Thorium Fuel for Nuclear Energy

An unconventional tactic might one day ease concerns that spent fuel could be used to make a bomb

Mujid S. Kazimi

How might a determined terrorist group get hold of the uranium or plutonium needed to make an atom bomb? That question has been weighing heavily on many people's minds. The easiest way is probably to buy it, perhaps from North Korea, which, according to intelligence reports, may have the means to produce a modest stockpile. Although the nuclear aspirations of Pyongyang have been much in the news this year, experts also worry about other "nations of concern" obtaining these terrifying weapons. The North Korean example is, however, rather clear-cut, and the details illuminate a longstanding problem of international security, one that nuclear engineers like myself would dearly like to help solve.

Almost a decade ago the world breathed a sigh of relief when diplomatic efforts, including those of former President Jimmy Carter, defused what then threatened to become a violent conflict: At the time, North Korea was interfering with the monitoring work of the International Atomic Energy Agency, in clear breach of that country's obligations as a signatory to the nuclear nonproliferation treaty. In particular, the North Koreans were asserting that they had produced just a tiny amount of plutonium from the spent fuel taken from their nuclear reactors—far too little to make even one bomb—but they refused to allow inspectors to verify this claim.

Why was North Korea reprocessing nuclear fuels in the first place? After all, the peaceful pursuit of civilian nuclear power does not require any reprocessing, as the United States and several other countries have demonstrated. (At U.S. power plants, the spent fuel materials are simply stored in dry casks or in cooling ponds, in preparation for their eventual disposal at the Yucca Mountain Repository in Nevada, which should begin operation around 2010.) Was not North Korea's decision to reprocess spent nuclear fuels *prima facie* evidence that it intended to extract the plutonium generated within its reactors and use it to fabricate nuclear bombs?

Not exactly. North Korea's nuclear power reactors are quite different in design from the ones now operating in the United States, which use water both as the coolant and the *moderator*, the substance that slows the neutrons released during nuclear fission, allowing them to initiate further fission reactions. The North Korean "magnox" reactors (a name derived from the magnesium oxide alloy that encloses the uranium fuel) use gas as the coolant and graphite as the moderator, having a design similar to one long in use in the United Kingdom. It turns out that the spent fuel from magnox reactors cannot safely be stored: It must be reprocessed to a form that is less susceptible to oxidation in air or water. So the fact that the North Koreans were reprocessing their spent fuels could not in itself be taken as evidence of ill intent. Their interference with international inspectors was, however, quite troubling.

The accommodation that Carter helped to work out alleviated many worries: In return for mothballing their graphite-based reactors, Pyongyang received assistance from Washington in obtaining nuclear power plants of the type used in the United States, along with a generous aid package. The solution was, at least in part, a technical fix, offering the North Koreans a way to develop a peaceful program of nuclear energy. They could then continue to operate nuclear power plants without creating so much concern abroad that in the course of reprocessing spent fuel they might extract plutonium for bombs.

Of course, without adequate oversight the North Koreans could conceivably use their newer reactors for breeding plutonium, by reprocessing the spent fuels at some secret site. Indeed, their penchant to work clandestinely to obtain bomb-making materials became obvious last year, when it was reported that Pakistan had sent North Korea high-speed centrifuges—equipment for making weapons-grade uranium—in return for missile technology. Such apparatus is growing increasingly easy to obtain, and thus efforts to transform ordinary uranium into the highly enriched form suitable for bombs are becoming harder and harder to police. So the world will probably always face that threat. But what of the problem of spent nuclear fuels being used for bomb making?

One of the important barriers to such a diversion of spent fuel is that it remains highly radioactive for centuries after discharge, thus requiring remote handling and facilities with adequate shielding for extracting the plutonium. Might there be effective technical solutions to further limit the problem of spent nuclear fuels being

Mujid S. Kazimi received his Ph.D. in nuclear engineering in 1973 from the Massachusetts Institute of Technology, where he is now the Tokyo Electric Power Company Professor of Nuclear Engineering. Kazimi directs MIT's Center for Advanced Nuclear Energy Systems (CANES), which studies new concepts for nuclear power with the aim of making it more economical and safe, lessening its environmental impact and raising the barriers to the proliferation of nuclear weapons. Address: CANES, Room 24-215, Massachusetts Institute of Technology, Cambridge, MA 02139. Internet: kazimi@mit.edu

