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NEW ENERGY TECHNOLOGIES:

A POLICY FRAMEWORK FOR MICRO-NUCLEAR TECHNOLOGY

COMMENTS ON THE DEVELOPMENT PATH NEEDED FOR PROLIFERATION-RESISTANT NUCLEAR POWER

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Introduction

I should like to divide this paper into three parts:

1. The overall energy context in which nuclear power will have to compete.

2. The significance of proliferation resistance as a criterion for future nuclear power and how well the new nuclear technologies under consideration achieve proliferation resistance goals.

3. Potential public, private, and international roles in the development, licensing, and commercialization of the new technologies.

It helps to think in examples, and I refer in what follows to three illustrative technologies:

1. The Radkowsky Thorium Power Corporation's attempt to develop and license a new more proliferation-resistant fuel (RTC fuel) that could be retrofitted into existing light water reactors.[1]

2. The attempt by a couple of utility groups and others to develop and license a pebble-bed modular high temperature gas-cooled reactor.[2]

3. The future prospect of developing, licensing, and deploying Small Innovative Reactors (SIR), especially reactors to be deployed under a wheel-spoke configuration, where the reactors would be fuelled at some central nuclear park and then sealed and sent out to client countries.[3]

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[11] Alex Galperin, Paul Reichert, and Alvin Radkowsky, "Thorium Fuel for Light Water Reactors – Reducing the Proliferation Potential of the Nuclear Power Fuel Cycle", *Science and Global Security*, 6 (1997), pp 265-290.

[2] Andrew Kadak, MIT, "MIT/INEEL Modular Pebble Bed Reactor," March 22, 2000. Exelon, "PBMR Briefing Presented to the U.S. NRC", January 31, 2001.

[3] E. Greenspan, et al, "The Encapsulated Nuclear Heat Source Reactor Concept for Developing and Industrial Countries," Fifth Nuclear Energy Symposium, Beijing, China, March 27-29, 2000; E. Greenspan and Neil Brown, "ENHS Reactor: Answer to Questions of the TOPS Task Force," presented at June 16-17, 2000 TOPS meeting by Mark Strauch; R.N. Hill, J.E. Cahalan, H.S. Khalil, and D.C. Wade, Argonne National Laboratory, in *Global 99: Nuclear Technology—Bridging the Millennia*, Proceedings of an International Conference on Future Nuclear Energy Systems, Jackson Hole, Wyoming, 29 August-3 September 1999.

The time spans for implementation of the three concepts could overlap some. But overall, the RTPC idea to replace the core in existing reactors would appear to have the most immediate impact if implemented. The pebble-bed reactor, a new reactor venture, could lead to implementation in the next generation – say a decade or so off -- of reactor deployments. And the SIR would appear more of a long-term concept targeted at a large expansion of nuclear power after the next couple of decades. Each concept, as indicated, claims proliferation-resistance advantages, as well as several others.

The Overall Energy Context

Two points seem to me of paramount importance:

1. ***Although nuclear power can play an important role in energy strategies to combat global warming, its role in this respect is likely to be limited. The nuclear industry cannot rely upon the greenhouse problem alone to justify a large expansion.***

That nuclear power is likely to play a limited role in combating the greenhouse problem may be surprising. At present, nuclear power worldwide generates approximately 2200 billion kwh per year.[4] Were this amount of electricity generated instead by coal plants, an additional quantity of carbon dioxide containing 550 million metric tons of carbon would be emitted to the atmosphere each year.[5] This is about 8.5% of total carbon emissions from fossil fuel combustion (6500 million tons per year). The comparable amount of carbon avoided by virtue of nuclear power in the U.S. is 155 million tons.[6]

Annual Carbon Emitted and "Saved" Today Worldwide Millions of tons Carbon		
	Coal (0.25 kgC/kwh)	Gas (0.10 kgC/kwh)
Carbon Saved Nuclear	550	220
Total Carbon Emitted	6500	6500

[4] U.S. Department of Energy, EIA, *Annual Energy Review 1997*, July 1998.
[5] This assumes an average carbon output from coal of about 0.25 kg C/kwh (based on 25 kg C/GJ and an average efficiency of 35.5%).

If, to look at matters the other way round, nuclear power were phased out, the carbon saving would be less since the replacement for nuclear would be not coal, but natural gas in combined cycle power plants (so long as natural gas remains in high supply). In this case, the extra carbon emitted by the gas plants would be about two-fifth of the 550 metric tons noted above, or 220 million tons per year.[7] During a (say) 30-year phase-out, the total extra carbon emitted would be 3.3 billion tons, out of a total of 225 billion tons expected to be emitted worldwide during that period – about 1.5 percent.

