissions and increased emissions lead to climate change that will eventually harm the economy. Nuclear energy offers one part of the way out of this circle. In this paper I discuss the reasons for and the size of the projected growth in nuclear energy; safety issues; and the coupled issues of waste disposition and proliferation prevention. An appendix describes the state of reactor technology and where it might be heading.

2. Why Nuclear?

Many forecasts of energy demand in the 21st century have been made and all give roughly the same answer. The International Institute of Applied Systems Analysis, for example, predicts in their mid-growth scenario (figure 1) primary energy demand increasing by a factor of two by mid-century and by nearly another factor of two by the end of this century. By the year 2030 the developing countries are projected to pass the industrialized ones in primary energy use, and China will pass the United States as the largest energy consumer. It is worth noting that economic growth in China and India is already higher than assumed in that scenario.

Fig. 1. IIASA Projection of Future Energy Demand



Supply constraints on two out of the three fossil fuels are already evident. Oil prices have surged and now are over $60 per barrel. Demand is rising at an average rate of about 1.5 million barrels per day per year (faster recently), requiring the output of another Saudi Arabia every ten years to keep up with increased demand.

While there is a lot of natural gas, there are transport constraints that are limiting availability to the big consumers. Natural gas prices have risen and now are at the unprecedented level of $9-$10 per million BTU.

The only fossil fuel in abundant supply is coal. However, it has serious pollution problems. Expensive technological fixes are required to control environmental problems that have large-scale economic consequences.

Concern about global warming is increasing and even the United States government has finally said that there is a problem. The Intergovernmental Panel on Climate Change (IPCC) forecasts, in the business-as-usual case, an increase in atmospheric carbon dioxide to 750 parts per million by the end of the century with a consequent global temperature rise of 2° to 5° C, less at the equator and more at the poles. We can surely adapt to this increase if it is small and occurs smoothly. If it is large and accompanied by instabilities in climate, economic and societal disruptions will be very severe.

The global-warming issue has caused prominent environmentalists to rethink their opposition to nuclear power. The question to be confronted is which devil would they rather live with, global warming or nuclear energy? James Lovelock, among others, has come down on the side of nuclear energy.

When economic self-interest and environmental self-interest both point in the same direction, things can begin to move in that direction. They now both point to the need for new large-scale energy sources and carbon-free energy is the most desirable. Nuclear energy is one such source. While it cannot be the entire solution to the energy supply and environmental problems, it can be an important part if the public can be assured that it is safe, that nuclear waste can be disposed of safely, and that the risk of weapons proliferation is not significantly increased by a major expansion.

3. Nuclear Power Growth Potential

At present there are about 440 reactors worldwide supplying 16% of world electricity (NEA Annual Report 2004). About 350 of these are in the OECD supplying 24% of their electricity. The country with the largest share of nuclear electricity is France at 78%, whose carbon-dioxide intensity (CO_2 per unit GDP in purchasing power parity terms) is half the world average (figure 2), encouraging for the environmentalists. About 30 new reactors are under construction now, mostly in Asia.

Fig. 2. CO_2 Intensity

Area	**GDP (ppp)** (Billions of U.S. Dollars)	**CO_2/GDP Kg/$(ppp)**
World	42,400	0.56
France	1,390	0.28

Projections for growth in nuclear power are uncertain because of uncertain costs along with the three potential problems mentioned earlier, safety, waste disposal, and proliferation risk. The IAEA projection (figure 3) of July 2004 for the year 2030 ranges from a high of 592 GWe (gigawatt-electrical) to a low of 423 GWe. This represents a net growth of between 16% and 60% over the next 25 years. The recent MIT study "The Future of Nuclear Power" (July 2003) projected about 1000 GWe by 2050 and a recent Electricite de France projection is for about 1300 GWe (private communication). The more aggressive growth numbers imply completions of about two 1-GWe power plants per month for the next 45 years.