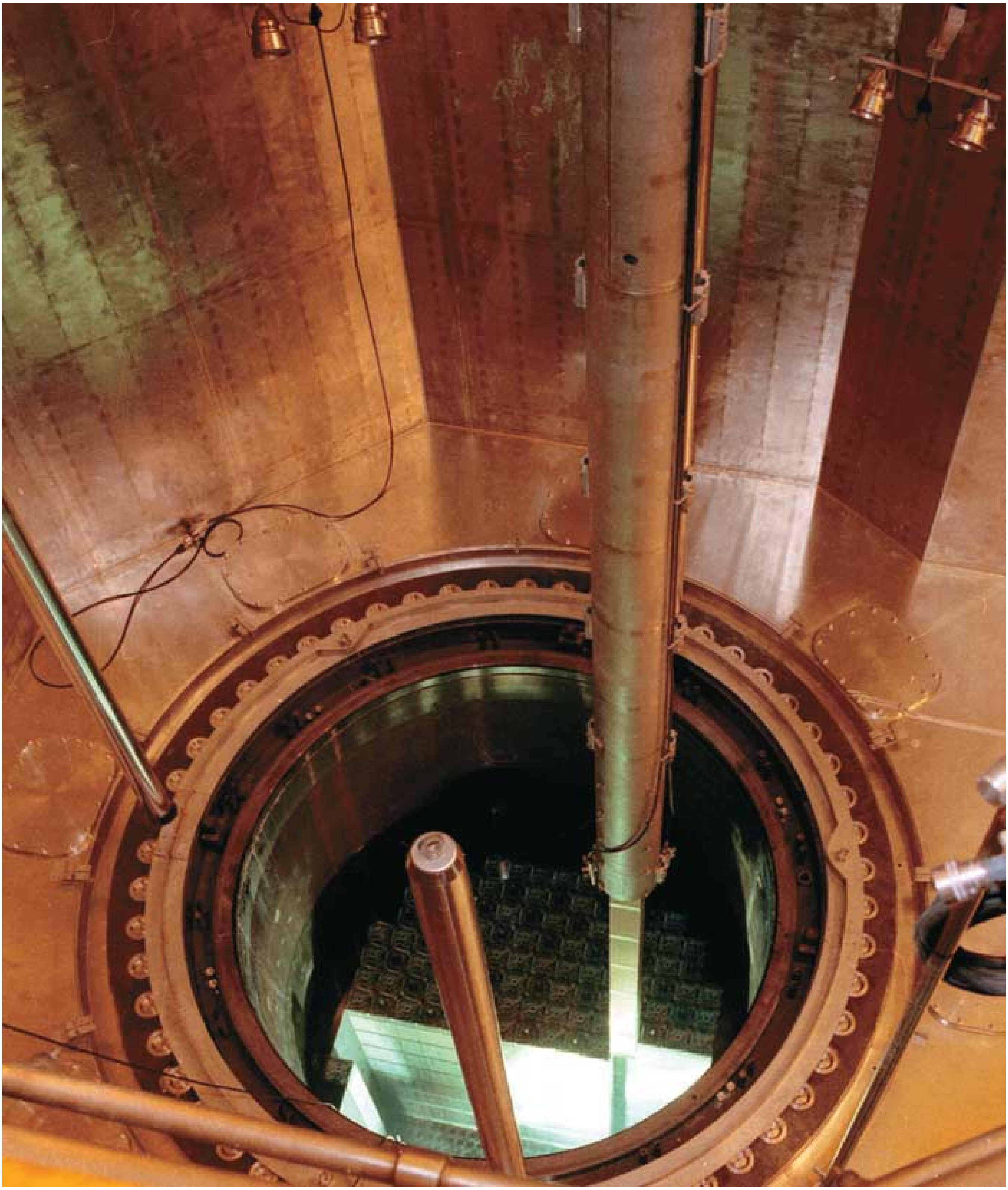


Figure 1. Uranium fuels most of the world's 439 nuclear reactors (103 in the United States), which together provide 16 percent of the planet's electricity. In most installations, uranium oxide pellets fill slender fuel rods, which are typically arranged in a square array within each fuel assembly. A modern power reactor houses roughly 200 such assemblies in its core. These are shuffled about and replaced periodically, the spent fuel being either reprocessed or stored. A troubling feature of this system of electricity generation is that it produces plutonium, which can be chemically extracted from the spent fuel and used in nuclear weapons. Using thorium as well as uranium in the fuel can diminish that threat: Thorium-based nuclear fuels produce substantially less plutonium, and the isotopic composition of the plutonium that they do create is unsuitable for bomb making. The ability to thwart the proliferation of nuclear weapons, coupled with the great abundance of thorium in the Earth's crust, has lately spurred nuclear engineers to reconsider this approach, which was abandoned in most parts of the world decades ago. (Photograph courtesy of British Energy.)

