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Thorium: The Preferred Nuclear Fuel of the Future

*Nuclear engineer Ramtanu Maitra shows, from the case study of India, how the development of thorium fuel cycles will enhance the efficiency and economy of nuclear power plants.**

Thorium is an abundant element in nature with multiple advantages as a nuclear fuel for future reactors of all types. Thorium ore, or monazite, exists in vast amounts in the dark beach sand of India, Australia, and Brazil. It is also found in large amounts in Norway, the United States, Canada, and South Africa. Thorium-based fuel cycles have been studied for about 30 years, but on a much smaller scale than uranium or uranium/plutonium cycles. Germany, India, Japan, Russia, the United Kingdom, and the United States have conducted research and development, including irradiating thorium fuel in test reactors to high burn-ups. Several reactors have used thorium-based fuel, as discussed below.

India is by far the nation most committed to study and use of thorium fuel; no other country has done as much neutron physics work on thorium as have Indian nuclear scientists. The positive results obtained in this neutron physics work have motivated the Indian nuclear engineers to use thorium-based fuels in their current plans for the more advanced reactors that are now under construction.

India decided on a three-stage nuclear program back in the 1950s, when its nuclear power generation program was set up. In the first stage, natural uranium (U-238) was used in pressurized heavy water reactors (PHWRs), of which there are now 12. In the second stage, the plutonium extracted from the spent fuel of the PHWRs was scheduled to be used to run fast breeder reactors. The fast breeders would burn a 70% mixed oxide (MOX) fuel to breed fissile uranium-233 (U-233) in a thorium-232 (Th-232) blanket around the core. In the final stage, the fast breeders would use Th-232 and produce U-233 for use in new reactors. One main advantage of using a combination of thorium and uranium is related to the proliferation question: There is a significant reduction in the plutonium content of the spent fuel, compared with what comes out of a conventional uranium-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, and 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, and the mix determines the plutonium production.

Indian Initiatives

To a certain extent, India has completed the first stage of its nuclear program, putting on line a dozen nuclear power plants so far, with a few more plants now in the construction process. The second stage is as yet realized only by a small experimental fast breeder reactor (13 megawatts), at Kalpakkam. Meanwhile, the Indian authorities have approved the Department of Atomic Energy's proposal to set up a 500-MW prototype of the next-generation fast breeder nuclear power reactor at Kalpakkam, thereby setting the stage for the commercial exploitation of thorium as a fuel source.

India's commitment to switch over to thorium stems, in

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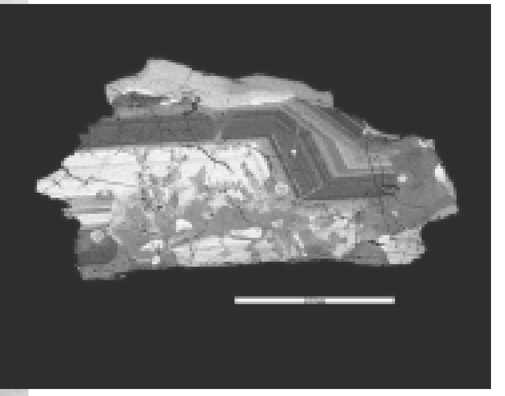


USGS

India has a plentiful supply of thorium in the rare earth monazite, found in its beach sands. Here workers transport sand to the Rare Earth Processing Plant at Alwaye. Inset is a backscattered electron image of a monazite crystal. Pure thorium is silver in color, but it becomes gray and then black as it oxidizes.

part, from its large indigenous thorium supply. India's estimated thorium reserves are 290,000 tons, second only to Australia. But the 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 is a nonsignatory of the Nuclear Non-Proliferation Treaty (NPT). Hence, India foresaw that it would be constrained in the long term by the provisions laid down by the commercial uranium suppliers, which would jeopardize India's nuclear power generation program. The 44-member nuclear suppliers group requires that purchasers sign the NPT, and thereby allow enough oversight to ensure that the fuel (or the plutonium spawned from it) is not used for making nuclear weapons.