Fig. 3. Nuclear Power Projection to 2030

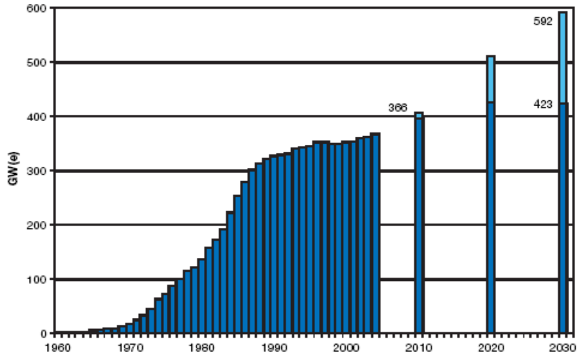


FIG.1. Historical growth in worldwide installed nuclear power capacity, 1960–2004, and the Agency's latest low and high projections through 2030 (low projections: dark blue bars; high projections: light blue bars). (Source: Energy, Electricity and Nuclear Power Estimates for the Period up to 2030, July 2004, *Reference Data Series No. 1, IAEA, Vienna (2004)).*

The cost of the new Finnish light water reactor (LWR) reactor is about Euro 1800 per KWe. Costs will come down with series production and locations more benign than northern Finland. Recent presentations to a DOE special committee on the future of nuclear energy in the U.S., by Westinghouse, General Electric and AREVA, claimed that cost of electricity from a new nuclear plant in the U.S. would be comparable to a coal plant after first-of-a-kind engineering costs have been recovered and after coming down the learning curve with five or so new plants. Even so, projections like those above will represent the expenditure of 1-2 trillion dollars on nuclear plants in the next 50 years. It is not clear that we have the trained personnel for the construction, operation, or regulatory needs of a system that large. However that is another story. We may not need all the people if the waste disposal and proliferation issues are not addressed soon.

4. Safety

There's little new to say on safety. Reactors of the Chernobyl type have never been used outside the old Soviet bloc. Even for reactors of that type, the accident would not have happened had not the operators, for reasons we will never know, systematically disabled all of the reactor's safety systems.

The new generation of light-water reactors has been designed to be simpler to operate and maintain than the old generation, and has been designed with more passive safety systems. Some designs are claimed to be passively safe in any kind of emergency.

With a strong regulation and inspection system, the safety of nuclear systems can be assured. Without one, the risks grow. No industry can be trusted to regulate itself when the consequences of a failure extend beyond the bounds of damage to that industry alone. Recent examples of corrosion problems in a U.S. reactor and in several Japanese reactors show again the need for rigorous inspections.

5. Spent Fuel Treatment

In discussing the safe disposition of spent fuel, I will set aside proliferation concerns for now, and return to them later. Looking separately at the three main elements of spent fuel (figure 4) might lead one to believe that there should be little problem. There is no real difficulty in principle with the uranium (U) which makes up the bulk of the spent fuel. It is not radioactive enough to be of concern; it contains more U-235 than natural ore and so could be input for enrichment, or could even be put back in the mines from which it came.

Fig. 4. 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

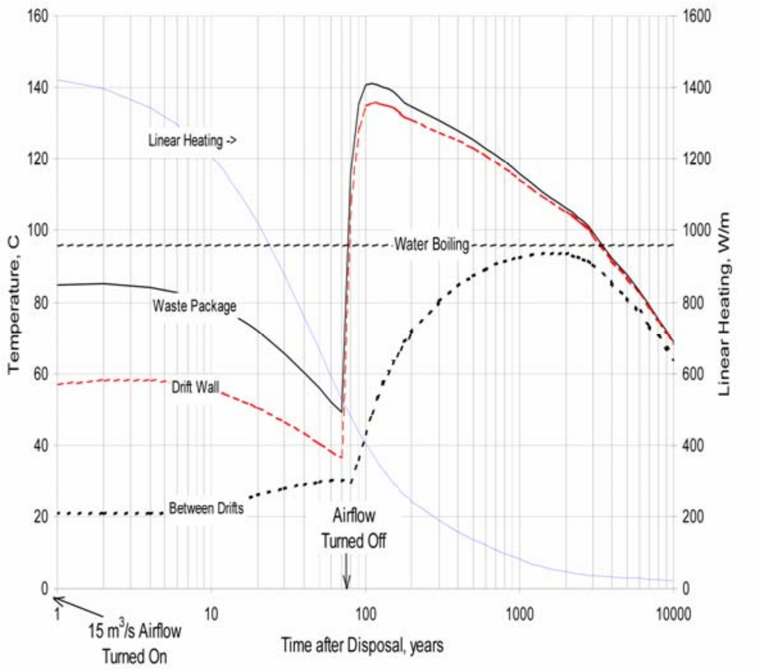
There is no scientific or engineering difficulty in dealing with fission fragments (FF) alone, the next most abundant component. The vast majority of them have to be stored for only a few hundred years. Robust containment is simple to build to last the requisite time. There are two long-lived FFs, Iodine-129 and Technetium (Tc)-99. No biological system has any ability to separate isotopes, so I-129 can simply be diluted with nonradioactive iodine. The Tc is relatively inert and only present at a low level. It can be handled with the actinides as described below.

