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The Search for Proliferation-Resistant Nuclear Power

By Harold Feiveson

Efforts are underway in the U.S., the European Community, and to a lesser extent in a few other countries, to design reactor technologies and fuel cycles that are safer, more efficient in their generation of nuclear waste, and more proliferation-resistant than today's systems.[1] This research, though its scope is modest at best given the enormous stakes involved, is potentially of great significance, if it succeeds in identifying technologies and fuel cycle options that could realistically be implemented. Of course, for this to happen, the new technologies and fuel cycles would also have to be attractive in all dimensions – conferring advantages in safety, waste disposal, and economics in addition to proliferation-resistance. But the focus here will be mainly on proliferation-resistance.

"Proliferation-resistance" refers to the adoption of reactor and fuel cycle concepts that would make more difficult, time-consuming, and transparent the diversion by states or sub-national groups of civilian nuclear fuel cycles to weapons purposes. The concepts examined here are those directed at providing what may be termed *intrinsic* or technical proliferation-resistance. There are also *extrinsic* or institutional innovations – for example, the application of improved safeguards and physical security protection systems – that could bolster barriers to proliferation. Both types of proliferation-resistance are essential, and neither should be considered sufficient by itself.

With respect to the intrinsic concepts, since none of those now being explored has yet been fully simulated, let alone resulted in actual prototype developments, and given also the vast political uncertainties involved, no hard and fast conclusions are possible. That said, many of the new concepts do appear promising – on paper. Among them are some featuring "once-through" fuel cycles, in which spent fuel is not reprocessed and fissile materials are not recycled, and which could potentially make fissile materials even less accessible for weapons uses for the next few decades than once-through fuel cycles based on today's light water reactors. However, over the long run, if nuclear power expands to a level sufficient to address concerns of global warming (that is, to a nuclear capacity ten to twenty fold that of today), these concepts will be viable only if essentially unlimited quantities of low-cost uranium can be found. And, even in this case, the scope of uranium flows and uranium enrichment that will be required will present a staggering challenge to assure that weapons materials are not diverted. Adding to this challenge will be the number of spent fuel repositories (each of them, in the long run, a potential plutonium "mine") which will have to be monitored for thousands of years. Fuel cycles that allow recycling will be still more vulnerable to diversions of weapons material. At least, no fuel cycle with recycling has been convincingly

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To Provide for the Common Defense

By Henry Kelly

The atrocious attacks on New York and Washington may force the first serious national debate on security issues in a generation. Isolated from the blood feuds of Europe and Asia, and protected by distance, wealth, and overwhelming military superiority, Americans have had the luxury of ignoring these issues. The absence of a draft made the issues even more remote. The discussions seemed to be about obscure issues in distant lands and none of them seemed to present a serious threat to our own territory. At the periphery of most citizens' attention, national security issues received almost no attention in the past few Presidential elections.

The price of public inattention has been high. It provided a shield behind which groups with financial interests or people obsessed with ideological zeal often dominated the debates. It was difficult to find a sober assessment of the nation's real security interests in the heat of this insiders' game. The public debate was cheapened by cynical focus on symbols instead of substance: "Did you avoid the draft in 1967?," "I propose to

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Call to Readers

A number of opinion pieces and letters have appeared in regional newspapers supporting the use of nuclear weapons in the ongoing conflict. Though these pieces may seem absurd, they could well increase Congressional support for developing a new generation of “bunker-buster” weapons and for possibly resuming nuclear testing to validate the designs. You can help restore sanity to this debate by writing letters to your local newspapers explaining the disastrous consequences of crossing the nuclear threshold. A sample letter may be found on the FAS website, www.fas.org. ❑

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shown to be otherwise.

The one concept under study that holds promise of being proliferation-resistant in a nuclear world 10-20 times expanded from today is the development of a hub-spoke arrangement where all sensitive activities are performed at a central, perhaps international, facility with sealed nuclear reactors, electricity, or hydrogen then sent out from the central facility to the “client” states. (By sensitive, I refer to activities in which weapons-usable materials can be isolated – for example, reprocessing of spent fuel to obtain plutonium or the isotope separation of uranium). But such a strategy faces enormous political and practical obstacles. And all the more so does the extreme of this strategy – to place all nuclear power under international control. One is led reluctantly to a pessimistic conclusion. This is that a nuclear power system worldwide of a scope to address global warming will pose unacceptable risks of nuclear proliferation without a drastic lessening of national control either over nuclear energy or over nuclear weapons.