Cumulative Carbon to 2000-2030 w and w/o Nuclear Phaseout (billion tons Carbon)	
Extra Carbon if Phaseout	3.3
Total Carbon Emitted	225

The role of nuclear power in reducing greenhouse gas emissions will also be quite limited for the next several decades at least. This is partly because nuclear power does not at present appear suitable for a role outside the electricity sector (even if eventually it could become important for desalination, process heat, and hydrogen production). The emissions of carbon worldwide in both the electric and non-electric sectors are expected to be considerable. According to the principal business-as-usual demand scenario (IS92a) of the Intergovernmental Panel on Climate Change (IPCC), total carbon emissions from the energy sector are expected to grow from today's 6.5 billion tons to 13 billion tons in 2050, with total cumulative emissions of carbon through 2050 of 440 billion tons.[8]

Nuclear power is not likely to make a significant dent in this period. Nuclear power appears either saturated or on the way to being phased out in most or all of the OECD countries. Although growth is still planned, at least on paper, in several Asian countries, there is so little nuclear power in most of these countries today that it will be many years before nuclear capacity

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[6] Nuclear Energy Institute, "Meeting Our Clean Air Needs With Emission-Free Generation", 1999 [available at www.nei.org]. This corresponds roughly to a 0.7 capacity factor for a total nuclear generating capacity of 100 Gwe, and 0.25 kg C/kwh generated.
[7] Natural gas emits about 15 kg C/GJ compared to 25 kg C/GJ for coal; and the efficiency of gas turbines is about 50% compared to 35.5% for coal. This means that the carbon emitted by a modern gas plant is approximately 0.1 kg/kwh.
[8] Intergovernmental Panel on Climate Change, *Climate Change 1995: Impacts, Adaptations, and Mitigation, Summary for Policymakers*, Figs. 5 and 6.

could achieve a penetration of the energy sector of more than a few percent.[9] Let us say that, nevertheless, worldwide nuclear power could grow at just over 2%/y until 2050 to an installed capacity in that year of 1000 Gwe.[10] That would lead to cumulative avoided carbon emissions to that time of about 36 billion tons – roughly 8% of the total cumulative carbon emissions projected during this period.[11]

In the very long run, nuclear power could play a more significant role if it reached say 50-75% of global-installed power after 2050. The installed nuclear capacities associated with these projections are 3000 Gwe in 2075 and 6500 Gwe in 2100, roughly a ten-fold and twenty-fold expansion from today.[12] In these circumstances, the total carbon emissions avoided cumulatively would be approximately 290 billion tons through 2100. The latter would be one-fourth the projected cumulative carbon emissions to 2100 of 1150 billion tons – significant, though not decisive.

Cumulative Carbon Emitted and "Saved" Next 100 Years
Billions of tons Carbon

	To 2050	To 2100
Total Carbon Emitted (IPCC)	440	1150
Carbon Saved Nuclear (0.175 kg/kwh)	36 1000 GW in 2050	290 6500 GW in 2100

[9] Suzanne Jones, "Nuclear Power Expansion, Global Climate Change, and Non-Proliferation: East Asia and the Fate of Nuclear Power", manuscript, UC Berkeley, January 1999. For example, Jones notes that even if China's nuclear capacity grew according to China's ambitious plans to 150 Gwe by 2050, nuclear would still account for no more than 5% of the total primary energy in the country.

[10] I realize that a steady growth over the next 50 years is unlikely. If anything growth might be slow or even negative for a while and then take off. So this is just a back-of-envelope calculation.

[11] Carbon avoided is calculated on basis of 0.175 kg carbon avoided per kwh. This is roughly equivalent to that if there were not the indicated nuclear power growth, one-half of the alternative electric capacity would be from coal-fired plants and one-half from gas turbines. The cumulative avoided emissions are for the 21st century.

[12] The IPCC high-demand variant corresponding to the IS92a projections shows approximate total primary energy as follows: 360 exajoules in 1990, 420 EJ in 2025, 660 EJ in 2050, 970 EJ in 2075, and 1350 EJ in 2100. By 2050 and thereafter, electricity is assumed to be about one-half that of total primary energy; and nuclear electricity 40% of total electricity in 2050, 50% in 2075, and 75% in 2100. The total non-nuclear primary energy associated with these data is 358 EJ in 2000, 460 EJ in 2025, 609 EJ in 2050, 777 EJ in 2075, and 964 EJ in 2100. This growth may be roughly approximated by a 1%/y growth rate. The avoided carbon emissions due to nuclear power are calculated on basis of 0.175 kg/kwh; the carbon contribution of non-nuclear primary energy is calculated on basis of 19 kg C per gigajoule, roughly the global average today.

That the impact of such a robust nuclear future on global warming would be so limited is sobering, since the management of a nuclear system with the capacities considered above would be truly formidable. For example, a worldwide capacity of 6500 Gwe, if based on a once-through fuel cycle using light water reactors, would generate roughly 1200 tons of plutonium *annually*. If based on liquid-metal plutonium breeder reactors, it would involve the fabrication into fresh fuel annually of over ten thousand tons of plutonium. Virtually whatever the reactor technology, given plausible burn-ups, the spent fuel generated annually could hardly be less than about 50,000 tons – equivalent roughly to one Yucca Mountain repository being constructed every 18 months or so!