The problem comes mainly from the last 1% of the spent fuel which is composed of plutonium (Pu) and the minor actinides, neptunium, americium and curium. For some of the components of this mix, the toxicities are high and the lifetimes are long. There are two general ways to protect the public from this material: isolation from the biosphere for hundreds of thousands of years, or transmutation by neutron bombardment to change them into more benign FFs.

Isolation is the principle behind the “once through” system as advocated by the United States since the late 1970s as a weapons-proliferation control mechanism.
The plutonium in the spent fuel is not separated from the rest of the material, and so cannot be used in a nuclear weapon. I do not believe the once-through system is workable in a world with a greatly expanded nuclear power program.. Its problem is a combination of public suspicion that the material cannot remain isolated from the biosphere for hundreds of thousands of years, and technical limitations.

The first technical problem comes from the heat generated in the first 1500 or so years of storage (figure 5) which limits the density of material that can be placed in a repository (the early heat generated from FFs is not difficult to deal with). The decay of plutonium-241 to americium-241 which then decays to neptunium-237 is the main source of heat during the first 1000 or so years. Limitations on the allowed temperature rise of the rock of a repository from this source determine its capacity.

Fig. 5. Computed Yucca Mountain Repository Temperatures for Direct Disposal of 25 Year Old, 50 GWD/MT PWR Fuel



The second technical problem is the very-long-term radiation. Here the same plutonium-to-americium-to-neptunium decay chain maximizes the long-lived component, requiring isolation from the biosphere for hundreds of thousands of years.

To use a United States example, if nuclear energy were to remain at the projected 20% fraction of U.S. electricity needs through the end of the century, the spent fuel in a once-through scenario would need nine repositories of the capacity of Yucca Mountain. If the number of reactors in the U.S. increases by mid-century to the 300 GWe projected in the MIT study, the U.S. would have to open a new Yucca Mountain every six or seven years. This would be quite a challenge since the U.S. has not been able to open the first one. In the world of expanded use of nuclear power, the once-through cycle does not seem workable.

The alternative to once-through is a reprocessing system that separates the major components, treating each appropriately and doing something specific to treat the component that produces the long-term risks. The most developed reprocessing system is that of France and I will use it as a model. They start by separating spent fuel into its three main components, FFs, uranium, and the actinides which are further split into Pu and the three minor actinides. They make mixed oxide fuel, MOX, by mixing the Pu with an appropriate amount of U. The extra U goes back to an enrichment facility. The fission fragments and minor actinides are vitrified for eventual emplacement in a repository. The glass used in vitrification appears to have a lifetime of many hundreds of thousands of years in the clay of the proposed French repository. The French Parliament has held a series of hearings early this year and is expected to soon issue its report on the acceptability of this system.

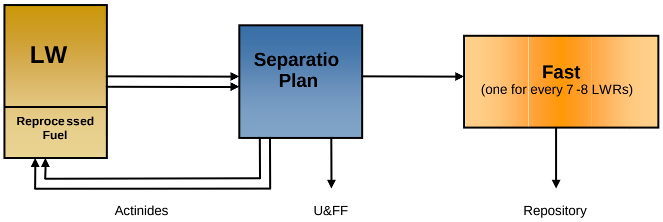
MOX fuel plus vitrification solves part of the problem but not all of it. The next question is what to do with the spent MOX fuel. The French plan is to keep it unreprocessed until fast-spectrum reactors are deployed commercially (see the appendix for a description of the reactor types). These fast-spectrum reactors have higher average neutron energy than the LWRs now in use and can burn a mix of plutonium and uranium-238 and, in principle, burn all of the minor actinides as well. It is possible to create a continuous recycling program where the plutonium from the spent MOX fuel is used to start the fast-spectrum system, the spent fuel from the fast-spectrum system is reprocessed; all the plutonium and minor actinides go back into new fuel, and so forth. In principle, nothing but fission fragments goes to a repository and these only need to be stored for a few hundred years.