The Concept of Proliferation Resistance

It should be recognized straight away that many in the nuclear industry

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worldwide believe that intrinsic or technical 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 nonproliferation 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 practice, it will be extraordinarily difficult to contrive an effective proliferation-resistant nuclear fuel cycle for sophisticated states, and difficult even to do so for unsophisticated states.

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 – as long as the world relies upon nuclear power. 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, whatever the connection of the nuclear fuel cycle to *national* proliferation, it is essential that it be configured to make diversion by terrorists and sub-national groups as difficult as possible. 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.

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Ideally, proliferation-resistance measures will address three broad categories of risk:

- The danger of fissile materials being diverted for weapons use by nations or sub-national groups;
- The danger that civilian nuclear facilities (power reactors, research reactors, reprocessing plants, uranium-enrichment plants, etc.) and trained cadres of nuclear scientists, engineers, and technicians in countries aspiring to acquire nuclear weapons will be used as a cover and/or training ground for a nuclear weapons program; and
- The danger of terrorist attacks that could scatter highly radioactive materials in populated areas either by directly attacking nuclear facilities or intercepting and dispersing shipments of materials.

For the most part, proliferation-resistance research has focused on the first category of danger. The nuclear concepts being investigated seek, for example, to ensure: that fissile materials are never isolated without a surrounding radioactive shield (a proliferation-resistance advantage of the current once-through fuel cycle); that the isotopic composition of plutonium in the spent fuel of a reactor is as unattractive for weapons use as possible[2]; that the quantities of plutonium generated in the spent fuel per kilowatt-hour of electricity is as small as possible; that the matrices in which the spent fuel are imbedded, by dint of size, discreteness, and weight, make diversion difficult or impossible and attempts at diversion highly transparent; and that shipments of fissile materials are minimized.

The second category of risk is more difficult to deal with. It is the goal of some of the concepts described below that the most “sensitive” parts of the fuel cycle could be located either in “safe” countries or at international centers. It is also a goal that some countries become willing to use nuclear power reactors imported from abroad without building up their own internal infrastructure of research reactors and other nuclear facilities. These are especially the goals of the hub-spoke concept. Such goals may represent wishful thinking. Which countries are “safe” will depend on who is making the judgement. Can the world build a secure nuclear future that depends on two classes of countries – one where certain activities and fuel cycles are barred and one where anything, or almost anything, goes?

To the extent that fissile and radioactive materials are made more difficult to obtain, some proliferation-resistance measures also address the third danger noted, that of radioactive-material scattering. But many of the

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proliferation-resistance concepts have little to do with this risk. The radioactivity of spent fuel and the radioactivity inside a reactor will be little affected whatever the fuel cycle. None of the measures being considered would reduce the risk, once terrorists got their hands on the material or got access to a reactor.

With respect to the other risks, however, researchers and developers are exploring several concepts. Although the list of concepts could be expanded, the following are fairly representative:

Thorium-based fuels which breed significantly less plutonium than current uranium fuel cycles and where any bred U-233 is denatured with U-238. The most developed variant of this concept is the Radkowsky Thorium Fuel (RTF) being developed by the Radkowsky Thorium Power Corporation. The intention is that the fuel could be retrofitted into existing light water reactors.[3]

High-temperature gas-cooled reactors. Utility groups in the U.S. and South Africa are in the process of developing one kind of such reactor, a pebble-bed modular high temperature gas-cooled reactor.[4]

Breeder reactors in which the plutonium is never completely separated from other actinides and in which the reprocessing and reactors are co-located.

Small Innovative Reactors (SIRs), where the reactors would be fueled at some central nuclear park and then sealed and sent out to client countries.[5, 6] The reactors would have lifetime cores, not requiring re-fueling, and at the end of the core life (say 15-20 years) would be sent back to the central facility unopened.

The time spans for implementation of the concepts could overlap some. But overall, the RTF concept 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. The breeder and SIR concepts are more long-term, targeted at a large expansion of nuclear power after the next couple of decades. Each concept claims proliferation-resistance advantages, as well as several others.

The rest of this paper looks first at the short and medium term, and then at the long term where nuclear power will either have to depend upon vast supplies of low-cost uranium (possibly from seawater) or on some sort of breeder reactor, combined with a hub-spoke arrangement in which sensitive parts of the fuel cycle are located in central, and heavily secured, facilities.

The recent renewed interest in nuclear power, and probably its principal ticket to a robust place in the world's energy future, is its potential contribution to coping with the problem of global warming.