India began the construction on the facility for reactor physics of the Advanced Heavy Water Reactor (AHWR) last year. The AHWR will use thorium, the "fuel of the future," to generate 300 megawatts of electricity, up from its original design output of 235 megawatts. The reactor will have a lifetime of 100 years, and is scheduled to be built on the campus of India's main nuclear research and development center, the Bhabha Atomic Research Center (BARC) at Trombay.

The construction of the AHWR will mark the beginning of the third phase of India's nuclear electricity-generation program. The fuel for the AHWR will be a hybrid core, partly thorium/uranium-233, and partly thorium-plutonium. The reactor will be a technology demonstrator for thorium utilization. According to B. Bhattacharjee, Director of the Bhabha Atomic Research Center, "At the international level, the AHWR has been selected for a case study at the IAEA [International Atomic Energy Agency] for acceptance as per international standards for next-generation reactors."

Abundance of Thorium

Although India's embrace of thorium as its future nuclear fuel is based mostly on necessity, the thorium fuel cycle itself has many attractive features. To begin with, thorium is much more abundant in nature than uranium. Soil commonly contains an average of around 6 parts per million (ppm) of thorium, three times as much as uranium.

Thorium occurs in several minerals, the most common being the rare earth thorium-phosphate mineral, monazite, which usually contains from 3 to 9%, and sometimes up to 12% thorium oxide. In India, the monazite is found in its southern beach sands.

TABLE 1
World Thorium Resources
(economically extractable)

Country	Reserves (tons)
Australia	300,000
India	290,000
Norway	170,000
USA	160,000
Canada	100,000
South Africa	35,000
Brazil	16,000
Other countries	95,000
World total	1,200,000

Source: U.S. Geological Survey, Mineral Commodity Summaries, January 1999.

Information Service of India

The Bhabha Atomic Research Center (BARC) in Trombay, India. Thorium fuel cycles have been intensively studied here, and the design phase of the thorium-fueled Advanced Heavy Water Reactor is under way. At an August meeting in Brussels on emerging reactor designs, two BARC scientists unveiled their design for an Advanced Thorium Breeder reactor (ATBR) that can produce 600 MW of electricity for two years, with no refueling.

Th-232 decays very slowly (its half-life is about three times the age of the Earth). Most other thorium isotopes are short-lived and thus much more radioactive than Th-232, but of negligible quantity.

In addition to thorium's abundance, all of the mined thorium is potentially usable in a reactor, compared with only 0.7% of natural uranium. In other words, thorium has some 40 times the amount of energy per unit mass that could be made available, compared with uranium.

From the technological angle, one reason that thorium is preferred over enriched uranium is that the breeding of U-233 from thorium is more efficient than the breeding of plutonium from U-238. This is so because the thorium fuel creates fewer non-fissile isotopes. Fuel-cycle 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 benefits. For example, thorium oxide, the form of thorium used for nuclear power, is a highly stable compound—more so than the uranium dioxide that is usually employed in today's conventional nuclear fuel. Also, the thermal conductivity of thorium oxide is 10 to 15% higher than that of uranium dioxide, making it easier for heat to flow out of the fuel rods used inside a reactor.

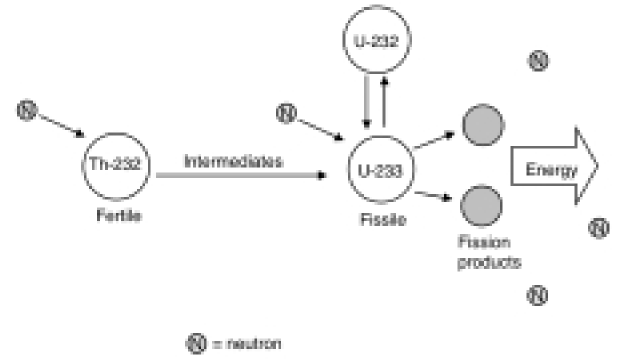
In addition, the melting point of thorium oxide is about 500 degrees Celsius *higher* than that of uranium dioxide, which gives the reactor an additional safety margin, if there is a temporary loss of coolant.

The one challenge in using thorium as a fuel is that it requires neutrons to start off its fission process. These neutrons can be provided by the conventional fissioning of uranium or plutonium fuel mixed into the thorium, or by a particle accelerator. Most of the past thorium research has involved combining thorium with conventional nuclear fuels to provide the neutrons to trigger the fission process.