This sounds good in principle, but there’s much work to do before putting it into practice. The only fast-spectrum system with which there is much experience is the sodium-cooled fast reactors (SFR). However, only plutonium-uranium fuel is qualified for the SFR. Fuel containing minor actinides is not. Facilities to test and qualify the new fuels are in short supply. The U.S. has foolishly killed off its Fast Flux Test Facility at Hanford. France plans to shut down the PHENIX reactor in 2009. The only facilities that will be left are in Japan and Russia. Clearly a coherent international program is needed to support and to use these remaining facilities in an international R&D program.

The two other fast-spectrum systems under discussion in the international Generation IV program, lead-cooled and gas-cooled, are far behind the SFR in readiness for deployment. In the U.S. there is talk of selecting a fast-spectrum candidate in 2012. In France the date is 2015. In both cases, it is doubtful that enough will be known about alternates to the SFR to allow them to be chosen.

The Nuclear Energy division of the U.S. DOE has been looking at a model system for treating spent fuel. The reference system (figure 6) uses both light-water reactors and fast-spectrum reactors. The light-water reactors are used to burn down the plutonium in the LWR spent fuel, followed by burning the remainder in fast-spectrum systems with continuous recycle. The idea is that Pu is stabilized in the thermal reactors and eventually burned down in the fast systems. One does not have to wait for large scale deployment of fast systems to begin the treatment of spent fuel.

Fig. 6. Two-Tier Schematic



The light-water reactors in the model burn half the plutonium. It is assumed that in the future, light-water reactors will reach a burn-up of 70 MW-d/kg and in that case it would take one recycle of an inert matrix fuel (plutonium plus minor actinides without additional uranium) or three recycles of MOX fuel to reach a 50% plutonium burn-up. The fast-spectrum system is configured as a burner rather than a breeder with a conversion ratio (plutonium out/plutonium in) of 0.25 or less. In this model one fast spectrum burner is required for every 7-8 LWRs. It is, thus, possible to deploy special burners and to begin a consumption of the spent fuel before the world has switched to fast-spectrum systems.

The only materials that go to a repository are fission fragments and the long-lived actinides that leak into the fission-fragment waste stream because of small inefficiencies in the separation process. If these can be held to about one percent or less, the required isolation time is on the order of 1000 years, a time for which isolation can be assured with very high confidence. Efficiencies of greater than 99% have been demonstrated on a laboratory scale.

The government could fund the construction and operation of the burners from the current 0.1 cent per KW-hr waste disposal fee built into the cost of nuclear electricity by selling the electricity and from savings from the much reduced cost of the simplified repository required.

If, for proliferation prevention reasons, one requires that the minor actinides be included in the LWR fuel it will take longer to deploy a system. Only standard MOX has been licensed for LWRs. For fast burners, no fuel containing the minor actinides have been licensed anywhere.

6. Proliferation Prevention

Preventing the proliferation of nuclear weapons is 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 effective inspection as a deterrent, and effective sanctions when the deterrent fails.

The science and technology (S&T) 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.

One issue that is being revisited is the relative proliferation resistance of the once-through fuel cycle compared to those of various reprocessing strategies. An analysis has been done recently by an international group of experts for the U.S. Department of Energy. Their report, “An Evaluation of Proliferation Resistant Characteristics of Light Water Reactor Fuels,” November 2004, is available on the DOE’s website (www.nuclear.gov) under Advisory Committee Reports. The methodology created in this analysis is to give a risk score for every phase of the nuclear fuel cycle and then sum the risks over time. An example comparison is shown in figure 7. The results of this analysis are shown in figure 8. Surprisingly, the once-through and all of the variants of reprocessing have about the same score. The increased risk during the phase where plutonium is available in reprocessing scenarios is balanced by the decreased risk of diversion during enrichment, where less enrichment is required, the increased radiation barrier after the second burn and the increased difficulty of fashioning the weapon from ever-more degraded materials. These scores should not be read as precision measurements. All they really say is that to sensible people once through is not that different from reprocessing.