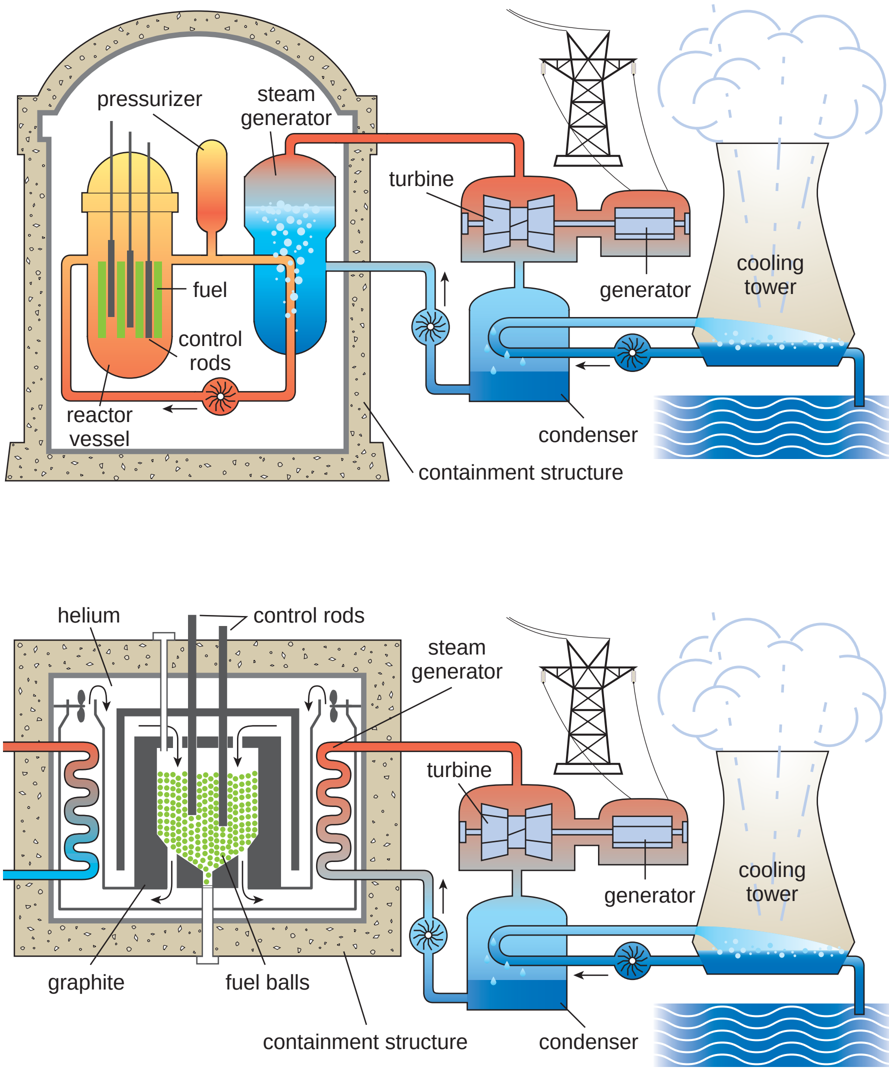


Figure 2. Thorium-based fuels are appropriate both for pressurized-water reactors, which use ordinary water to transfer heat from the core and to slow the neutrons generated in the fission reactions *(top)*, and for high-temperature gas reactors, which use a gas such as helium to transfer heat and solid graphite to slow the neutrons *(bottom)*. Several pressurized-water reactors (including the very first reactor built for commercial power generation) were run on thorium during various early trials. And some high-temperature gas-cooled reactors have operated with thorium-based fuels as well, including the German THTR-300, a 300-megawatt reactor built near Hamburg in the 1980s. This reactor was of the "pebble-bed" design indicated above, wherein fuel in the form of many small balls is placed in a hopper-like vessel. This arrangement allows refueling to take place continually, avoiding the costly outages that periodically take place at most nuclear power plants, where reactors must be shut down for refueling.

exploited for military ends? That is a question that the designers of nuclear fuels have asked themselves over and over. Here, I would like to explore one possible answer that has garnered much recent interest: thorium.

Now You're Cooking with Thorium

The use of thorium in power reactors has been considered since the birth of nuclear energy in the 1950s, in large part because thorium is considerably more abundant than uranium in the Earth's crust. Roughly speaking, there is about three times more thorium than uranium. Unfortunately, thorium atoms cannot themselves be easily induced to split—the basic requirement of a fission reactor. But when a quantity of thorium-232 (the common isotope of that element) is placed within a nuclear reactor, it readily absorbs neutrons and transforms into uranium-233, which, like the uranium-235 typically used for generating nuclear power, supports fission chain reactions.

Thorium is thus said to be "fertile" rather than fissile. In this respect it is similar to uranium-238, which makes up more than 95 percent of most nuclear fuels. A conventional reactor breeds various isotopes of plutonium from uranium-238, and some of that plutonium in turn undergoes fission in the reactor, adding to the power the uranium-235 provides.

The hitch with using thorium as a fuel is that breeding must occur before any power can be extracted from it—and that requires neutrons. Some engineers have proposed using particle accelerators to generate the needed neutrons, but this process is costly, and the only practical scheme at the moment is to combine the thorium with conventional nuclear fuels (made up of either plutonium or enriched uranium or both), the fissioning of which provides the neutrons to start things off.

The breeding of uranium-233 from thorium is more efficient than the breeding of plutonium from uranium-238, because less of various nonfissile isotopes is created along the way. Designers can take advantage of this efficiency to decrease the amount of spent fuel per unit of energy generated, which reduces the amount of waste to be disposed of. There are some other pluses as well. For example, thorium dioxide, the form of thorium used for nuclear power, is a highly stable compound—more so than the uranium dioxide typically employed in today's fuel. So there is less concern that the fuel pellets could react chemically with the metal cladding around them or with the cooling water should there be a breach in the protective cladding. Also, the thermal conductivity of thorium dioxide is 10 to 15 percent higher than that of uranium dioxide, making it easier for heat to flow out of the slender fuel rods used inside a reactor. What is more, the melting point of thorium dioxide is about 500 degrees Celsius higher than that of uranium dioxide, and this difference provides an added margin of safety in the event of a temporary power surge or loss of coolant.

Knowledge of such advantages has repeatedly spurred nuclear engineers to conduct experiments, and some groups have even gained experience running commercial power reactors on thorium-based fuels. For example, a gas-cooled, graphite-moderated reactor called Peach Bottom Unit One, located in southeastern Pennsylvania, used a combination of thorium and highly enriched uranium in the mid-1960s. Another gas-cooled reactor at Fort St. Vrain in Colorado was run on a similar thorium-based fuel between 1976 and 1989. Tests with relatively simple mixtures of thorium oxide and highly enriched uranium oxide also began with water-cooled reactors during the 1960s, at the "BORAX" (Idaho) and Elk River (Minnesota) facilities and at the Indian Point (New York) power plant. And between 1977 and 1982, more complicated combinations of thorium and either uranium-235 or uranium-233 were also employed in a water-cooled reactor at Shippingport, Pennsylvania, in an experimental program seeking to develop a fuel that produces more fissile material than it consumes. Interestingly, Shippingport, which began operation in 1957, was the very first nuclear power plant built in the United States for the commercial generation of electricity.

Work with thorium-based nuclear fuels has by no means been restricted to the United States. German engineers, for example, have used combinations of thorium and highly enriched uranium, or thorium and plutonium, in both gas- and water-cooled power reactors. Thorium-based fuels have also been tried in the United Kingdom, France, Japan, Russia, Canada and Brazil. But despite these considerable early efforts, most nations long ago abandoned the notion of using thorium to power their nuclear generating stations. One country that has maintained interest is India, which began fueling some of its power reactors in the mid-1990s with bundles containing thorium. Although one of the reasons for employing thorium was simply to even out the distribution of power within the cores of these reactors, Indian engineers also took the opportunity to test how well thorium could function as a fuel source. The positive results they obtained motivated their current plans to use thorium-based fuels in more advanced reactors now under construction.

India's attraction to thorium-based fuels stems, in part, from its large indigenous supply. (With estimated thorium reserves of some 290,000 tons, it ranks second only to Australia.) But that nation's pursuit of thorium, which helps bring it independence from overseas uranium sources, came about for a reason that has nothing to do with its balance of trade: India uses some of its reactors to make plutonium for atomic bombs. Thus India refuses to be constrained by the provisions that commercial uranium suppliers in countries such as Canada require: They demand that purchasers of their ore allow enough oversight to ensure that the fuel (or the plutonium spawned from it) is not used for nuclear weapons.