The approach undergoing the most investigation now is a combination that keeps a uranium-rich "seed" in the core, 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, when he was chief scientist of the U.S. Naval Reactors Program. Radkowsky, who died in 2002 at age 86, headed up the design team that built the first U.S. civilian nuclear reactor at Shippingport, Pennsylvania, and made significant contributions to the commercial nuclear industry during the 1960s and 1970s.

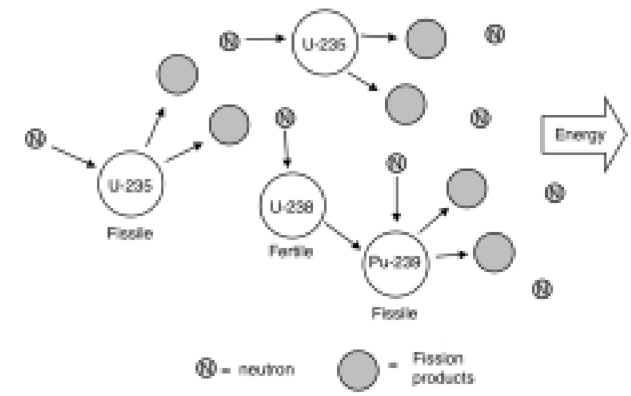
Although thorium is not fissile like U-235, Th-232 absorbs slow neutrons to produce U-233, which is fissile. In other words, Th-232 is fertile, like U-238. The Th-232 absorbs a neutron to become Th-233, which decays to protactinium-233 (Pa-233) and then to fissionable U-233. When the irradiated fuel is unloaded from the reactor, the U-233 can be separated from the thorium, and then used as fuel in another nuclear reactor. Uranium-233 is superior to the conventional nuclear fuels, U-235 and Pu-239, because it has a higher neu-

FIGURE 1
Simplified Diagram of the Thorium Fuel Cycle



The neutron trigger to start the thorium cycle can come from the fissioning of conventional nuclear fuels (uranium or plutonium) or an accelerator. When neutrons hit the fertile thorium-232 it decays to the fissile U-233 plus fission fragments (lighter elements) and more neutrons. (Not shown is the short-lived intermediate stage of protactinium-233.)

FIGURE 2
Simplified Diagram of the Uranium Fuel Cycle



In the conventional uranium fuel cycle, the fuel mix contains fissionable U-235 and fertile U-238. A few fast neutrons are released into the reactor core (for example, from a beryllium source), and when a neutron hits a U-235 nucleus, it splits apart, producing two fission fragments (lighter elements) and two or three new neutrons. Once the fission process is initiated, it can continue by itself in a chain reaction, as the neutrons from each fissioned uranium nucleus trigger new fissions in nearby nuclei. Some of the U-238, when hit by a neutron, decays to plutonium-239, which is also fissionable.

tron yield per neutron absorbed. This means that once it is activated by neutrons from fissile U-235 or Pu-239, thorium's breeding cycle is more efficient than that using U-238 and plutonium.

The Russian-U.S. Program

Since the early 1990s, Russia has had a program based at Moscow's Kurchatov Institute to develop a thorium-uranium fuel. The Russian program involves the U.S. company Thorium Power, Inc. (founded by Radkowsky), which has U.S. government and private funding to design fuel for the conventional Russian VVER-1000 reactors. Unlike the usual nuclear fuel, which uses enriched uranium oxide, the new fuel assembly design has the plutonium in the center as the "seed," in a demountable arrangement, with the thorium and uranium around it as a "blanket."

A normal VVER-1000 fuel assembly has 331 fuel rods, each of 9-millimeter diameter, forming a hexagonal assembly 235-mm wide. The center portion of each assembly is 155-mm across and holds the seed material, consisting of metallic plutonium-zirconium alloy (about 10% of the alloy is plutonium, of which more than 90% is the isotope Pu-239) in the form of 108 twisted three-section rods, which are 12.75-mm wide, with cladding of zirconium alloy.