Fig. 7.

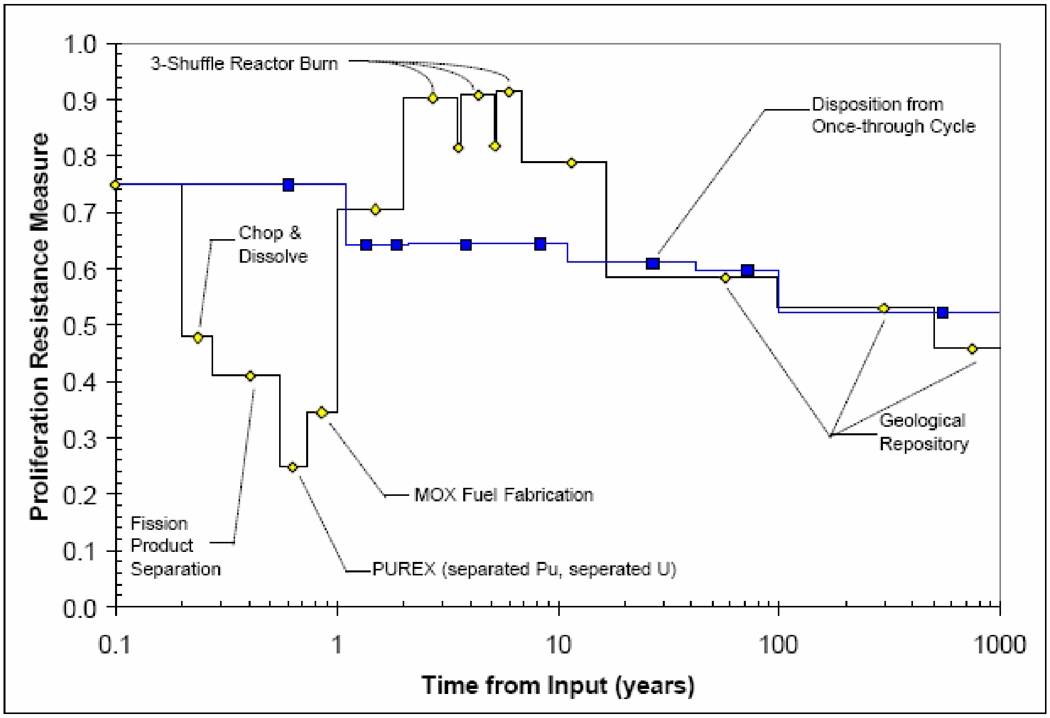
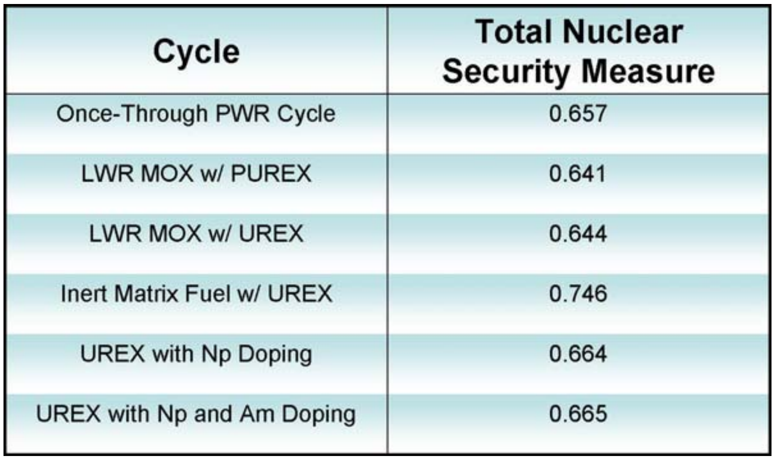


Figure 3 – Relative Proliferation Resistance Measure as a Function of Time for the PUREX/MOX Process (back-end of once-through cycle shown for comparison)

Fig. 8. Relative Proliferation Resistance Score (higher is better)