Proliferation-Resistance – the Short and Medium Term

How well do these technologies succeed in providing enhanced proliferation-resistance? In the short term, the RTF fuel allows a technical fix for current light water reactors aimed at making the spent fuel 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 per kilowatt-hour of electricity produced. Moreover, the Pu-238 concentration in the discharged fuel would be 6.5 percent in the seed, and 12 percent in the blanket, compared to about 1 percent in today's pressurized water reactor (PWR) uranium fuel. This is significant because Pu-238 has a very high specific decay heat (560 watts/kg compared to 1.9 watts/kg for Pu-239 and 6.8 watts/kg for Pu-240). The decay heat emission then for the RTF seed is about three times that of normal PWR reactor grade fuel and for the RTF-blanket fuel about six times that of PWR fuel. The higher heat loads are likely to require special heat removal measures in the design of a weapon. The spontaneous fission rate of the RTF plutonium isotopic mixture will also be far greater than for PWR uranium fuel, making the design of a weapon somewhat more difficult, and for a crude weapon increasing the probability of a fizzle yield. 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 make more difficult any attempt to use the material for weapons, and also any diverted material more detectable.[7]

However, in this connection, it is vital to point out that the isotopic composition of plutonium, while adding complications to a weapons design, cannot preclude the use of the plutonium for weapons. In January 1997, the U.S. Department of Energy described the problems posed by high concentrations in the plutonium of Pu-238 and Pu-240. But it concluded that "virtually any combination of plutonium isotopes … can be used to make a nuclear weapon. … In short, reactor-grade plutonium is weapons-usable, whether by unsophisticated proliferators or by advanced nuclear weapon states. Theft of separated plutonium, whether weapons-grade or reactor-grade, would pose a grave security risk."[8]

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

FAS Website Update

While the FAS website has added considerable material on the post Sept. 11 conflict, we have also removed a smaller number of pages that might pose security concerns in the current environment. We will continue to balance the public's need to know with the need to uphold prudent security measures in the public interest. ☐

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 (at about 8 percent U-235) in the fresh fuel in 11,000 microspheres (0.9mm diameter). [9] 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 (almost 6 percent). The total content of the plutonium will be about 5 kilograms per ton of uranium fuel, so that perhaps 200,000 pebbles would have to be diverted to obtain a critical mass.[10]

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. First, 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, since the build-up of plutonium is relatively slow, extraction of plutonium at lower burn-ups would require correspondingly larger amounts of material to be diverted. Secondly, over time the decay of the 30-year half life fission products will lower the radiation barrier of spent fuel, while the decay of the 88-year half life Pu-238 will make it easier to use the extracted plutonium for weapons. Thirdly, and perhaps more importantly, they use uranium that is more highly enriched than typical today. Uranium enriched to 8-20% cannot be 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.[11] 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 have proliferation-resistance attractions, and if attractive on other grounds of safety, waste disposal, and economics, should be further developed and studied.

The Long Term Challenge – Nuclear Power and Global Warming

The quest for proliferation-resistance – for a new generation of reactors and fuel cycles — is driven by the long run. The reason for this is manifest. The recent renewed interest in nuclear power, and probably its principal ticket to a robust place in the world's energy future, is its potential contribution to coping with the problem of global warming. To make such a contribution, nuclear power would have to expand ten-fold at least over the next 100 years.

At present, nuclear power worldwide generates approximately 2200 billion kwh per year.[12] 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.[13] 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.[14]

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, and indeed many renewable-energy technologies such as wind power and photovoltaics, are not now being used or planned for a significant role outside the electricity sector (even if eventually these technologies 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.[15]

Nuclear power is not likely to make a decisive dent in this period. Even if, as appears unlikely, nuclear power worldwide grew at just over 2% per year until 2050 to an installed capacity in that year of 1000 GWe,[16] that would lead to a cumulative avoided carbon emissions to that time of about 36 billion tons – roughly 8% of the total cumulative carbon emissions projected during this period.[17]

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 capacity associated with these projections under the IPCC projections are 3000 GWe in 2075 and 6500 GWe in 2100, roughly a ten-fold and twenty-fold expansion from today.[18] In these circumstances, the total carbon emissions avoided cumulatively

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would be approximately 290 billion tons through 2100. The latter figure constitutes one-fourth the projected cumulative carbon emissions to 2100 of 1150 billion tons – significant, though not decisive.

The management of a nuclear system of a scope such as above would be truly formidable. For example, a worldwide capacity of 3500 GWe (a figure of illustrative convenience, ten times current capacity), if based on a once-through fuel cycle using light water reactors, would generate roughly 700 tons of plutonium *annually*, and would require on the order of one-half million tons of natural uranium annually. If based on liquid-metal plutonium breeder reactors, it would involve the fabrication into fresh fuel annually of over five thousand tons of plutonium. Without a nuclear system of formidable proliferation-resistance, is a nuclear future of such magnitude thinkable?