2. ***Advanced nuclear systems must be compared to similarly advanced fossil fuel and renewable energy configurations. The efforts now going into developing new non-polluting fossil fuel and renewable technologies are very substantial and provide rapidly moving targets against which nuclear will have to compete.***

Let's stipulate that any long-term competitor to nuclear will have to be pollution free, or almost so, with respect to particulates, sulphur oxides, and nitric oxides, and that it will have to have very low or zero emissions of carbon dioxide. Such technologies are, in fact, in the works, in two realms: fossil fuel technologies with decarbonization and renewable technologies. The recently released World Energy Assessment of the United Nations Development Programme provides a snapshot of the potential of these technologies.[13] By way of illustration, I note a couple of technologies and systems described in this report.

First, there are many ventures worldwide to develop coal gasification schemes that would drastically cut all significant air pollutants and allow for the sequestration of carbon dioxide. The following table summarizes some of these ventures now under development or investigation.

[13] United Nations Development Programme, *World Energy Assessment: Energy and the Challenge of Sustainability*, UNDP, 2000.

Alternative Technologies for Reducing Carbon Dioxide Emissions from 400 MW Coal Plants				
	Capital cost ($/kw)	Generation cost (c/kw-h)	CO_2 emissions (g/kw-h)	Cost of avoiding CO_2 emissions ($/t C)
Reference	1114	3.3	196.0	----
Pulverized coal	1661	5.3	0	111
Fluid-Bed	1675	5.2	0	104
IGCC	1466	4.5	20.4	73
SOFC	1427	4.3	6.8	60

Adopted from: World Energy Assessment, Chapter 8, Table 8.9
The Reference plant is an ultrasupercritical steam-electric plant without carbon-dioxide removal. The other technologies in the table are: a ultrasupercritical pulverized coal steam turbine plant, a pressurized fluidised-bed combustion plant, an integrated gasifier-combined cycle plant (IGCC), and a solid oxide fuel cell plant (SOFC).The annual charge rate is 11.5%; the coal price assumed is $1/gigajoule. A coal plant with carbon dioxide vented would emit about 200 grams C per kilowatt-hour. $100 per tonne of carbon avoided corresponds to about 2.0 cents per kilowatt-hour.

The alternative technologies noted in the table have all been subject to considerable development work and analysis. The pulverized-coal and fluidised-bed concepts are based on near-term technologies, capable of commercialization by 2005. The last two concepts will require further development of solid-oxide fuel cells and advanced gas separation technologies, potentially commercial by 2015.

The sequestration step allied with the technologies is at present still a concept not fully tested. However, there is much experience already in the use of carbon dioxide injection for enhanced oil recovery. For instance, one project begun in 2000 in Saskatchewan is injecting yearly up to 1.5 million tonnes of carbon dioxide, which is transported 300 kilometers to the injection site from a synthetic natural gas plant in North Dakota. And two very large projects are underway or planned for sequestration of carbon dioxide in aquifers. One is a Statoil project begun in 1996 to recover 1 million tonnes of carbon dioxide per year from the Sleipner Vest offshore natural gas field in Norway. A second now planned will involve the recovery and sequestration of more than 100 million tonnes of carbon dioxide from the Natuna natural gas field in the South China Sea.[14]

[14] *World Energy Assessment*, Chapter 8, pp 289-290.

In the long run, these and other projects to use fossil fuels with carbon sequestration will look most attractive economically if there develops a strong demand for hydrogen, either for direct burning, or more likely for use in fuel cells. And here there are many projects underway both to further develop solid oxide fuel cells and to develop low-temperature fuel cells that might be used in automobiles. The *World Energy Assessment* reports two examples of the scope of work now being done. One, by the end of 1999 the four largest Japanese manufacturers had already spent $546 million on fuel cell development. Secondly, the report notes that DaimlerChrysler expects that it will have spent $1.4 *billion* by 2004, when it intends to start producing engines for fuel cell vehicles.[15]

Aside from the technological issues that have to be sorted out in the development of these various advanced technologies, they face questions of public acceptance, as do new nuclear technologies. Predominant among these questions are two. One is the safety of hydrogen, which is widely viewed as an unsafe fuel, because it burns or detonates over a wider range of mixture with air than other fuels. Public acceptability is also likely to be a major issue with regard to carbon-dioxide sequestration, also an unfamiliar concept at least on the scales that will have to be involved. Reassurances based on theory alone are not likely to be convincing. One imagines that public acceptability could only be gained over time by the gradual introduction and spread of these technologies in demonstration and commercial applications.

Along with the work on decarbonized fossil fuel, there has been worldwide an impressive expansion of research and development of renewable technologies, including work on wind energy, biomass, and photovoltaics. For illustration, I refer to a couple of items relating to the last of these technologies. These illustrations are taken partly from papers by Robert Williams:[16]

PV sales grew 15%/y from 1983-1999, reaching 200 MWp/y in 1999. Systems costs have fallen correspondingly, from $17/Wp in 1984 to $6/Wp in 1996. There are good prospects that the systems cost could fall to less than $3/Wp after about 2005. At this cost, PV could actually become cost effective for over 10 million U.S. homes. (At 4 kW units with mortgage financing

[15] *World Energy Assessment*, Chapter 8, fn 45, p. 320.
[16] Robert Williams, “Addressing Challenges to Sustainable Development with Innovative Energy Technologies in a Competitive Electric Industry,” Princeton University, January 2001.

plus net metering – 10-12 cents per kilowatt-hour.) [17] In the longer term (~ 2025), PV costs of 6 cents per kilowatt-hour appear feasible – possibly low enough for central station applications with compressed air storage.[18]

The Concept of Proliferation Resistance

Certainly, one of the driving purposes of the current interest in new nuclear technologies is the goal of proliferation resistance. However, many experts believe that proliferation resistance should not be given much attention in the development of nuclear power. Their arguments are several. For example:

Proliferation is manifestly a political problem. Therefore, it is counterproductive to impose technical constraints on the development of nuclear power except in a few problem countries, such as Iraq and North Korea.