Cycle	Total Nuclear Security Measure
Once-Through PWR Cycle	0.657
LWR MOX w/ PUREX	0.641
LWR MOX w/ UREX	0.644
Inert Matrix Fuel w/ UREX	0.746
UREX with Np Doping	0.664
UREX with Np and Am Doping	0.665

The isotopic vectors from these various scenarios are shown in figure 9. As one goes down the table, heat generation and radiation levels increase, and it becomes more and more difficult to fashion a weapon from the residual plutonium. The last two entries in the table for IMF (Pu or Pu plus MA without the U that is in MOX) give heat and radiation levels that is very difficult to deal with. Needless to say this report has generated considerable controversy. A second and independent analysis is being done by a group in the international Generation IV program. It will be interesting to see if they get the same answer.

Recently the 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.

Fig. 9. Plutonium Isotopic Mixture and Properties after Various Reactor Treatments (ANL)

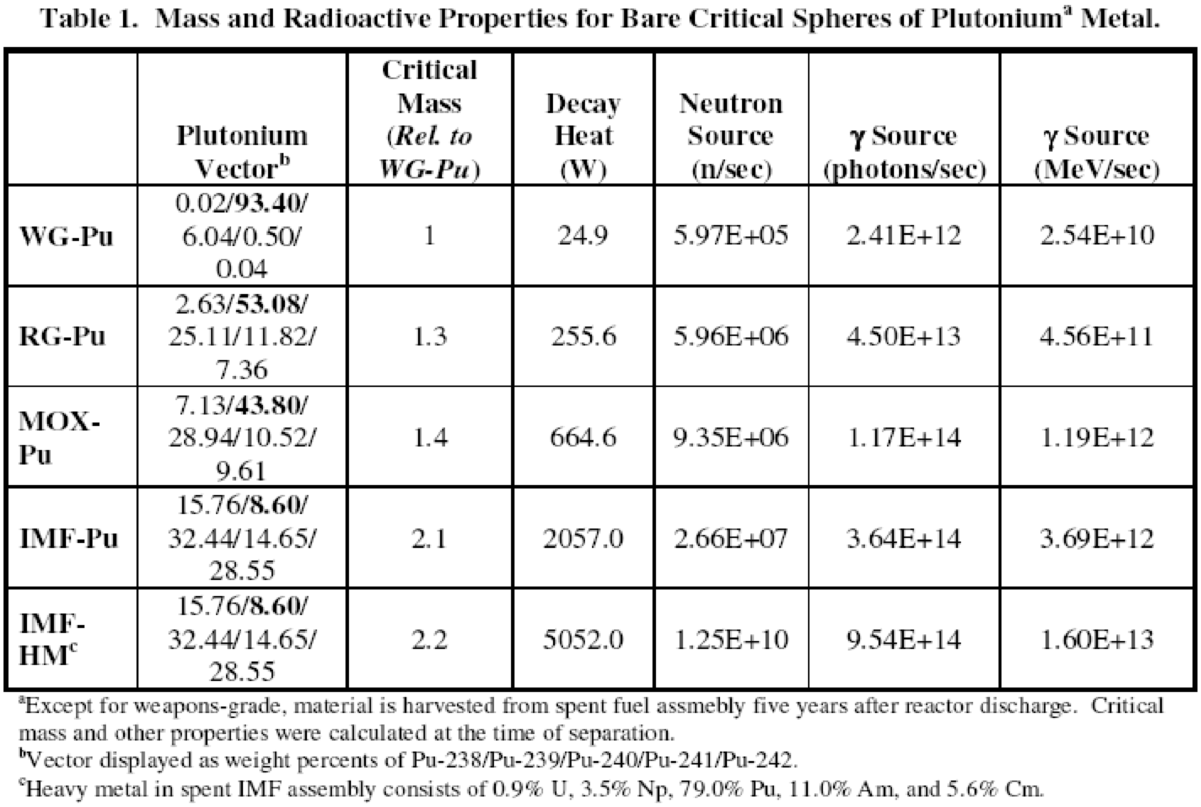


Table 1. Mass and Radioactive Properties for Bare Critical Spheres of Plutonium[a] Metal.