Previous work on thorium elsewhere in the world did not lead to its adoption, largely because its performance in water reactors, such as the first core at the Indian Point power station, did not live up to expectations. Given this history, it may come as something of a surprise that thorium-based nuclear fuels are once again being considered, this time as the means to stem the potential proliferation of nuclear weapons. Using thorium to prevent the buildup of plutonium requires that the fuel be configured differently than in most of the experiments of years past. Those trials incorporated highly enriched uranium (something that is currently discouraged because of worries over proliferation) and presupposed that the spent fuel would be reprocessed for the extraction of its fissile contents. Neither practice is now envisaged. The thorium-based fuel assemblies currently being designed are different from past examples in other ways too. For example, they can withstand greater exposure to the heat and radiation experienced inside the core of a reactor, which allows more of the fertile thorium-232 to be converted into fissile uranium-233. So what's being talked about now is definitely not your father's thorium-based nuclear fuel.

Averting Proliferation

As I mentioned, the lack of uranium-233 in nature necessitates using a different fissile material, such as uranium-235 (or perhaps plutonium-239), to prime a reactor running on thorium.

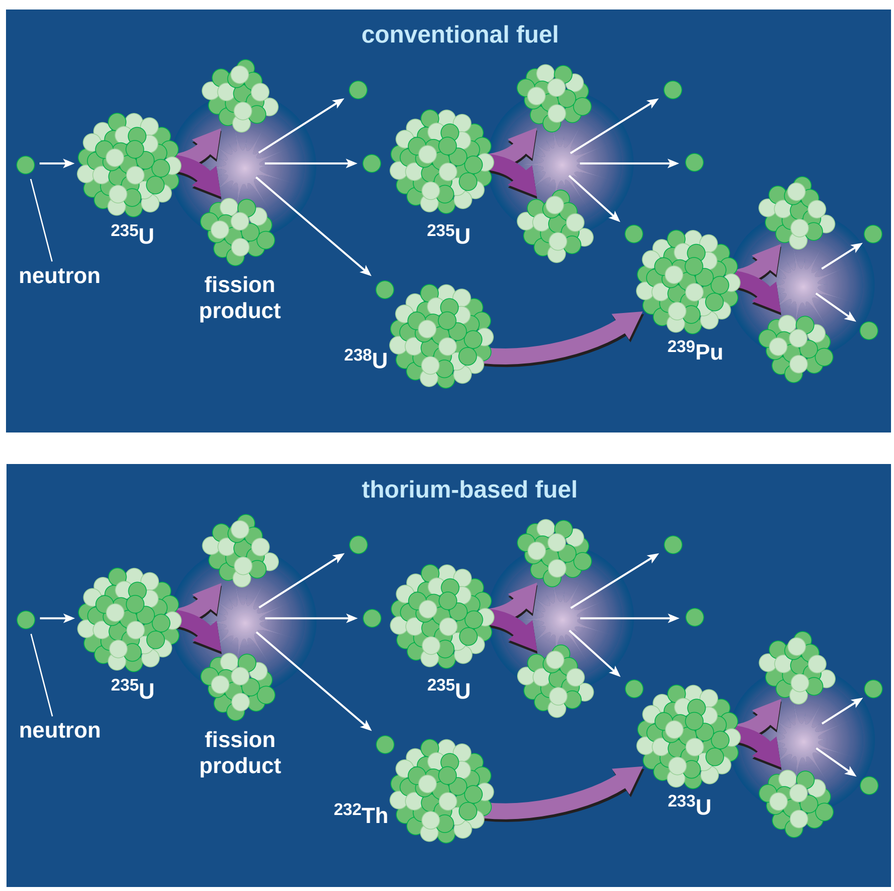
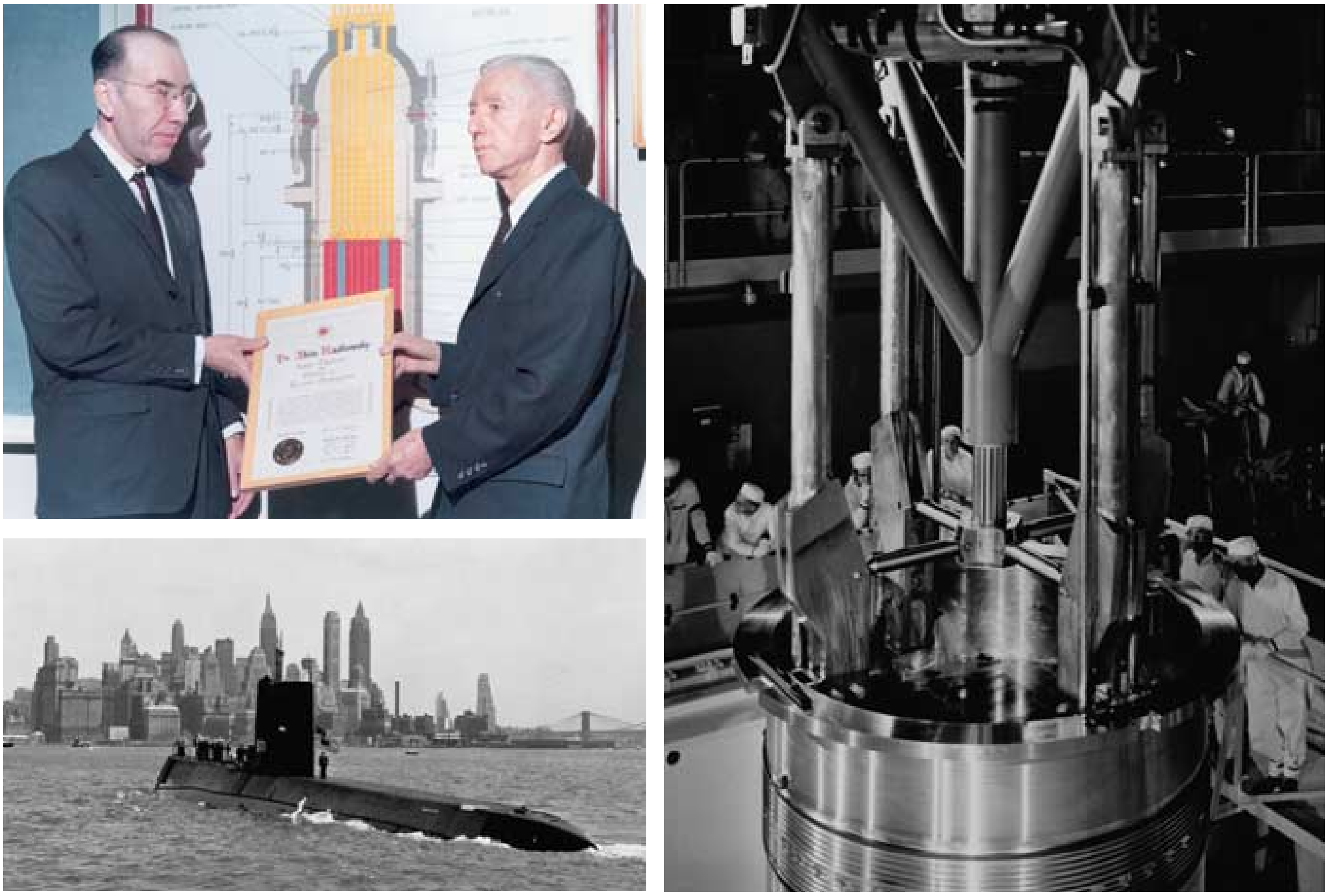