If countries are determined to obtain nuclear weapons they can do so most directly via a dedicated program and not through civil nuclear power.

Institutional constraints – that is, the entire non-proliferation regime defined by the NPT, safeguards agreements, supplier agreements, etc. -- are adequate and could be improved further without imposing technical constraints on nuclear power.

The shape of technology, international politics, and ways people think about weapons of mass destruction are impossible to gauge over the long term. Indeed, nuclear weapons may in the future be far less a matter of concern than other weapons of mass destruction. Therefore, we cannot sensibly attempt today to design a proliferation-resistant nuclear future for the long term.

In any case, as analyzed recently by a NERAC task force[19], in practice, it will be extraordinarily difficult to contrive an effective proliferation resistant nuclear fuel cycle for sophisticated states,

[17] Adam Payne, Richard Duke, and Robert Williams, "Accelerating Residential PV Expansion: Supply Analysis for Competitive Electricity Markets," *Energy Policy* (in press), March 2, 2001.
[18] Williams, op cit.

and difficult even to do so for unsophisticated states. But effective barriers could be erected against sub-national diversions of nuclear material.

To a point, there is merit in all of these arguments, and taken together they underscore the truth that the civilian nuclear fuel cycle is only a part, possibly even a small part, of the greater problem of addressing the proliferation of nuclear weapons and other weapons of mass destruction.

Nevertheless, although technical fixes against national proliferation will be extraordinarily difficult to achieve, it seems a worthy endeavor to at least try. Institutional arrangements, including international safeguards, are vital but it seems unwise to invest complete trust in such arrangements, unless there is no other choice. Still more important, however relevant or irrelevant the civil nuclear fuel cycle is to national proliferation, no one really denies that it certainly should be configured to make diversion by terrorists and sub-national groups as difficult as possible. The NERAC study, though as noted pessimistic about technical fixes against national proliferation, does argue that effective technical barriers could be erected against sub-national diversions of nuclear material. It really is hard to gainsay that we should – and, in regard to the terrorist threat, *must* -- explore ways to increase proliferation resistance through technical as well as institutional means.

How well do the technologies referred to earlier succeed in providing enhanced proliferation resistance? As noted, in the short term, the RTF fuel allows a technical fix for current light water reactors aimed at making the spent fuel extremely difficult to use for weapons purposes. The fuel is designed to operate on a denatured uranium-thorium once-through fuel cycle in current light water reactors and to achieve very high burn-up. In such a fuel cycle, the reactor would generate about 1/5 the plutonium generated in today's light water reactors, and the plutonium would contain a significant amount of Pu-238, and in general a mixture of plutonium isotopes very uncongenial to use in nuclear weapons. The U-233 generated would always be denatured with U-238 and it is contaminated with the gamma-emitting U-232 decay chain, which would

[19] Report by the TOPS Task Force of the Nuclear Research Advisory Committee (NERAC), *Technological Opportunities to Increase the Proliferation Resistance of Global Civilian Nuclear Power Systems (TOPS)*, October 2000, p. A2-5.

make more difficult any attempt to use the material for weapons, and also any diverted material more detectable.

The pebble bed modular reactor, in a slightly longer time frame, derives its proliferation resistance from the fact that the spent fuel would be high burn-up material in thousands of tiny carbon-coated spheres making it a comparatively unattractive source from which to recover weapons-usable materials. At any given time, the core of the reactor (nominally 110 Mwe) would consist of 360,000 pebbles (60mm in diameter), each containing about 7 grams of uranium (in the fresh fuel) in 11,000 microspheres (0.9mm diameter). [20] In the spent fuel, there will be plutonium. But at low burn-up, when the weapon-grade quality of the plutonium is relatively high, the plutonium content will be very low. At full burn-up, there will be more plutonium but far from weapon-grade quality with a high fraction of Pu-238. The total content of the plutonium even here will be about 5 kilograms per ton of uranium fuel, so that perhaps two hundred thousand pebbles would have to be diverted to obtain a critical mass.[21] (Though each pebble would weigh less than half a kilogram, as noted a tremendous number would have to be diverted if one was to acquire a critical mass). In addition, advocates of the gas-cooled reactor claim another virtue of the pebble-bed reactors – that they "don't need research reactors to train people to run [the] plants safely."[22]