	Plutonium Vector[b]	Critical Mass (*Rel. to WG-Pu*)	Decay Heat (W)	Neutron Source (n/sec)	γ Source (photons/sec)	γ Source (MeV/sec)
WG-Pu	0.02/**93.40**/ 6.04/0.50/ 0.04	1	24.9	5.97E+05	2.41E+12	2.54E+10
RG-Pu	2.63/**53.08**/ 25.11/11.82/ 7.36	1.3	255.6	5.96E+06	4.50E+13	4.56E+11
MOX-Pu	7.13/**43.80**/ 28.94/10.52/ 9.61	1.4	664.6	9.35E+06	1.17E+14	1.19E+12
IMF-Pu	15.76/**8.60**/ 32.44/14.65/ 28.55	2.1	2057.0	2.66E+07	3.64E+14	3.69E+12
IMF-HM[c]	15.76/**8.60**/ 32.44/14.65/ 28.55	2.2	5052.0	1.25E+10	9.54E+14	1.60E+13

[a] Except for weapons-grade, material is harvested from spent fuel assmebly five years after reactor discharge. Critical mass and other properties were calculated at the time of separation.

[b] Vector displayed as weight percents of Pu-238/Pu-239/Pu-240/Pu-241/Pu-242.

[c] Heavy metal in spent IMF assembly consists of 0.9% U, 3.5% Np, 79.0% Pu, 11.0% Am, and 5.6% Cm.

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 may not be available with the proper geology in small countries for 100,000-year storage. 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 supplier 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 producing more than 20,000 tons of spent fuel per year. This spent fuel contains about 200 tons of plutonium and minor actinides and 800 tons of fission fragments. The once-through fuel cycle cannot handle it without requiring a new repository on the scale of 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. 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.

7. Conclusion

In summary, nuclear energy can be an important component of a strategy to give the world the energy resources it needs for economic development while reducing consumption of fossil fuels with their greenhouse-gas emissions. If this is to happen on a large scale, advances in both physical science and technology and political S&T will be required.

The physical S&T can produce better and safer reactors, better ways to dispose of spent fuel, and better safeguards technology. This can best be done in an international context to spread the cost and to create an international technical consensus on what should be done. Countries will be more comfortable with what comes out of such developments if they are part of them.

While the physical S&T development can best be done in an international context, the political S&T to create better mechanisms for proliferation control can only be done internationally. The IAEA seems to be the best place to start and the first baby steps may be in progress. However, it will be difficult for an organization as large as the IAEA to create a framework for a new international nuclear enterprise if too many voices are involved at the start. It might be better if a broadly-based, but compact, subgroup does the initial work. If I were setting up such a group, the minimum membership would include Canada, China, France, India, Japan, Russia, South Korea, United States, and representatives of the larger potential user states, Brazil and Indonesia, for example.

I think it will not be difficult to create mechanisms for the front end of the fuel cycle. The back end will be the problem and the most intractable issue is likely to be where the final waste product is stored.

Appendix 1

Reactor Types

This section aims to give a quick summary of the reactor types in use or under development. Three good general web sites for more information are the Uranium Information Center (www.uic.com.au), the World Nuclear Association (www.world-nuclear.org), and the DOE's Nuclear Energy division web site (www.nuclear.gov).

1. The Workhorses

Most of the world's power reactors are fueled with enriched uranium and cooled with light water (LWRs). They come in two varieties; pressurized water and boiling water cooled. For the purposes of this summary they are equivalent. Until recently the U-235 enrichment was about 3.5%. The fuel produced about 33 GWt-d/MT (gigawatts-thermal days per metric ton of heavy metal). Enrichment has been going up and the energy produced per MT has been going up as well. It is forecast that with enrichments of 5%-6%, burn-up of up to 70 GWt-d/MT will be achieved within a decade or so.

Work on very long-lived cores is in progress and Toshiba is willing to sell a 100-MWe reactor with a life time of 20 years without refueling. While these reactors are expensive, they may be economical for places far from standard power grids and where the very large standard reactors are not needed.

2. Heavy Water Moderated

The original version of this type of the reactor is the Canadian CANDU. These are fueled with natural uranium, heavy-water moderated, and heavy-water cooled. They are continuously refueled, eliminating the shutdowns required to refuel the LWRs. Advanced versions are being developed in Canada and India. These are still heavy-water moderated, but light-water cooled. In addition, they may use enriched uranium. Canada is promoting a system that uses 2 % enrichment which together with the light-water cooling is said to allow a considerable simplification in design with a consequent reduction in capital and operating costs.