Figure 3. Conventional nuclear fuel *(top)* contains both a fissionable isotope of uranium (^{235}U) and a nonfissionable isotope (^{238}U). Sparked by an incoming neutron, the fissioning of a ^{235}U nucleus releases two or three more neutrons. These in turn can cause another ^{235}U nucleus to split, or they can induce atoms of ^{238}U to change into plutonium-239, which, being itself fissionable, then helps to power the reactor. Thorium-based nuclear fuels *(bottom)* operate in much the same fashion, except that instead of breeding plutonium from ^{238}U, they breed a fissionable isotope of uranium, ^{233}U.



Corbis

Corbis

Figure 4. Alvin Radkowsky was a pioneer in the use of thorium-based fuel and was perhaps its greatest proponent until his death in 2002. Radkowsky served as chief scientist for the U.S. Naval Reactors Program under the direction of Admiral Hyman Rickover, who is often remembered as the father of the nuclear Navy. In 1954, their program produced the first nuclear powered submarine, the *USS Nautilus (bottom left)*. Here the bespectacled Radkowsky is seen receiving an award for technical achievement from Rickover *(top left)*. Behind them is a diagram of the first nuclear reactor designed specifically for commercial power generation, which was constructed near Shippingport, Pennsylvania, in the late 1950s *(right)*. (Photograph of Radkowsky and Rickover courtesy of Thorium Power, Inc.)

Given the present-day proscription against commercial fuels that are too highly enriched in uranium-235, a considerable amount of (nonfissionable) uranium-238 would clearly need to be included in the primer; current standards require at least 80 percent, and more is typical. As is the case with conventional reactors, this would make it impossible to use the fresh fuel for a bomb without first having to go through the technically difficult step of isotopically enriching the uranium.

The main advantage of using a combination of thorium and uranium is the significant reduction in plutonium content of the spent fuel compared with what comes out of a conventionally fueled reactor. Just how much less plutonium is made? The answer depends on exactly how the uranium and thorium are combined. For example, uranium and thorium can be mixed homogeneously within each fuel rod. In this case the amount of plutonium produced is roughly halved. But mixing them uniformly is not the only way to combine the two elements.

Indeed, the approach undergoing the most investigation now is a combination that keeps a uranium-rich "seed" separate from a thorium-rich "blanket." The chief proponent of this concept was the late Alvin Radkowsky, a nuclear pioneer who, under the direction of Admiral Hyman Rickover, helped to launch America's nuclear Navy during the 1950s as chief scientist of the U.S. Naval Reactors Program. Radkowsky went on to make significant contributions to the commercial nuclear industry during the 1960s and '70s. Then, at the urging of Edward Teller (one of his former teachers) to find a way to reduce the threat of nuclear weapons getting into the wrong hands, Radkowsky turned his attention to the use of thorium-based fuels, which he had already recognized as a means of lessening the amount of nuclear waste created. In 1992 he helped to found a private company, Thorium Power, Inc., to commercialize this technique. Sadly, Radkowsky would not live to see his vision materialize: He died last year, at the age of 86.

Radkowsky's idea was to construct special fuel assemblies that could be used in typical water-cooled reactors with very little modification. These units are made up of a central seed region containing fuel rods filled with reactor-grade uranium (that is, having no more than 20 percent uranium-235). Surrounding the seed is a blanket region with fuel rods containing thorium and a small amount of uranium. Having uranium-238 in the blanket prevents anyone from withdrawing these rods and using only chemical means to separate out the fissionable uranium-233 that is created over time.

With support from the U.S. Department of Energy and technical assistance from Brookhaven National Laboratory, Thorium Power is now working with the Kurchatov Institute in Moscow to investigate this strategy more fully. Their concept calls for using a metallic alloy as the seed fuel and for keeping the seed units in a Russian reactor for three years before replacing them but leaving the blanket rods in the reactor for 10 years. Their results are not going to be directly applicable to the nuclear power stations in most other parts of the world, however, because the fuel material is not in the form of an oxide (as preferred in the West) and because the Russian reactors involved in these tests use a hexagonal array of rods for each fuel assembly, whereas most facilities operating in Western countries use a square array.

Radkowsky and his colleagues had calculated that their scheme would reduce the amount of plutonium produced by 80 percent compared with what goes on in a conventionally fueled reactor of the same energy output. What is more, they found that the mix of plutonium isotopes generated, mostly in the seed fuel, would not be particularly desirable for military use, because a bomb made from it would be extremely unlikely to give much explosive yield—in the slang of weapons designers, it would probably "fizzle." Also, the plutonium has such a high content of the ^{238}Pu isotope that its decay heat may be sufficient to melt or damage the other materials used in constructing a weapon.