The blanket consists of uranium-thorium oxide fuel pellets (in a ratio of uranium to thorium of 1:9, with the uranium enriched up to almost 20%) in 228 cladding tubes of zirconium alloy, 8.4-mm diameter. These pellets are in four layers around the center portion. The blanket material achieves 100 gigawatt-days burn-up. Together as one fuel assembly, the seed and blanket have the same geometry as a normal VVER-100 fuel assembly. As reported by Grae et al. (see note 4), thorium fuel burns 75% of the originally loaded weapons-grade plutonium, compared with a 31% burn for mixed oxide (MOX) fuel, which is made of a mixture of uranium and plutonium. But unlike MOX, thorium fuel does not produce more plutonium and has cost advantages over MOX. Grae et al. conclude:

"Thorium fuel offers a promising means to dispose of excess weapons-grade plutonium in Russian VVER-1000 reactors. Using the thorium fuel technology, plutonium can be disposed of up to three times as fast as MOX at a significantly lower cost. Spent thorium fuel would be more proliferation-resistant than spent MOX fuel. . . . [The thorium fuel technology] will not require significant and costly reactor modifications. Thorium fuel also offers additional benefits in terms of reduced weight and volume of spent fuel and therefore lower disposal costs."

Four Decades of R&D

Concepts for advanced reactors based on thorium fuel cycles include:

Light Water Reactors. Fuels based on plutonium oxide (PuO_2), thorium oxide (ThO_2), and/or uranium oxide (UO_2) particles are arranged in fuel rods.

High-Temperature Gas-cooled Reactors (HTGR). These are of of two kinds: the pebble bed and the prismatic fuel design.

The Pebble Bed Modular Reactor (PBMR) originated in Germany, and is now being developed in South Africa and in China. It can potentially use thorium in its fuel pebbles.

The Gas Turbine-Modular Helium Reactor (GT-MHR) was developed in the United States by General Atomics using a prismatic fuel. The use of helium as a coolant at high temperature, and the relatively small power output per module (600 megawatts-thermal), permit direct coupling of the reactor to a gas turbine (a Brayton cycle), resulting in power generation at 48 percent thermal efficiency (which is 50% more efficient than the conventional nuclear reactors in use today). The GT-MHR core can accommodate a wide range of fuel options, including highly enriched uranium/thorium, U-233/Th, and Pu/Th. The use of highly enriched uranium/thorium fuel was demonstrated in General Atomics' Fort St. Vrain reactor in Colorado (see below).

Molten salt reactors. This advanced breeder concept circulates the fuel in molten salt, without any external coolant in the core. The primary circuit runs through a heat exchanger, which transfers the heat from fission to a secondary salt circuit for steam generation. It was studied in depth in the 1960s, and is now being revived because of the availability of advanced technology for the materials and components.

Advanced Heavy Water Reactor (AHWR). India is working on this, and like the Canadian CANDU-NG, this 250-megawatt-electric (MWe) design is light-water cooled. The main part of the core is subcritical, with Th/U-233 oxide, mixed so that the system is self-sustaining in U-233. A few seed regions with conventional MOX fuel will drive the reaction and give it a negative void coefficient overall. (In other words, as the reactor heats up, the fission process slows down.)

Accelerator Driven Systems (ADS). In accelerator driven systems, high-energy neutrons are produced through the spallation reaction of high-energy protons from an accelerator striking target heavy nuclei (lead, lead-bismuth, or other materials). These neutrons can be directed to a subcritical reactor containing thorium, where the neutrons breed U-233 and promote its fission. There is therefore the possibility of sustaining a fission reaction which can readily be turned off, and used either for power generation or destruction of actinides resulting from the uranium/plutonium fuel cycle. The use of thorium instead of uranium means that fewer new actinides are produced in the accelerator-driven system itself.