Proliferation-Resistance – the Long Term

For a nuclear power system of a magnitude necessary to address global warming, three overall approaches appear possible:

- Stay with once-through, high burn-up fuel cycles of the type discussed above, perhaps by exploiting uranium from seawater.
- 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.
- 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.

No plutonium recycling – continued reliance on once-through fuel cycles. Let us assume that uranium sufficient to sustain a nuclear capacity of 3500 GWe can be extracted from seawater or otherwise 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,[19] how proliferation-resistant would such a world be?

... perhaps it is necessary to go still further and to turn all nuclear energy over to international control. In such a system, the central park and the reactors themselves would come under international management and control.

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. A nuclear capacity of 3500 GWe will require 35,000 such reactors, and an enrichment capacity worldwide of about 450 million SWUs per year.[20] If one takes 2 million SWUs per year as a nominal capacity of one enrichment plant – about the size of a URENCO plant – 225 such plants would be required. A 2-million SWU plant could make about 600 bombs per year starting with natural uranium. It could make 3500 bombs per year starting with 8% uranium, the fuel enrichment of the gas-reactor fuel.[21]

Although arguably enrichment plants can be highly centralized, it is clear that a nuclear system based on a once-through fuel cycle will involve massive flows of natural and low-enriched uranium, lots of separation plants, and lots of incentive for innovation to make isotope separation cheaper and quicker.

Consider also the scope of the spent fuel (and contained plutonium) that will be generated in such a once-through world. The spent fuel would be on the order of 28,000 tons of heavy metal per year, approximately 0.4 of the capacity that has been planned for Yucca Mountain (70,000 tons).[22] So nominally we can imagine one Yucca Mountain being constructed every 2 ½ years. And each one will have to be guarded indefinitely, since after several decades, the radioactivity surrounding the plutonium will decay substantially making the spent fuel repositories prospective "plutonium mines."[23] Each repository (using the Yucca Mountain scale) would contain some 1400 tons of plutonium-239.[24]

These are unsettling prospects. And naturally what is unsettling derives from the magnitude of the nuclear enterprise; note that a high-temperature gas-cooled reactor is being used for illustration here. Any other reactor type on a once-through fuel cycle will generate equally or even more daunting quantities of nuclear materials.

Breeder Reactors. Because a once-through fuel cycle will involve such prodigious use of uranium and enrichment services, it is likely that a 3500 GWe nuclear power system will drive the nuclear industry toward breeder reactors. Such a development would minimize flows of uranium; but it would increase material flows of plutonium. For example, if a nuclear power system were based on the traditional liquid-metal plutonium breeder, a total capacity of 3500 GWe would involve the separation and fabrication annually of approximately 5 million kilograms of plutonium. For this reason, breeder concepts in which the plutonium is never fully separated from the fission products and/or other actinides have appeared worthy of study on proliferation-resistance grounds. Among these are:[25]

- Integrated fast reactors (which have been studied at Argonne National Laboratory and elsewhere), which employ pyro-processing technologies that do not separate the plutonium from the minor actinides and which integrate the reprocessing and reactor operation at a single site.
- Metal-cooled fast reactors using lead or lead/bismuth, where the reprocessing is designed to extract not all the fission products.
- Molten-salt thermal breeder reactors that would integrate continuous reprocessing with reactor operations.[26]

The questions they all raise are several. First, are the reactors conducive to allowing accurate material accounting by a safeguards' agency or would they demand almost complete reliance on containment and surveillance measures? (This is not to say that pyro-processing will be more difficult to safeguard than more traditional reprocessing). Second, can the fuel recycling equipment be operated in a manner that would allow the extraction of large amounts of plutonium fairly quickly, for example, by changing the reagents used in the reprocessing or adding a cleanup stage? And, finally, a question relevant to all nuclear power under national control: do the fuel cycles inevitably provide their operators with highly-useful knowledge for the acquisition of weapons- usable materials?

International Energy Parks. There is one manifestation of future nuclear power that is not open to many of the 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, or hub-spoke, concepts. Long-life reactor-cores would be assembled at the central facility, perhaps 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 15-20 years, the core/spent fuel would be returned to the central facility or to some international spent fuel repository. During the 15-20 years of operation, there would be no refueling. 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 by engineering teams at the Berkeley Department of Nuclear Engineering, the Lawrence Livermore National Laboratory, the Argonne National Laboratory, and Westinghouse Electric Company for the Encapsulated Nuclear Heat Source (ENHS) Reactor.[27]

First, appropriation 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, which could either be 13 percent enriched uranium, or a uranium-plutonium fuel having 11-12 percent plutonium, is embedded in a mass of lead-bismuth (solid during transport, liquid during operation) throughout the core life. It would further be possible to "seed" the reactor with gamma-emitting cesium-137 before shipment, thus surrounding even the fresh fuel in a radiation shield.[28] Furthermore, the ENHS does not give a country a useful source of neutrons: it is not possible to insert fertile material for irradiation. As noted, the core life of the reactor would be 15-20 years and during this period there would be no refueling. If operated on the hub-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 hub-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,

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FAS New Staff

FAS is pleased to announce several new staff members who have joined FAS.