3. Thorium Cycle Reactors

Thorium itself is not fissionable but has a large neutron capture cross-section leading to the production of U-233 which is fissionable. Thorium reactors have been operated for development purposes in Europe, Russia, India, and the United States. India, which has large reserves of thorium and small reserves of uranium, has said it plans to develop thorium-cycle reactors for power production. The Indian plan starts with a heavy-water reactor to produce plutonium. The plutonium is used with thorium in a reactor operating as a breeder to produce U-233. The U-233 is then used with thorium in an advanced heavy-water reactor operating as a U-233 breeder.

4. Gas-Cooled Reactors

Reactors using carbon dioxide as a coolant have operated for many years in the United Kingdom. This design is now out of favor. Helium-cooled reactors are under development in several places. The most advanced is the Pebble Bed Reactor whose tennis-ball-sized fuel elements are composed of a uranium nugget surrounded by a carbon coating. The fuel elements move continuously through the reactor and no down time is required for refueling. Most work is based on a German design. A German 15-MWe prototype operated from 1966 –1988. South Africa and China are building models at the 100 -200 MWe scale. These are to be modular allowing the construction of large plants by combining many modules.

5. Sodium-Cooled Reactor

This reactor uses uranium and plutonium, produces a “fast” neutron spectrum (higher average neutron energy that the “thermal” spectrum of the LWRs), and can operate as a breeder producing more fuel than it consumes. Such reactors can use U-238 with plutonium as a fuel, thereby increasing the fuel supply more than a 100-fold compared with the natural abundance of U-235.

6. Generation IV

The Generation IV International Forum (GIF) was formed in January 2000 by ten countries (Argentina, Brazil, Canada, France, Japan, South Africa, South Korea, Switzerland, United Kingdom, and United States) and the European Union. The GIF looked at opportunities for development of the next generation of nuclear reactors and sorted through all the proposals selecting six for future R&D. These six are briefly described below.

> 6.1 Very High-Temperature Reactor: The VHTR is a thermal spectrum, helium gas-cooled reactor that is to operate at temperatures of 950° C or above. The main interest is in its potential to produce hydrogen. It would also have a higher thermal efficiency for electricity production. Hydrogen is to be produced through the sulfur-iodine process, but the efficiency of this process and its rate constants are not known at the temperatures being discussed. Difficult materials problems exist in building a reactor to operate at these high temperatures.
>
> 6.2 Super-Critical Water Reactor: This water-cooled thermal spectrum reactor operates with single-phase fluid flow above the critical point of water, hence its name. The purported advantages are higher thermal efficiency because of the higher temperature of the water allowed, and simplification in the design of the plant because there is no change in phase from water to steam.
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> 6.3 Molten-Salt Reactor: This uses a bath of molten fluoride salts with an epithermal spectrum. It is capable of continuous fueling and no fuel rods have to be fabricated. A small molten-salt reactor was operated in the United States years ago. The main problem of this type of reactor is the extremely corrosive nature of the fluoride salts.

6.4 Sodium Fast Reactor: This is to be an advanced version of the reactor described in section 5.6. This kind of reactor has been operated for many years in the U.S., France, Russia, and Japan. Its fast spectrum makes it potentially effective in transmutation of nuclear waste as well as in breeding. The concern with this type of reactor has been with leaks of highly flammable sodium cooling fluid. Japan has a proposed simplified design that uses much less sodium in its cooling system than the previous designs.

6.5 Gas Fast Reactor: This fast-spectrum reactor is helium gas-cooled. It has a potentially higher electrical efficiency as well and is purported to have safety advantages.

6.6 Lead Fast Reactor: This fast system is cooled with molten lead. The only real experience with it is in the Alpha-class submarines of the former Soviet Union. Two of these submarines were lost at sea for unknown reasons. The rest are sitting in the docks in Russia with their reactors cold and their lead frozen. Russia has been unwilling to allow the dismantlement and inspection of the reactors to look at the state of the piping. Lead is a highly corrosive fluid.