The difficulties, as of now, in developing the thorium fuel cycle include the high cost of fuel fabrication. This is

Thorium Converter Reactor Ready for Development

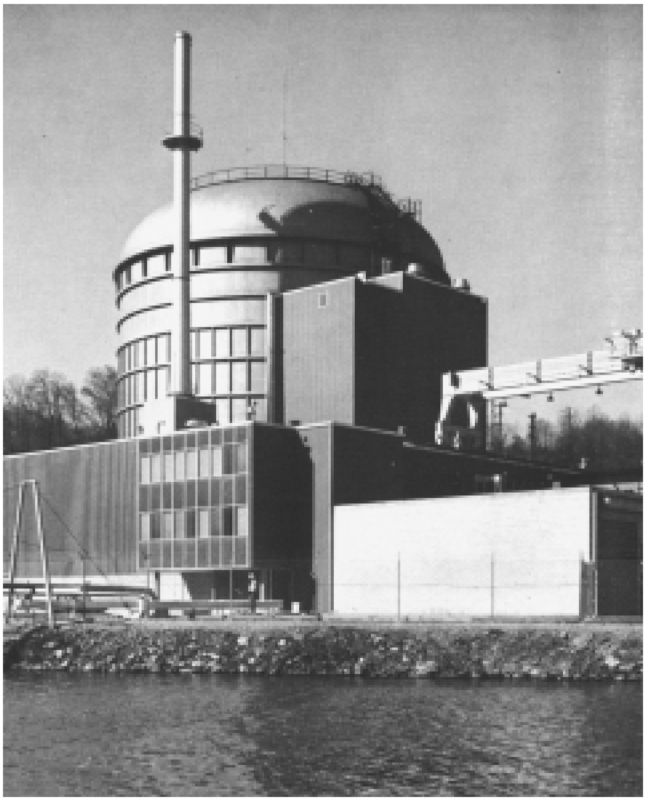
An attorney-inventor working with Lawrence Berkeley National Laboratory physicists has proposed a small 50-megawatt-thermal thorium converter reactor for multiple uses: producing electricity (15 megawatts), burning up high-level actinides from spent fuel, and producing low-cost, high-temperature steam (or process industrial heat). This high-temperature steam can be used for extraction of oil from tar sands, or desalinating, purifying, and cracking water. The reactor's fuel matrix can be "tuned" to provide the right output for each particular work process.

Designed by Charles S. Holden, working with physicist Tak Pui Lou, the reactor core is a squat cylinder, about 3 meters wide and 1 meter tall. Its size makes it portable, so that it can be brought to a remote work site and supply electricity there without dependence on long-distance transmission lines. Its small size also allows it to be factory built and transported to its destination, "plugged in" in a deep underground containment structure, and put to work quickly. The core can be shipped back to the factory when the fuel needs to be changed.

The reactor configuration is different from the Radkowsky design in the Russian thorium-burning reactors. Its ceramic fuel is dispersed in an inert metal matrix covered by Holden's provisional patents. This solid state metal alloy is composed of four materials. The thorium and uranium fuel particles are embedded in the alloy, which both slows and moderates the fissioning process. Using the metal as a moderator (instead of the water used in other thorium reactor designs) allows the reactor to operate in a more energetic neutron spectrum so that its core can have a long life.

The self-regulating reactor is expected to operate for 10 years without needing refueling. The neutrons to start it up will be provided by a fusion-driven neutron generator, designed by Dr. Ka-No Leung, head of Plasma and Ion Source Technology under the Accelerator and Fusion Research Division of the Lawrence Berkeley National Laboratory. The alloy and fuel configuration are expected to be tested at the Advanced Thermal Reactor testing complex at the Idaho National Lab; computer modelling of the system will also be done in the national laboratory system.

Holden and Pui's company, Thorenco LLC, is now looking for investors to develop a commercial prototype. Thorenco is based in San Francisco, and can be reached by e-mail at rusthold@mindspring.com or by telephone 415-398-7878.—*Marjorie Mazel Hecht*



Philadelphia Electric Co.

General Atomics' Peach Bottom reactor, 65 miles southwest of Philadelphia, began commercial operation in 1967. This high-temperature, graphite-moderated, helium-cooled reactor operated between 1967 and 1974 at 110-MWt, using highly enriched uranium with thorium.

partly because of the high radioactivity of U-233, which is always contaminated with traces of U-232; similar problems in recycling thorium because of the highly radioactive Th-228, and some weapons proliferation risk of U-233; and the technical problems (not yet satisfactorily solved) in reprocessing.