Drew Wynn, our new Director of Development, arrived in October. He is responsible for building FAS' membership program, increasing contributions from individuals, and coordinating project directors' efforts to secure grants from foundations, government agencies, and corporations. Drew has extensive experience in raising organizational support for public interest and advocacy organizations. Before coming to FAS, Drew was the Director of Development at the Urban Institute, working with the President and trustees to raise corporate sponsorships and individual gifts for the Institute's general program. Any questions about benefiting FAS through bequests, deferred gifts, or other financial support can be addressed to Drew at (202) 454-4692 or by email at dwynn@fas.org.

Rajendra Aldis also joined us in October as an administrative assistant. Having recently graduated from Williams College with a BA in political science, Rajendra will be assisting with core administrative duties as well as providing support to the Learning Technology and Biological and Chemical Weapons Nonproliferation Projects. ❑

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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 days to weeks.

Opposed to these advantages, there are some matters of concern. First, the spent fuel of the reactor (using a nominal 40 MWe capacity) will contain roughly 600 kilograms of plutonium if the uranium fuel is used, and 1.4 tons of plutonium if the uranium-plutonium fuel is used.

Also, if the fuel is removed from the reactor before its full lifetime, the plutonium could be weapon grade or close to that. The uranium fuel, if obtained by a would-be proliferant, would not be weapons usable, but would require less separative work for production of weapons grade uranium than ordinary light water uranium fuel. However, the buildup of weapon-grade plutonium could be forestalled if, as appears possible, spent light water reactor fuel is used in the initial core, though in this case, some separation technologies applied to the LWR spent fuel would be required which may, in some configurations, allow the separation of plutonium.

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 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-ton units into and out of port cities and coastal locations. The safety of such shipments would have to be demonstrated beyond doubt to the public. Above all, the hub-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 over their nuclear energy programs. Beyond these considerations, countries will also be wary of concentrating too much of their energy future in a few places, with their attendant risks of common-mode failures, disruption of transmission lines or shipping, etc.

With respect to economics, the SIR hub-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:

- The generation of electricity at a central nuclear park, with the electricity then sent out by transmission lines to distant sites.
- The generation of electricity at a central nuclear park, the electricity used to disassociate water to produce hydrogen, and the hydrogen then sent out to distant sites.
- The production of hydrogen directly from fossil fuels at a 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 previously discussed. It appears at least as proliferation-resistant as the SIR concept, though its safety and economics would have to be compared to the SIR. 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 hydrogen becomes widely used as an energy fuel, the second option might be considered. The nuclear electricity would be used to produce hydrogen either by electrolytic processes or thermo-chemical processes; and the hydrogen then disseminated. Again, this scheme appears as or more proliferation-resistant than the SIR concept. But its economics are questionable.[29] The electrolysis of water to produce hydrogen will look better economically if the electricity used is off-peak and where most of the costs of the electricity production could be charged to the on-peak production. Such a strategy might provide an opening for electrolysis, but under conditions where much of the electricity generated is used directly. (This will be true, of course, also for hydrogen produced from electricity generated by renewables, such as wind or photovoltaics.) Similarly, the prospects appear poor – or at least uncertain — that hydrogen could be produced from water through thermo-chemical processes at costs competitive with hydrogen from fossil fuels.[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 pipelines 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, the scale of the centralized facility would be a matter of economics mostly, though again there might be some issues of energy independence involved.

Conclusion

The challenge of making nuclear power proliferation-resistant over the long haul is great. Perhaps it will not be necessary to do so, if nuclear power, rather than increasing ten and twenty-fold, is instead gradually phased out. This would be possible only if energy technologies using fossil fuels and renewables can be developed that are economic and do not release appreciable amounts of carbon dioxide to the atmosphere. It is too early to say with confidence that such alternatives will be available. But it is noteworthy that the most recently published *World Energy Assessment* includes analysis of several relevant technologies on which industry is currently spending considerable development resources.[31]

If, however, nuclear power does grow to meet the challenge of global warming, some variant of the hub-spoke arrangement appears at present the best hope of developing a proliferation-resistant system. But such an arrangement, as noted, must confront the dilemma that countries (those on the spokes) will be loathe to rely on reactor technologies that they have little capacity to monitor independently. It is uncertain how this dilemma can be fully resolved short of carrying the logic of the hub-spoke arrangement to 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. ❑

About the Author

Harold Feiveson currently serves as the Secretary-Treasurer of the Federation of American Scientists Council and is a Senior Research Policy Scientist of the Program on Science and Global Security at Princeton University.