Neither the Radkowsky fuel cycle or that of the Pebble Bed reactor can be said to be proliferation proof; no fuel cycle can be completely so. In general, they have three potential weaknesses. One, while the proliferation resistance advantages derive in part from the very high burn-up, the reactors do not have to be operated to full burn-up; removing the fuel early can make the weapons-quality of plutonium produced quite high. However, opposed to this, since the build-up of plutonium is relatively slow, extraction of plutonium at lower burn-ups would require a huge amount of material to be diverted. Two, over time the decay of the fission products will lower the radiation barrier of spent fuel, while the decay of Pu-238 will make it easier to use the extracted plutonium for weapons. Three, and most important, they all use uranium that is more highly enriched than typical today. Uranium enriched to 8-20% cannot be

[20] Andrew Kadak, MIT, MIT/INEEL, *Modular Pebble Bed Reactor*, March 22, 2000, PowerPoint view graphs.
[21] Andrew Kadak, "The Politically Correct Reactor," MIT, viewgraphs, undated. Kadak notes that 211,000 pebbles would have to be diverted for a weapon.

used for weapons, but the routes to weapon-grade uranium from such feed materials are easier than if one started with natural or 4% low-enriched uranium.[23] I come back to this point in a moment. The fabrication of the pebble-bed fuel and the fuel handling operations will require special attention when safeguards are developed.

On balance, however, overall these fuel cycles certainly have proliferation-resistance attractions, and if attractive on other grounds of safety, waste disposal, and economics, should be further developed and studied.

The above strategy of reliance on high-burn-up once-through fuel cycles does not look sustainable in the long run, if we are talking about a 3000-6500 GW capacity. For a nuclear power system of such magnitude, three overall approaches appear possible:

1. Stay with once-through high burn-up by exploiting uranium from seawater.

2. Employ breeder or particle-accelerator driven reactors that, to the extent possible, co-locate sensitive processes (such as reprocessing) with the reactor, do not separate the plutonium from other actinides, and otherwise seek to ensure that weapons-usable materials are never isolated.

3. Restrict nuclear power to large, international energy parks that would then export to individual countries, electricity, hydrogen, or possibly long-lifetime, sealed reactor cores that would be returned to the park as spent fuel after many years.

[22] Kadak, Ibid.
[23] As noted later, the RTF fuel is being developed and tested in part in Russia. The Russians are interested evidently in using highly enriched uranium in their VVERs, and apparently the RTF fuel can incorporate use of HEU. Certainly the RTF fuel using 20% uranium could be produced by blending down Russian weapon-grade uranium – so that 20% fuel obtained this way could be less expensive than low-enriched uranium fuel. That is an economic advantage to the RTF fuel and conceivably could encourage still greater blend down of Russian stocks of HEU than already agreed to by the U.S. and Russia. But, if the Russians actually wish to use HEU in their reactors, that may be a cause for concern.

Let me here examine the first of these and the last. I have dealt with the second alternative elsewhere.[24]

No Plutonium Recycling – Reliance on Once-Through Fuel Cycles

Let us assume that uranium sufficient to sustain a nuclear capacity of 3500 GWe (that is, a ten-fold expansion from today) can be extracted from seawater at a cost that has tolerable impact on the cost of nuclear power. It is uncertain if this can be done, but even if so[25], how proliferation resistant would such a world be?

For sake of specificity, let's assume a pebble-bed reactor of 100 Mwe. The uranium fuel for this reactor is about 8% U-235 and the projected burn-up is about 80,000 MWd/t. To get 1 kg of 8%U from natural U feed, requires about 17 Kg SWU and 15.6 kg of uranium feed (0.2% tails). At 80% capacity factor, this means that a 100 MWe reactor needs 1.1 t 8% U/y or 19 t SWU/y.

A 1000 t SWU enrichment plant could thus service about 50 reactors, so this could be taken as a reasonable size (Each URENCO plant, I believe, has capacity of 2000 t SWU). Okay, now consider a nuclear capacity of 3500 GWe. This will require 3500*187 t SWU/GWe = 654,500 t/y SWU, or about 650 1000 t SWU plants. 1 kg of 90%U requires about 225 kg SWU starting from natural uranium (and using a 0.2% tails assay). For a critical mass of 15 kg, this means 3.4 t SWU per bomb. So a 1000 t SWU plant could make about 300 bombs per year. Still more vexing, if one started with 8%U, approximately 84% of the separative work to get to 90% would already be done; so that a 1000 t SWU enrichment plant could make over 1750 bombs per year.[26]

[24] H.A. Feiveson, "Diversion-Resistant Nuclear Power," Stanford Workshop on the Future of Nuclear Power, June 2000.

[25] Marvin Miller, MIT, private communication, June 16, 2000. There is lots of uranium in seawater of course. But temperature limitations and/or other problems might make recovery below 100 meters impractical. And there are other difficulties of extraction that are far from having been worked out.

[26] To go from natural uranium to 90% U-235 with 0.2% tails assay requires 225 SWU and 180 kg of feed per kg of product. To go from 8% U-235 to 90% U-235 requires only 38 SWU and 11 kg of feed per kg of product. So about 84% of the separative work would have been done. Another way to see this is that to go from natural uranium to 8% U-235 requires 17 SWU and 15.6 kg of feed per kg of product. So that the total separation work required to get the needed 11 kg of 8% product used as feed to obtain 1 kg of 90% U-235 is 11*17 = 187 SWU. An additional 38 SWU is then needed, so that total separative work done would be 187 + 38 = 225 SWU. Note that it is not the 8% enrichment, instead of say 4% LEU that is the culprit. If one started with 4% U-235, about 2/3 of the work to get a kilogram of 90% U-235 would have been done.