Thorium Fuel Operating Experience

Between 1967 and 1988, the AVR experimental pebble bed reactor at Jülich, Germany, operated for more than 750 weeks at 15 megawatts-electric, about 95 percent of the time with thorium-based fuel. The fuel used consisted of about 100,000 billiard ball-size fuel elements. Overall, a total of 1,360 kilograms of thorium was used, mixed with highly enriched uranium (HEU). Maximum burn-ups of 150,000 megawatt-days were achieved. Thorium fuel elements with a 10:1 ratio of thorium to highly enriched uranium were irradiated in the 20-megawatts-thermal (MWt) Dragon reactor at Winfrith, United Kingdom, for 741 full-power days. Dragon was run as a cooperative project of the Organization of Economic Cooperation and Development and Euratom, involving Austria, Denmark, Sweden, Norway, and Switzerland, in addition to the United Kingdom, from 1964 to 1973. The thorium-uranium fuel was used to "breed and feed," so that the U-233 that was formed, replaced the U-235 at about the same rate, and fuel could be left in the reactor for about six years. The General Atomics Peach Bottom high-temperature, graphite-moderated, helium-cooled reactor (HTGR) in the United States operated between 1967 and 1974 at 110-MWt, using highly enriched uranium with thorium.

In India, the Kamini 30-kWt experimental neutron-source research reactor started up in 1996 near Kalpakkam, using U-233 which was recovered from thorium-dioxide fuel that had been irradiated in another reactor. The Kamini reactor is adjacent to the 40-MWt Fast Breeder Test Reactor, in which the thorium-dioxide is irradiated.

In the Netherlands, an aqueous homogenous suspension reactor has operated at 1 megawatt-thermal for three years. The highly enriched uranium/thorium fuel is circulated in solution, and reprocessing occurs continuously to remove fission products, resulting in a high conversion rate to U-233.

Thorium in Power Reactors

The 300-MWe THTR reactor in Germany was developed from the AVR, and operated between 1983 and 1989 with 674,000 pebbles, over half of them containing thorium/highly enriched uranium fuel (the rest of the pebbles were graphite moderator and some neutron absorbers). These pebbles were continuously recycled on load, and on average the fuel passed six times through the core. Fuel fabrication was on an industrial scale.

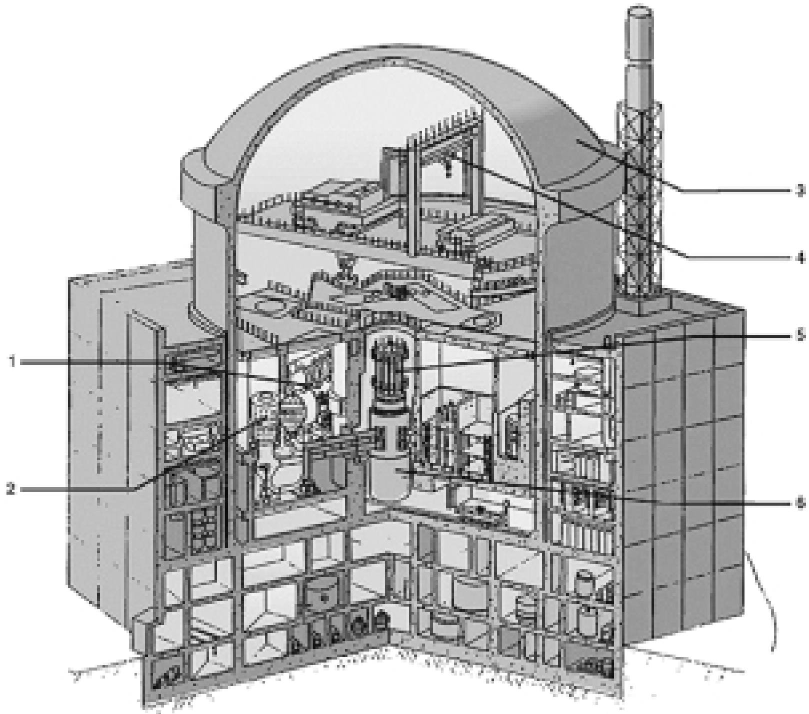
The Fort St. Vrain reactor in Colorado was the only commercial thorium-fueled nuclear plant in the United States. Developed from the AVR in Germany, it operated from 1976 to 1989. It was a high-temperature (700°C), graphite-moderated, helium-cooled reactor with a thorium/highly enriched uranium fuel, which was designed to operate at 842 megawatts-thermal (330 MWe). The fuel was contained in microspheres of thorium carbide and Th/U-235 carbide, coated with silicon oxide and pyrolytic carbon to retain fission products.