Notes

[1] See, for example, the description of Generation IV nuclear energy systems, a project of the U.S. Department of Energy (gen-iv.ne.doe.gov); and Directorate General for Research, European Parliament, "Emerging Nuclear Energy Systems, their Possible Safety and Proliferation Risks," Working Paper, November 1999.

[2] The view that the isotopic composition of plutonium could provide a strong barrier to proliferation is disputable, and is discussed further shortly.

[3] 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.

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

[5] E. Greenspan, et al., "The Encapsulated Nuclear Heat Source – A Generation IV Reactor," Global 2001, September 9-13, 2001, Paris. E. Greenspan, et al., "The Encapsulated Nuclear Heat Source Reactor for Proliferation-Resistant Nuclear Energy," Global 2001, September 9-13, 2001, Paris.

[6] E. Greenspan, et al., "The Encapsulated Nuclear Heat Source Reactor for Proliferation-Resistant Nuclear Energy," Global 2001, September 9-13, 2001, Paris.

[7] Galperin, et al., pp 284-286.

[8] U.S. Department of Energy, *Non-Proliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Excess Plutonium Disposition Alternatives*, January 1997.

[9] Andrew Kadak, MIT, MIT/INEEL, *Modular Pebble Bed Reactor*, March 22, 2000, powerpoint view graphs.

[10] Andrew Kadak, "The Politically Correct Reactor," MIT, viewgraphs, undated. Kadak notes that 211,000 pebbles would have to be diverted for a weapon.

[11] 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.

[12] U.S. Department of Energy, EIA, *Annual Energy Review 1997*, July 1998.

[13] 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%).

[14] 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.

[15] Intergovernmental Panel on Climate Change, *Climate Change 1995: Impacts, Adaptations, and Mitigation, Summary for Policymakers*, Figs. 5 and 6.

[16] 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.

[17] Carbon avoided is calculated on basis of 0.175 kg carbon avoided per kwh. This is roughly equivalent to that if there was 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.

[18] 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

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Common Defense *continued from p. 1*

spend more money for defense than you do" (without bothering to explain whether funds would translate into real security), "Will you support the *God Bless America Defense System*?"

Even Secretary Rumsfeld's plans to force a sclerotic military and intelligence bureaucracy into a new era appear to have foundered in the face of some of the nation's most skillfully manned defenses – an energized lobbying community. While many of the changes he proposed are wrongheaded, he deserves credit for attempting to focus defense investments on the needs of a new era, and upgrade defense technology.

It would be bad enough if we were simply wasting money. But the misappropriation of resources starves legitimate defense and domestic needs – including new intelligence, training, and next-generation conventional weaponry that would actually be used by US forces, strengthened domestic and international defenses against terrorism, and defenses against chemical and biological attacks. Even worse, the fictions created to justify fanciful programs in the ethereal world of press releases can lead to real harm to our security. Our unilateral obsession with missile defense undermines our ability to work in alliances and weakens efforts to control proliferation of nuclear weapons.

The reality is that against the advice of our own military, we stint on advanced research and technology to pour money into aircraft and ships designed to fight wars we know will never be fought, and maintain scores of expensive, unneeded bases and laboratories to satisfy political, not military, needs. Nuclear weapons cannot contribute to any military action contemplated in the Middle East, or any conflict the US can conceivably enter. Any use of nuclear weapons in any conflict by any party would weaken, not strengthen, US interests. Yet despite the end of the Cold War we have made virtually no changes to our enormous nuclear weapons complex. We pay to maintain nearly 6000 nuclear weapons on a state of high readiness ready attack targets that no one seems able to define. And we put domestic politics above security interests by risking international programs to control nuclear proliferation and valuable alliances to pursue a program to build an enormously expensive missile defense system – a system designed for a highly unlikely threat and that only the faithful believe has a chance of working.

In the long-term, the best investment will be in measures that remove the forces that drive terrorism and compromise our ability to promote the spread of democratic governments.