If one used 6500 GWe (the IS92a projection with nuclear composing 3/4 of total electricity), matters would be worse. With that nuclear capacity, and let's say an average enrichment plant of 500 t SWU/y (reasonable still – for a plant this size would serve about 24 reactors), the total number of enrichment plants would be 2500.

So what is the bottom-line? Lots of enriched uranium too close to bomb quality, lots of separation plants, and lots of incentive for innovation to make isotope separation cheaper and quicker. To me this is an unsettling prospect.

International Energy Parks

There is one manifestation of future nuclear power that is not open to many of the proliferation-resistant objections noted above. This is to cluster all sensitive nuclear facilities in centralized, heavily guarded nuclear parks, perhaps under international control.

This is what is imagined in some of the SIR (let us call them, wheel-spoke) concepts. Long-life reactor-cores would be assembled at the central facility, imagined either as an international center or a center located in a "safe" and stable country with established nuclear power programs. The reactors would be sealed, and then exported to users in other countries where it could be "plugged in" to the remainder of the electric generation system. After some years (say, 15), the core/spent fuel would be returned to the central facility or to some international spent fuel repository. During the 15 years of operation, there would be no re-fuelling. In such a system, a country would need relatively few research facilities, operators, and other trained nuclear technicians and engineers.

This reactor concept has impressive proliferation-resistance credentials. These may be summarized as follows, adopting the analysis presented for the Encapsulated Nuclear Heat Source (ENHS) Reactor.[27]

[27] Ehud Greenspan and Neil Brown, "ENHS Reactor: Answer to Questions of the TOPS Task Force," partially presented at the June 16-17, 2000 TOPS meeting by Mark Strauch.

First, intercept by a sub-national group of the reactor, though it is transportable, would be a daunting challenge. The reactor is roughly 20 meters long, with a 3-meter diameter and weighs during transport approximately 200 tons. The fuel is embedded in a mass of lead-bismuth (solid during transport, liquid during operation) throughout the core life. As the authors of the ENHS note, the ENHS does not give a country a useful source of neutrons: "there are no blanket assemblies in or around the core and it is physically impossible to insert fertile material for irradiation." It would further be possible to "seed" the reactor with cesium before shipment, thus surrounding even the fresh fuel in a radiation shield.[28] If operated on the wheel-spoke concept, the client country would need no fuel fabrication facility and no fuel management capability. Because the reactor operates "almost autonomously," the client country would need few operators of the nuclear system. Overall, the wheel-spoke concept could diminish the rationale and opportunities for a country developing various research facilities and trained cadres of scientists and technicians that could later be diverted to weapons activities.

Presumably, the client country, unlike a terrorist group, would be able to break into the sealed reactor – but it should be possible to ensure that such an attempt to obtain nuclear fuel could not be done undetected. Moreover, the acquisition of the fuel after a break-in would probably take some time, days to weeks.

Opposed to these advantages, there are a couple of matters of concern. One, the spent fuel of the reactor (using a nominal 40 Mwe capacity) will contain roughly one tonne of plutonium and if the fuel is removed from the reactor before its full life time, the plutonium could be weapon grade or close to that. Secondly, the initial loading of the reactor would nominally be either 13 percent uranium or mixed-oxide LWR spent fuel. The uranium fuel, if obtained by a would-be proliferant, would not be weapons useable, but would require less separative work for production of weapons grade uranium than ordinary light water uranium fuel. If LWR spent fuel is used then some separation technologies applied to the LWR spent fuel would be required which may, in some configurations, allow the separation of plutonium.

[28] Ibid, "It is relatively easy to seed the fuel loaded into the ENHS module with gamma-ray emitters. The lead-bismuth in which the fuel is embedded will protect the transporting and installing personnel but will not protect potential proliferators."

These problems notwithstanding, a nuclear system based on international energy parks, if it could be developed, does promise an arguably proliferation-resistant strategy for nuclear power in the long run.

But are international energy parks realistic alternatives on political and economic and grounds? Politically, international energy parks run against the strong wish of many countries to become energy independent. Furthermore, one wonders whether countries will accept the idea of importing sealed nuclear reactors while eschewing any effort to develop a domestic cadre of nuclear engineers and scientists, and at least some nuclear research facilities. After all, the concept involves shipment of 200-tonne units into port cities and coastal locations. The safety of such shipments would have to be demonstrated beyond doubt to the public. Above all, the wheel-spoke concept will require either that client countries accept discriminatory restrictions on its nuclear activities not accepted by the countries hosting the nuclear parks, or that all countries, including the industrialized countries, accept a high degree of international control of their nuclear energy programs.

With respect to economics, the SIR wheel-spoke system must be compared to other schemes in which substantial activities occur at some central energy park with fuel, or electricity, or technology being sent out to distant places. In particular, consider three such schemes:

1. The generation of electricity at some similar central nuclear park, with the electricity then sent out by transmission lines to distant sites.