Unlike the pebble bed design, the fuel was arranged in hexagonal columns ("prisms") in an annular configuration. Almost 25 tons of thorium were used in the reactor fuel, achieving a 170,000-megawatt-days burn-up.

Thorium-based fuel for Pressurized Water Reactors (PWRs) was investigated at the Shippingport reactor in the United States (the first U.S. commercial reactor, started up in 1957), using both U-235 and plutonium as the initial fissile material. It was concluded that thorium would not significantly affect operating strategies or core margins. The light water breeder reactor (LWBR) concept was also successfully tested at Shippingport, from 1977 to 1982, with thorium and U-233 fuel clad with zircaloy, using the "seed/blanket" concept.

Another reactor type, the 60-MWe Lingen Boiling Water

FIGURE 3
Cutaway View of the VVER-1000



(1) Horizontal steam generator
(2) Reactor coolant pump
(3) Containment building
(4) Refueling crane
(5) Control rod drive assemblies
(6) Reactor vessel

Source: Argonne National Laboratory

The 1,000-MW VVER, Russia's conventional reactor design is shown here in its third generation version. It is a pressurized light-water-cooled and -moderated reactor, similar to Western pressurized water reactors in operation and safety standards. The Thorium Power/Radkowsky design would modify the core for a thorium fuel cycle that would burn up weapons plutonium.

Reactor (BWR) in Germany also utilized fuel test elements that were thorium-plutonium based.

Proliferation Issues

In the early days of the civilian nuclear program, the Acheson-Lilienthal Report in 1946 warned of the connection between civilian nuclear power and nuclear weapons, and concluded that the world could not rely on safeguards alone "to protect complying states against the hazards of violations and evasions"-illicit nuclear weapons. Acheson-Lilienthal proposed international controls over nuclear power, but also considered possible technical innovations that would make it harder to divert nuclear materials into bomb-making. The thorium fuel cycle is one such technical innovation—as yet untapped.

A 1998 paper by Radkowsky and Galparin (see note 8) describes the most advanced work in developing a practical nuclear power system that could be made more "proliferation resistant" than conventional reactors and fuel cycles. Based on a thorium fuel cycle, it has the potential to reduce the amount of plutonium generated per gigawatt-year by a factor of five, compared to conventional uranium-fueled reactors. It would also make the generated plutonium and uranium-233 much more difficult to use for producing bomb material.

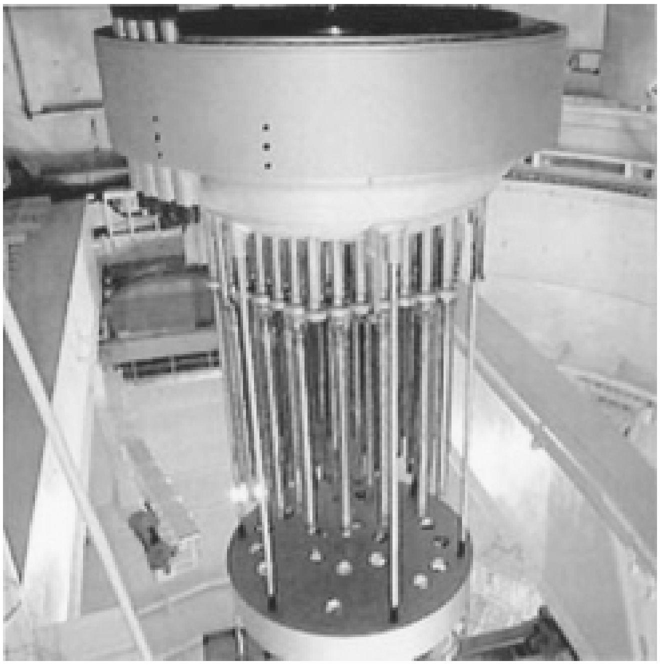
Heightened current concerns about preventing the spread of bomb-making materials, have led to an increase in interest in developing thorium-based fuels. The U.S. Department of Energy has funded Radkowsky's company (Thorium Power) and its partners in their tests with Russian reactors, as well as three other efforts (two national laboratories, two fuel fabrication companies, and a consortium of three universities). This research is geared to designing a thorium fuel system that will fit with conventional reactors. (See box, p. 68, for another thorium design.) There is also a new company, Novastar Resources, that is buying up thorium mines in anticipation of thorium-fueled reactors in the future. The proliferation potential of the light water reactor fuel cycle may be significantly reduced by using thorium as a fertile component of the nuclear fuel, as noted above. The main challenge of thorium utilization is to design a core and a fuel cycle that would be proliferation-resistant and economically feasible. This challenge is met by the Radkowsky Thorium Reactor concept. So far, the concept has been applied to a Russian design of a 1,000-MW pressurized water reactor VVER, designated as VVERT. The main results of the preliminary reference design are as follows: The amount of plutonium contained in the Radkowsky Thorium Reactor spent fuel stockpile is reduced by 80%, in comparison with a VVER of conventional design. The isotopic composition of the reactor's plutonium greatly increases the probability of pre-initiation and yield degradation of a nuclear explosion. An extremely large Pu-238 content causes correspondingly large heat emission, which would complicate the design of an explosive device based on plutonium from this reactor.