Programs put together to deal with the urgent problems of terrorism must be imbedded in a longer-term strategy that builds security out of domestic defense investments, coupled with multinational efforts to contain and eliminate threats of violence and lay the foundations for sustainable economic development worldwide. Force must be used, but used skillfully. Our military must be able to react quickly, intelligently, and with appropriate levels of violence. But most, if not all, of the plausible threats to US security can only be met through multinational action. In the long-term, the best investment will be in measures that remove the forces that drive terrorism and compromise our ability to promote the spread of democratic governments.

The misery of Middle Eastern and Central Asian nations impoverished by brutal and incompetent governments provides a natural breeding ground for terror. It would be hard to find another region so poorly governed or where so few governments show movement toward open societies or functioning markets. It is a naked secret, however, that the US tolerates these governments because they ensure stability in world oil markets. More than half of all the oil in international markets today comes from the Persian Gulf and by 2020, these nations could be supplying 60-70%. Does anyone seriously believe that we fought the Gulf War to "preserve democracy in Kuwait?" Yet this fiction remains an unchallenged part of the US official canon. When did we last denounce civil rights abuses in Saudi Arabia?

One result of this hypocrisy is to hide the real price of gasoline that appears so cheap at the pump. Our room for diplomatic maneuver in the Gulf is limited and the pressing need to mount an attack on targets in Afghanistan forces us, once again, to associate ourselves with regimes that breed resentment for which there is no legitimate outlet.

Supplying the equivalent of a few months of US oil consumption by destroying an Alaskan wilderness is an absurd response to our petroleum dependence. We need a strategic energy policy that points to a long-term solution based on research, regulation, and incentives to encourage a new generation of highly efficient vehicles, environmentally sustainable substitutes for petroleum, and new strategies of urban design and transportation.

We have also not mustered the courage to stand up to extremist factions in either Israel or Palestine that make demands obviously inconsistent with permanent peace in the region. The enormous diplomatic and economic leverage we have applied to build an alliance to support military action in Afghanistan would surely be as usefully applied in forcing a just resolution of this dangerous issue. Our vacillation, and reluctance to use our considerable power to influence all parties to the dispute, makes it easy to misinterpret our intentions.

A final point is that nuclear weapons make the world less, and not more, safe for the United States. Nuclear weapons are the ultimate weapons of terror – they cannot be used without inflicting massive casualties on civilians. Overwhelming US superiority in conventional weapons means that anything we can do to discourage development, testing, and deployment of nuclear weapons would be in our interest. The presence of nuclear weapons in Pakistan and loosely accounted nuclear materials in the Former Soviet Union represents one of the greatest dangers facing the US today. It is absurd for the US to cut funding aimed at making the Russian material more secure, oppose the nuclear test ban, and threaten to withdraw from existing international arms control agreements. We should instead be taking the lead in a worldwide ban on nuclear weapons testing, strengthening safeguards for nuclear material, and pursuing agreements that reduce the number of nuclear weapons and quantity of weapon-usable fissile material worldwide. The US and Russia should immediately cut their nuclear weapons inventories to 1000 or less and put pressure on China not to expand its arsenal.

If we can extract one thing from September's tragedy, it is to engage in a serious national assessment of where real dangers to national security lie and how we can combat them. This debate is long overdue.

In dangerous times we have always managed to summon America's greatest strength – our openness to change and our confidence that a free people will choose wisely in open debate. The debate surely must begin. As usual, Lincoln put it best: "We must disenthrall ourselves, and then we shall save our country." ❑

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electricity in 2050, 50% in 2075, and 75% in 2100. The total non-nuclear primary energy associated with these data are 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% per year 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.

[19] While the total amount of uranium in seawater (~4.5 billion tonnes) is much greater than current estimates of terrestrial uranium resources (~15 million tonnes), the latter is likely an underestimate, while the former does not account for the daunting challenge of extracting uranium economically at its very low concentration in seawater (3.2 parts per billion). Also, temperature limitations on the efficiency of seawater extraction probably effectively restrict recovery to about the top 100 meters of the ocean. It is not yet possible to say confidently what the practical uranium resources are either for terrestrial or seawater extraction. Marvin Miller, private communication, September 2001.

[20] To get 1 kg of 8%U from natural U feed requires enrichment work amounting to about 16 kg separative work units (SWU) and 15.6 kg uranium feed (assuming 0.2% U-235 left in the depleted uranium "tails"). At 80% capacity factor, and an efficiency of electricity production of 45% this means that a 100 MWe reactor needs 0.8 t, 8% U/y, and 13 t SWU/y. A nuclear capacity of 3500 GWe will require 3500*130 t SWU/GWe = 455,000 t/y SWU. 1 kg of weapon-grade uranium (90%U-235) 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 2-million SWU plant could make about 600 bombs per year.