2. The generation of electricity at such a central nuclear park, the electricity used to disassociate water to produce hydrogen, and the hydrogen then sent out to distant sites.

3. The production of hydrogen directly from fossil fuels at some central location with the hydrogen then sent out to distant sites. Of course, here the central park does not have to be under international control or under international safeguards.

The first option would probably drive nuclear power to large units rather than the smaller, modular units we have been discussing. It appears at least as proliferation resistant as the SIR concept. Its safety and economics, as I have noted, would have to be compared to the SIR, or that of the SIR to it. There may be circumstances where electricity generation, say within a continent, would in fact be less costly than exporting sealed reactors, while the reactor option would look more attractive for shipments across water. And in the latter case, it may be important whether or not the intended electricity use is on a coast or inland.

If for whatever reason, the long-distance transmission of electricity does not look practical in some regions of the world and the commercialization of hydrogen as an energy fuel really does materialize, the second option might be considered. The nuclear electricity would be used to produce hydrogen either by electrolytic processes or thermochemical processes; and the hydrogen then disseminated. Again, this scheme appears as or more proliferation resistant than the SIR concept. But its economics are questionable. The electrolysis of water is relatively expensive. For example, at an electricity price of 3 cents per kilowatt-hour, the cost of electrolytic hydrogen would be about $18 per gigajoule. For comparison, the *World Energy Assessment* estimates the cost of making hydrogen from natural gas and coal today as $6 per gigajoule for natural gas and $11 per gigajoule for coal. These costs include the cost of storing the separated carbon dioxide underground.[29] Similarly, the prospects appear poor that hydrogen could be produced through thermochemical processes at costs competitive with hydrogen from natural gas technologies.[30] There is also an issue here of how the hydrogen, if it is produced at a central facility, could be transported. For example, where suitable pipelines could be built, the transport of hydrogen might look more attractive than in instances where they are not (though there might be other ways to transport hydrogen economically – for example, in hydrides carried by tankers).

This comparison immediately suggests an alternative energy park concept that does not involve nuclear power – and thus end-runs issues of proliferation resistance altogether. This is the third option -- to produce hydrogen directly from fossil fuels with carbon sequestration. In this case,

[29] *World Energy Assessment*, Chapter 8, p. 320, fn 43.
[30] Robert Williams, "Nuclear and Alternative Energy Supply Options for an Environmentally Constrained World, Nuclear Control Institute, Washington, D.C., April 9, 2001.

the scale of the centralized facility would be a matter of economics mostly, though again there might be some issues of energy independence also involved.

Development and Licensing Strategies

Government Support for Research, Development, and Commercialization

A critical question is the degree of government support for the development and commercialization of the new proliferation-resistance technologies. This question also arises for the fossil fuel and renewable technologies invoked earlier. Conventional wisdom holds that government should restrict support to research and development and leave any commercialization to the private sector. But recent work by Duke and Kammen, and Williams suggests that for radically new energy technologies government support for commercialization makes good economic sense.[31]

In theory, if a producing firm could retain the full benefits of its early commercial ventures (full-scale prototypes and beyond), it could "forward price," producing initially at a loss to bring down costs but, by so doing, gain market share and therefore maximize profit over the long term. However, in many fields, energy being one, the benefits of production experience can spill over to competitors (through reverse engineering, hiring the first firm's employees, and so forth). Duke and Kammen show that for these reasons and others, firms will always forward price less than what is socially optimal. Another consideration pointed out by Williams is that energy is a "commodity product." For many new high-technology products (e.g. pharmaceuticals), initial high cost is often not a serious constraint on commercialization, because such products offer benefits that the products they seek to replace do not. But this is not the case with radically new energy technologies – and the energy the consumer purchases is simply energy (the consumer cannot easily distinguish a green electron). Most of the benefits offered by the new energy technologies we have been considering are public, rather than private, benefits – such as improved proliferation resistance.

[31] R. Duke and D.M. Kammen, "The Economics of Energy Market Transformation Programs," *The Energy Journal, 20*, 1999; Robert Williams, "Addressing Challenges to Sustainable Development with Innovative Energy

There is, therefore, a strong argument for public-sector investment in improved energy technologies with significant environmental claims – such as potentially some of the new nuclear technologies under consideration here. The trick, however, will be to ensure that the government does not pick winners – say nuclear over clean coal, or clean coal over nuclear without considerable study.

Licensing Issues

Naturally, the development paths and licensing strategies for the new reactors will involve issues beyond proliferation resistance. For licensing, demonstration of safety and reliability will be of paramount importance. The strategies being pursued or proposed by the RTPC and pebble-bed reactor developers are instructive.

The Radkowsky-Reactor Fuel

Like the SIR concept, the RTF involves introduction of a new fuel. But unlike the SIR, the RTF does not involve new departures in coolants and control rod concepts. Still, it is instructive to note the efforts expended by RTPC as it moves toward licensing. The goal of RTPC is to license the Radkowsky fuel designs and eventually to act as a franchiser to license fabrication of the fuel in various countries.