Even if a terrorist group wanted to use the blanket plutonium for making a terrifying (if not terribly powerful) bomb, extracting it from Radkowsky's thorium fuel—indeed from any thorium fuel used in a reactor—would be more difficult than removing it from today's spent fuel. The spent blanket fuel contains uranium-232, which in the course of a few months decays into isotopes that emit high-energy gamma rays. Thus pulling out the plutonium would require significantly beefed-up radiation shielding and a more widespread use of remotely operated equipment within the reprocessing facility, further complicating an already challenging task. And the abundance of uranium-232 and its highly radioactive products in the spent fuel would probably thwart any effort to separate uranium-233 (which, being fissionable, could also be used for a bomb) from uranium-238.

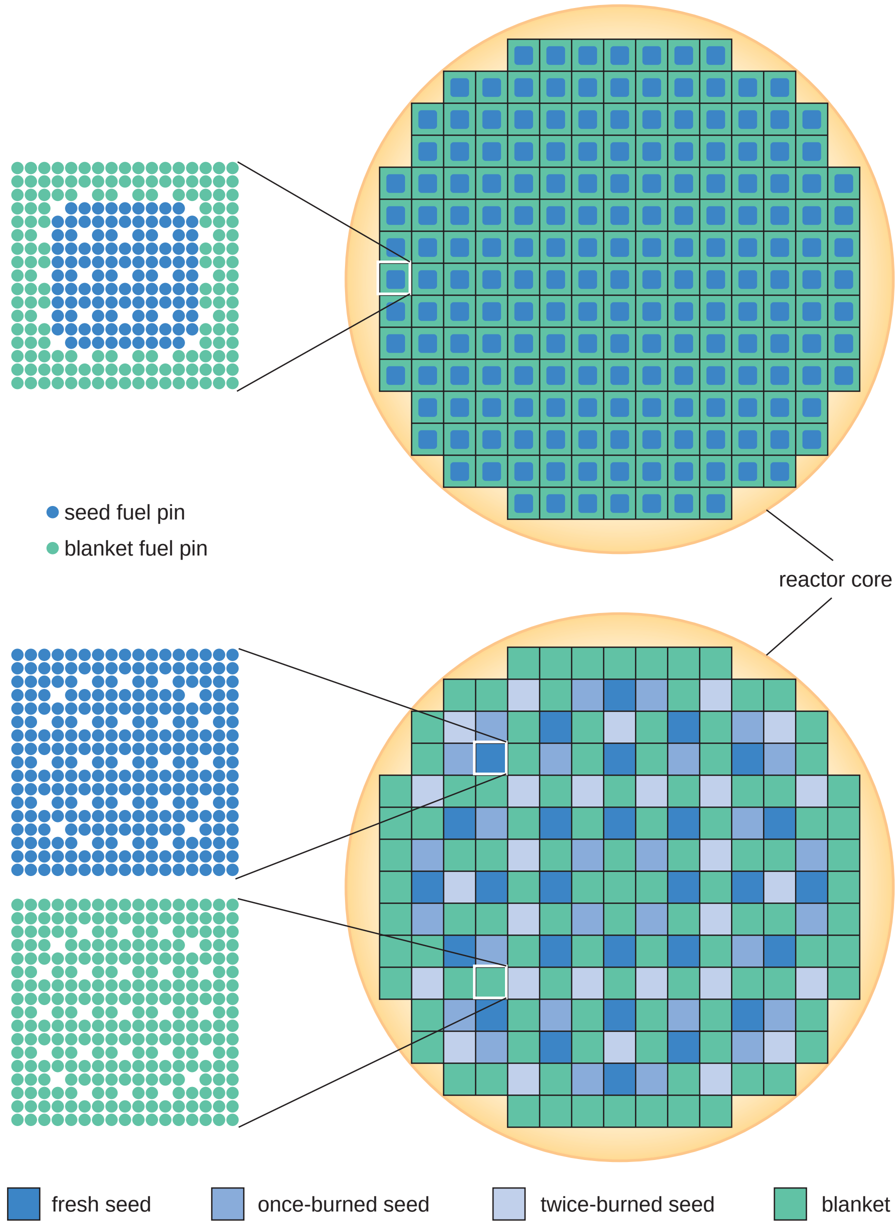


Figure 5. Thorium-based nuclear fuels can be designed in different ways. One general scheme, first conceived by Radkowsky, is to have each nuclear fuel assembly *(squares)* composed of uranium-rich "seed" rods surrounded by thorium-rich "blanket" rods *(top)*. The uranium, which includes up to 20 percent of the fissionable isotope ^{235}U, produces enough neutrons to transform the "fertile" thorium around it into another fissionable isotope of uranium, ^{233}U. This mixing of fuel types within an assembly complicates the refueling of a nuclear reactor, because the seed rods need to be replaced much more frequently than the blanket rods. An alternative approach, called the whole-assembly seed-and-blanket core *(bottom)*, utilizes fuel assemblies that each contain only uranium-rich seed rods or thorium-rich blanket rods. These assemblies can be more easily shuffled or replaced at prescribed intervals.