[21] To go from natural uranium to 90% U-235 with 0.2% tails assay requires 227 SWU and 180 kg of feed per kg of product. To go from 8% U-235 to 90% U-235 requires only 43 SWU and 11.5 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 16 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 11.5*16 = 184 SWU. An additional 43 SWU is then needed, so that total separative work done would be 184 + 43 = 227 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.

[22] This is assuming a 45% efficiency of the reactor and a capacity factor of 0.8. So a 100 MWe reactor would generate roughly 65,000 MWd per year. So a burnup of 80,000 MWd/t implies about 0.8 t spent fuel per year, 8 t spent fuel per 1000 MWe, and 28,000 t spent fuel for a nuclear capacity of 3500 GWe.

[23] Per Peterson, "Issues for Detecting Undeclared Post-Closure Excavation of Geologic Repositories," *Science and Global Security*, Vol. 8, No. 1, 1999; Per Peterson, "Long-term Safeguards for Plutonium in Geologic Repositories," *Science and Global Security*, Vol. 6, No. 1, 1997; Edwin Lyman and H.A. Feiveson, "The Proliferation Risks of Plutonium Mines," *Science and Global Security*, Vol. 7, No. 1, 1998.

[24] At a burn-up of 80 MWd/kg, the total plutonium concentration in the spent fuel would be 5.4 kg/t. (Kadak, op cit.) The Pu-239 isotopic concentration is about 36%. As noted earlier, this is very poor plutonium for weapons purposes. But it could still be used for weapons. And after time, not only will the fission products decay substantially, but so will the Pu-238 which is perhaps the most troublesome of the plutonium isotopes for weapons purposes.

[25] I base some of the discussion here and in next section on Robert H.Williams, "Advanced Energy Supply Technologies," Chapter 8, prepared for the World Energy Assessment, 19 April 2000 (draft manuscript).

[26] B. Tinturier, B. Esteve, and H. Mouney, "Innovative Concepts: An EDF viewpoint," in *Global 99: Nuclear Technology—Bridging the Millenia*, Proceedings of an International Conference on Future Nuclear Energy Systems, Jackson Hole, Wyoming, 29 August-3 September 1999.

[27] E. Greenspan, et al., Ref. 4.

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

[29] 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.*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.

[31] *World Energy Assessment*, Chapters 7 and 8.

September 11 & the Future of National Security

By Steven Aftergood

The horrors of the September 11 terrorist attacks have already changed the security environment in which we all live, and will undoubtedly lead to many more yet unforeseen changes.

Just as the 1941 attack on Pearl Harbor provided much of the impetus for the creation of a "central" intelligence agency, so the attacks of September 11, which killed an even larger number of Americans, are likely to shape the future design of US national security policy in equally fundamental ways.

But the lessons learned from this cruel act need to be drawn carefully and inasmuch as it is possible, dispassionately.

"Tragic events almost inevitably result in the promulgation of legislative and executive action that reacts to the moment," says one experienced Administration official. "Most often, these 'solutions' turn out to be shortsighted."

It is time to recall first principles.

On September 20, FAS joined with some 150 other NGO's of nearly every political and cultural stripe to endorse the following declaration "In Defense of Freedom." For a list of signing organizations and for more information, see www.indefenseoffreedom.org. ❑

IN DEFENSE OF FREEDOM

1. On September 11, 2001 thousands of people lost their lives in a brutal assault on the American people and the American form of government. We mourn the loss of these innocent lives and insist that those who perpetrated these acts be held accountable.
2. This tragedy requires all Americans to examine carefully the steps our country may now take to reduce the risk of future terrorist attacks.
3. We need to consider proposals calmly and deliberately with a determination not to erode the liberties and freedoms that are at the core of the American way of life.
4. We need to ensure that actions by our government uphold the principles of a democratic society, accountable government and international law, and that all decisions are taken in a manner consistent with the Constitution.
5. We can, as we have in the past, in times of war and of peace, reconcile the requirements of security with the demands of liberty.
6. We should resist the temptation to enact proposals in the mistaken belief that anything that may be called anti-terrorist will necessarily provide greater security.
7. We should resist efforts to target people because of their race, religion, ethnic background or appearance, including immigrants in general, Arab Americans and Muslims.
8. We affirm the right of peaceful dissent, protected by the First Amendment, now, when it is most at risk.
9. We should applaud our political leaders in the days ahead who have the courage to say that our freedoms should not be limited.
10. We must have faith in our democratic system and our Constitution, and in our ability to protect at the same time both the freedom and the security of all Americans.

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