One unusual step toward licensing is that RTPC has formed a wholly owned subsidiary to license the RTPC fuel technology in Russia for use in VVER nuclear power plants. The hope is that in a second stage this subsidiary will be used to license the technology in the U.S. and Europe, presumably after considerable experience with the fuels has been achieved in Russia. However, in prospect of licensing for the U.S. market, RTPC has proposed also a development program consisting of steps that must be taken to receive the necessary NRC licenses.

Technologies in a Competitive Electric Industry," Center for Energy and Environmental Studies, Princeton University, January 15, 2001.

Pebble-Bed Modular Reactor

If I understand this correctly, two partly intertwined licensing strategies have been proposed for the pebble-bed reactor. One, outlined by Exelon in a briefing to the Nuclear Regulatory Commission in January of this year[32], outlines a licensing approach that would rely to some extent upon the construction of a pebble-bed reactor in South Africa. [The pebble-bed consortium funding the development of the reactor proposed for South Africa includes Exelon (12.5% interest), the government-owned South African utility, ESKOM (40%), the Industrial Development Corporation of South Africa (25%), and British Nuclear Fuels Ltd (22.5%).]

A second, more radical, approach has been forwarded by a MIT/INEEL group.[33] The essence of the approach here is to short-circuit some of the licensing hurdles by moving fairly quickly to a series of actual tests on possibly a full-size prototype.

Under this approach, as outlined by Andrew Kadak, the MIT group would perform a probabilistic risk assessment (PRA) either on the MIT design of a pebble-bed reactor or would obtain a PRA of the ESKOM reactor. The PRA and deterministic analyses would be used to identify critical systems requiring tests. The tests would be conducted on a prototype (full scale if the plant is small enough) that would demonstrate the safety of the plant. According to Kadak,

> With the advent of new safer plants that derive their safety from inherent deterministic safety features as opposed to active or passive safety systems that must work, we have an opportunity to apply the license by test concept on a real plant on an integrated basis. The challenge is to develop the test envelope to validate safety in a licensing sense. What is desired is to avoid years of paper analyses and simulations which can be costly and still leave doubts in the regulator's and the public's minds about the real safety of the plant.[34]

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[32] "PMBR Briefing Presented to the US NRC," White Flint-Rockville, Maryland, January 31, 2001.
[33] Andrew Kadak, "Establishing a Safety and Licensing Basis for Generation IV Advanced Reactors," Nuclear Energy Research Initiative Proposal Program Announcement, Number DE-PS03-01SF22221, undated.
[34] Ibid, p. 8.

It is likely, I believe, that such license by test would be done with a containment, though the actual reactor, once licensed, would (in the view of proponents) not have to have one.[35]

The SIR

Licensing of SIRs presents, it seems to me, a difficult-to-resolve dilemma. In full operation, a nuclear power system based on the SIR wheel-spoke concept will require countries to accept as an integral part of their electricity generation capacity sealed reactors designed to run essentially unattended for 15-20 years. The promise of the SIR concept is that this will allow the country to forego the development of a nuclear infrastructure. But could a country gain enough confidence in the reactor and its safe operation without participating fully in its development and testing? That is, would not a country have to involve itself in exactly the sort of activities that SIR advocates believe is not needed and that confer the SIR concept much of its proliferation-resistance advantages?

Advocates of the SIR argue that it is not necessarily so that countries will insist on an indigenous capacity to test and oversee nuclear reactors, and they see an analog in the commercial aircraft industry. For example, many countries rely upon the U.S., French, or other aircraft supplier to certify the airworthiness of the aircraft. And they do this without significant participation in the process. Often, even aircraft servicing is done by the foreign supplier. More generally, the SIR advocates insist that a country relying upon foreign-supplied reactors is no different than countries relying today on Arab oil.[36]

But the aircraft analogy is not fully reassuring. Many – perhaps most – countries do maintain a significant indigenous capability to assess aircraft technology, albeit not one capable of building and testing the most advanced commercial jets. For this reason, the analogy does not really sweep away the aforementioned dilemma that countries will be loath to rely on reactor technologies that they have little capacity to monitor independently. I am not sure how this dilemma can be fully resolved short of carrying the logic of the SIR wheel-spoke arrangement to

[35] Personal communication, Andrew Kadak, March 8, 2001.
[36] Neil Brown, private communication, March 2001.

its extreme conclusion. The arrangement as envisioned requires the countries receiving the sealed reactors to abandon substantial sovereignty over their energy system. But perhaps it is necessary to go still further and to turn all nuclear energy over to international control. In such a system, the central parks and the reactors themselves would come under international management and control. This is indeed the view put forward at the beginning of the nuclear age by the Acheson-Lilienthal Report of 1946. This report (which formed the basis for the Baruch Plan for international control of nuclear weapons submitted to the United Nations by the U.S. in 1946) concluded as follows:

> … there is no prospect of security against atomic warfare in a system of international agreements to outlaw such weapons controlled only by a system which relies on inspection and similar police-like methods. The reasons supporting this conclusion are not merely technical but primarily the inseparable political, social, and organizational problems involved in enforcing agreements between nations, each free to develop atomic energy but only pledged not to use bombs. So long as intrinsically dangerous activities may be carried out by nations, rivalries are inevitable and fears are engendered that place so great a pressure on a system of enforcement by police methods that no degree of ingenuity or technical competence could possibly cope with them.