Reality Check

In light of the potential advantages for reducing the quantity of nuclear waste and preventing the dissemination of bomb-making materials, it is not surprising that interest in thorium-based fuels has recently undergone something of a renaissance. The U.S. Department of Energy has been particularly eager to foster research activities in this area. In addition to funding Radkowsky's company and its partners in their tests with Russian reactors, the DOE has lent support to three other recent efforts. One involves a consortium made up of two national labs (the Idaho National Engineering and Environmental Laboratory, and

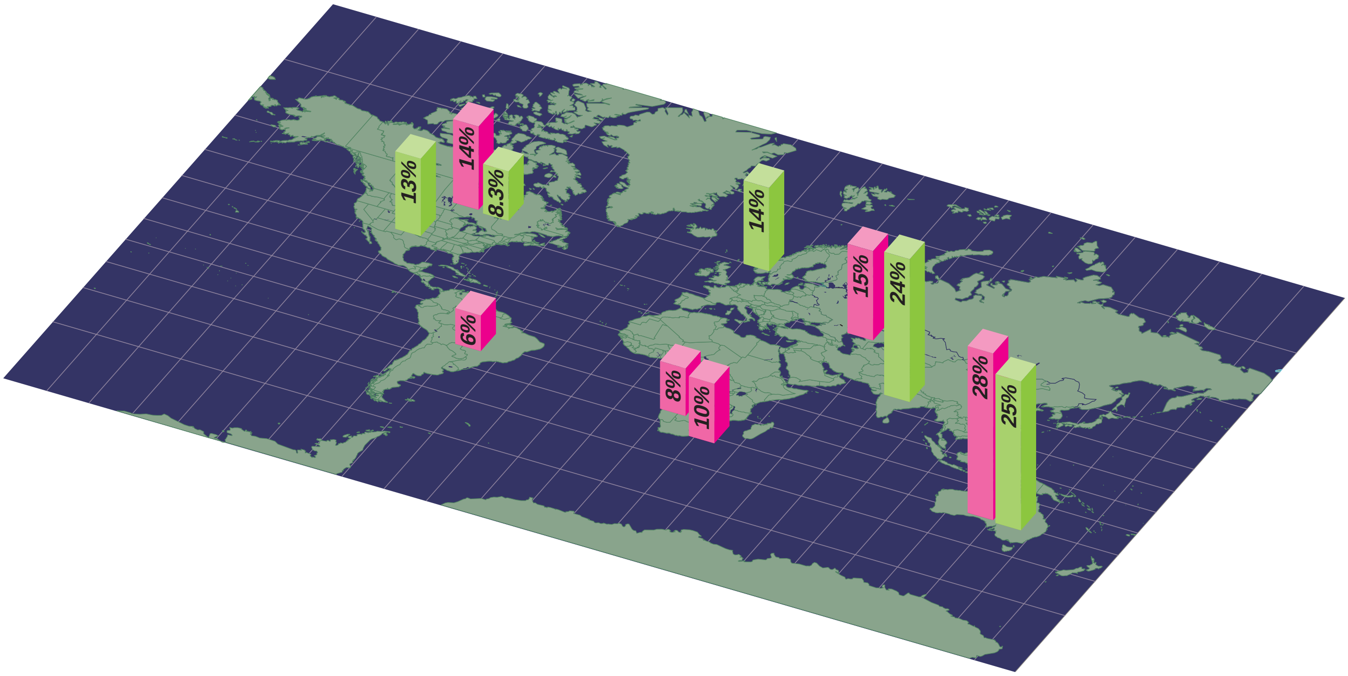


Figure 6. India is the only country actively pursuing thorium-based fuels at this time, in part because this tactic offers that nation a degree of independence from foreign uranium suppliers. India claims almost a quarter of the world's established thorium reserves, whereas it has comparatively little uranium. Countries with at least 5 percent of the global uranium *(pink)* or thorium *(green)* reserves are indicated. Thorium reserves are not as well known as those of uranium, because the current uses of thorium are limited. (Reserve estimates from the World Nuclear Association.)

Argonne National Laboratory), two private companies in the business of fabricating nuclear fuels (Framatome Technologies and Westinghouse) and three universities (the University of Florida, Purdue University and my own institution, the Massachusetts Institute of Technology). The goal has been to come up with a scheme for using thorium in reactors without the added complication of dealing with separate types of fuel arrays (from the seed and blanket units), as is required in Radkowsky's design.

In another program that brought investigators at Brookhaven National Laboratory together with the Center for Advanced Nuclear Energy Systems (CANES) at MIT, the objective is to look at practical ways to simplify the design of the separated seed and blanket units. This could be done by assigning entire fuel assemblies to be either seeds or blankets. Although the terminology of "seeds" and "blankets" has been kept (we name this arrangement the whole-assembly seed-and-blanket core), the metaphor is less applicable in this case, which calls for these assemblies to be arranged, more or less, in a checkerboard array within the core of a reactor.

In a third research thrust, nuclear engineers at Brookhaven and Purdue University examined the use of plutonium-primed thorium as fuel for boiling-water reactors: These designs are distinct from the more common pressurized-water variety, which keep the cooling water under high pressure so that it always remains a liquid. The idea behind this program is that it may provide an economical means to consume surplus weapons plutonium—without producing yet another generation of plutonium waste, as would happen with the leading plan currently being contemplated, something known as the mixed oxide option. In this respect, the Brookhaven-Purdue research on plutonium-seeded thorium fuel is similar to some of the work that Thorium Power and its Russian partners are hoping soon to engage in.

My CANES colleagues and I have devoted considerable effort over the past few years to evaluating the details of various designs, including ways of combining uranium and thorium within individual fuel rods. As might be expected, our conclusions about the technical and economic feasibility vary depending on the particular design under consideration. Here I would like to describe just a few of our results for the seed-and-blanket arrangements, the strategy that in my view has the best chances of commercial success.

The Bottom Line

Even with a whole-assembly seed-and-blanket core, where each type of fuel assembly is of homogenous construction, it is clear that the manufacture of the fuel and its management within the reactor would be more complicated than usual. In a typical power reactor, the fuel assemblies are shuffled at intervals so that each will be exposed, on average, to the same conditions of heat and radiation. In a seed-and-blanket core, the seeds must sustain power levels that are significantly above average, while the blanket assemblies experience far less stressful conditions. Thus the fuel in the seed rods reaches higher temperatures, releases more of the gaseous fission products into the limited space allowed for them within the fuel rods and requires more cooling than does the fuel used in the blanket regions.