The economic incentive to reprocess and reuse the fissile component of the Radkowsky Thorium Reactor spent fuel is also decreased. The once-through cycle is economically optimal for its core and cycle.

To reiterate the proliferation difficulties: the replacement

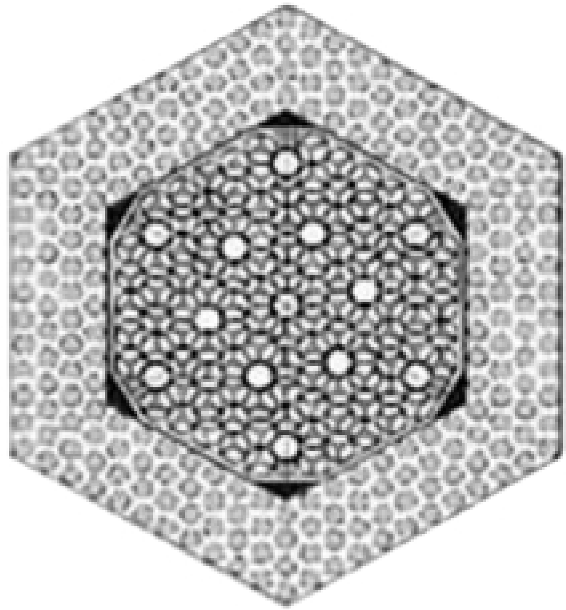
FIGURE 4

(A) VVER Fuel Rod Assembly



Nukeworker.com

(B) Design for Thorium Seed/Blanket Assembly



Thorium Power, Inc.

Radkowsky design for the thorium seed/blanket assembly. The seed fuel is the inner part of the fuel rod (three-sectioned), and the blanket fuel is the outer part. The thorium fuel assembly is designed to replace the current fuel assembly, without requiring a major design rehaul.

of a standard (uranium-based) fuel for nuclear reactors of current generation by the Radkowsky Thorium Reactor fuel will provide a strong barrier for nuclear weapon proliferation. This barrier, in combination with existing safeguard measures and procedures, is adequate to unambiguously disassociate civilian nuclear power from military nuclear power.

Other scientists point out that even if a terrorist group wanted to use the blanket plutonium for making a bomb, the process of extracting it from thorium fuel would be more difficult than removing it from conventional spent fuel. This is because the spent blanket fuel from a thorium fuel cycle would contain uranium-232, which over time decays into isotopes that emit high-energy gamma rays. To extract the plutonium from this spent fuel would require significantly more radiation shielding plus additional remotely operated equipment in order to reprocess it for weapons use, making a daunting task even more difficult. It would also be more complicated to separate the fissionable U-233 from uranium-238, because of the highly radioactive products present.

Overall, the development of thorium fuel cycles makes sense for the future, for advancing the efficiency and economy of nuclear power plants, ease of recycling, and making it more difficult to divert radioactive materials for weapons.

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