These demands can be accommodated in various ways—for example, by allowing more coolant to flow through the seeds and by making the fuel materials less resistant to the flow of heat. In the Radkowsky-Kurchatov approach, the seed rods are made from a metallic uranium alloy (following designs that have been tested in Russian submarines), which improves their thermal conductivity. In the MIT-Brookhaven

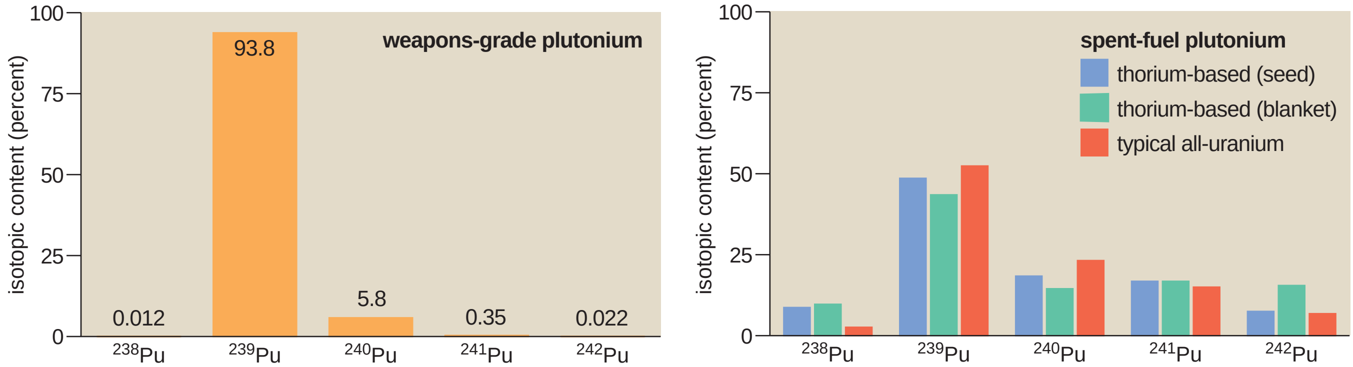


Figure 7. Nuclear power reactors produce plutonium as a byproduct, which raises concerns that this material could be diverted to the production of nuclear weapons. But not all plutonium is alike. Weapons-grade plutonium must be rich in the isotope ^{239}Pu and should have little of the highly radioactive isotope ^{238}Pu *(left)*. The plutonium left over from thorium-based nuclear fuels is thus much less suitable for use in bombs than is the plutonium from a conventional water-cooled reactor, because the highly radioactive isotope, ^{238}Pu, makes up a larger proportion of the resultant plutonium *(right)*. Thorium-fired reactors are also attractive because they produce less plutonium overall. For example, a thorium-fueled reactor using a whole-assembly seed-and-blanket core (the type considered for the chart at right) would produce a total of 92 kilograms of plutonium per gigawatt-year of electricity generated, whereas a conventional water-cooled reactor would result in 232 kilograms.

scheme, the uranium oxide pellets within the seed rods are hollow, which lowers their temperature. Although the blanket rods are less problematic in this regard, they too must be carefully engineered so that the exterior cladding holds up well, the working lifetime of these rods being in some designs as long as 13 or 14 years.

In addition to examining these various engineering concerns, investigators at CANES have also quantified the advantages of the seed-and-blanket designs in terms of their contribution to averting the proliferation of bomb-making materials, and we have also tried to evaluate their economics. We found that the seed-and-blanket arrangements produce less plutonium than competing schemes in which uranium and thorium are mixed at finer scales. But our results are not quite as optimistic as Radkowsky's earlier work had indicated: We calculate a reduction of only 60 percent (for the whole-assembly system) or 70 percent (if both seed and blanket rods are used within each assembly), compared with Radkowsky's estimate of an 80-percent reduction for the latter.

Our calculations of plutonium production do, however, support Radkowsky's assertions that the spent fuel would contain appreciable amounts of plutonium-238, a highly radioactive isotope, which thus produces a lot of heat. Indeed, the plutonium-238 content would be three to four times higher than with conventional uranium fuels. As Radkowsky pointed out, the heat given off by this isotope would make it quite difficult if not impossible to fabricate and maintain a nuclear weapon.

The production of such large amounts of plutonium-238 comes about because more of the fuel is consumed (or "burned up," in the lingo of nuclear engineers) than is the case in conventional uranium-fueled reactors. An equivalent amount of plutonium-238 could be created using an all-uranium fuel, but this would require a higher initial amount of fissile uranium (^{235}U) than is typical in today's practice, and the economic projections for that are discouraging.

Thus our recent work amply confirms that the various engineering concerns can be met and that running reactors on thorium could indeed forestall clandestine efforts to use the spent fuel for making bombs. But the results of our investigation into the economics of thorium are less clear-cut. We estimate that thorium-based fuels could cost anywhere from 10 percent less to about 10 percent more than conventional nuclear fuels. The wide range stems from fundamental uncertainties about the cost of the seed uranium (which must be four times more enriched in uranium-235 than is the case with typical nuclear fuels), the cost of fabricating the fuel assemblies and the savings that might accrue in the future as a result of the reduction in the amount of spent fuel in need of disposal.

Although it seems unlikely that economics alone could drive the adoption of thorium fuels, there are no technical "show-stoppers" here. Modifications to the existing commercial infrastructure would clearly be needed, but no fundamentally new technology is required. And the fact that the relevant materials (thorium and enriched uranium) have a long record of experimental use in reactors lends credibility to the notion that this scheme could one day find widespread application, should policymakers push the nuclear industry in that direction.

Bibliography

Garwin, R. L.,and G. Charpak. 2002. *Megawatts and Megatons*. Chicago: University of Chicago Press.

Mark, C. 1992. Explosive properties of reactor-grade plutonium. *Science and Global Security* 3:1–13.

Radkowsky, A., and A. Galperin. 1998. The nonproliferative light water reactor: A new approach to light water reactor core technology. *Nuclear Technology* 124:215–222.

Shwageraus, S. , X. Zhao, , M. Driscoll, P. Hejzlar, M. S. Kazimi and J. S. Herring. In press. Micro-heterogeneous thoria-urania fuels for pressurized water reactors. *Nuclear Technology*.

For relevant Web links, consult this issue of *American Scientist Online:*

http://www.americanscientist.org/template/IssueTOC/issue/400