Liquid Fluoride Thorium Reactors

An old idea in nuclear power gets reexamined

Robert Hargraves and Ralph Moir

What if we could turn back the clock to 1965 and have an energy do-over? In June of that year, the Molten Salt Reactor Experiment (MSRE) achieved criticality for the first time at Oak Ridge National Laboratory (ORNL) in Tennessee. In place of the familiar fuel rods of modern nuclear plants, the MSRE used liquid fuel—hot fluoride salt containing dissolved fissile material in a solution roughly the viscosity of water at operating temperature. The MSRE ran successfully for five years, opening a new window on nuclear technology. Then the window banged closed when the molten-salt research program was terminated.

Knowing what we now know about climate change, peak oil, Three Mile Island, Chernobyl, and the Deepwater Horizon oil well gushing in the Gulf of Mexico in the summer of 2010, what if we could have taken a different energy path? Many feel that there is good reason to wish that the liquid-fuel MSRE had been allowed to mature. An increasingly popular vision of the future sees liquid-fuel reactors playing a central role in the energy economy, utilizing relatively abundant thorium instead of uranium, mass producible, free of carbon emissions, inherently safe and generating a trifling amount of waste.

Of course we can't turn back the clock. Maddeningly to advocates of liquid-fuel thorium power, it is proving just as hard to simply restart the clock. Historical, technological and regulatory reasons conspire to make it hugely difficult to diverge from our current path of solid-fuel, uranium-based plants. And yet an alternative future that includes liquid-fuel thorium-based power beckons enticingly. We'll review the history, technology, chemistry and economics of thorium power and weigh the pros and cons of thorium versus uranium. We'll conclude by asking the question we started with: What if?

The Choice

The idea of a liquid-fuel nuclear reactor is not new. Enrico Fermi, creator in 1942 of the first nuclear reactor in a pile of graphite and uranium blocks at the University of Chicago, started up the world's first liquid-fuel reactor two years later in 1944, using uranium sulfate fuel dissolved in water. In all nuclear chain reactions, fissile material absorbs a neutron, then fission of the atom releases tremendous energy and additional neutrons. The emitted neutrons, traveling at close to 10 percent of the speed of light, would be very unlikely to cause further fission in a reactor like Fermi's Chicago Pile-1 unless they were drastically slowed—moderated—to speeds of a few kilometers per second. In Fermi's device, the blocks of graphite between pellets of uranium fuel slowed the neutrons down. The control system for Fermi's reactor consisted of cadmium-coated rods that upon insertion would capture neutrons, quenching the chain reaction by reducing neutron generation. The same principles of neutron moderation and control of the chain reaction by regulation of the neutron economy continue to be central concepts of nuclear reactor design.

In the era immediately following Fermi's breakthrough, a large variety of options needed to be explored. Alvin Weinberg, director of ORNL from 1955 to 1973, where he presided over one of the major research hubs during the development of nuclear power, describes the situation in his memoir, *The First Nuclear Era:*

> In the early days we explored all sorts of power reactors, comparing the advantages and disadvantages of each type. The number of possibilities was enormous, since there are many possibilities for each component of a reactor—fuel, coolant, moderator. The fissile material may be U-233, U-235, or Pu-239; the coolant may be: water, heavy water, gas, or liquid metal; the moderator may be: water, heavy water, beryllium, graphite—or, in a fast-neutron reactor, no moderator….if one calculated all the combinations of fuel, coolant, and moderator, one could identify about a thousand distinct reactors. Thus, at the very beginning of nuclear power, we had to choose which possibilities to pursue, which to ignore.

Among the many choices made, perhaps the most important choice for the future trajectory of nuclear power was decided by Admiral Hyman Rickover, the strong-willed Director of Naval Reactors. He decided that the first nuclear submarine, the *USS Nautilus*, would be powered by solid uranium oxide enriched in uranium-235, using water as coolant and moderator. The *Nautilus* took to sea successfully in 1955. Building on the momentum of research and spending for the *Nautilus* reactor, a reactor of similar design was installed at the Shippingport Atomic Power

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Figure 1. Thorium is a relatively abundant, slightly radioactive element that at one time looked like the future of nuclear power. It was supplanted when the age of uranium began with the launching of the nuclear-powered *USS Nautilus,* whose reactor core was the technological ancestor of today's nuclear fleet. Thorium is nonfissile but can be converted to fissile uranium-233, the overlooked sibling of fissile uranium isotopes. The chemistry, economics, safety features and nonproliferation aspects of the thorium/uranium fuel cycle are earning it a hard new look as a potential solution to today's problems of climate change, climbing requirements for energy in the developing world, and the threat of diversion of nuclear materials to illicit purposes. Shown are thorium pellets fabricated in the Bhabha Atomic Research Centre in Mumbai, India, which has the task of developing a long-range program to convert India to thorium-based power over the next fifty years, making the most of India's modest uranium reserves and vast thorium reserves.

Station in Pennsylvania to become the first commercial nuclear power plant when it went online in 1957.

Rickover could cite many reasons for choosing to power the *Nautilus* with the S1W reactor (S1W stands for submarine, 1st generation, Westinghouse). At the time it was the most suitable design for a submarine. It was the likeliest to be ready soonest. And the uranium fuel cycle offered as a byproduct plutonium-239, which was used for the development of thermonuclear ordnance. These reasons have marginal relevance today, but they were critical in defining the nuclear track we have been on ever since the 1950s. The down sides of Rickover's choice remain with us as well. Solid uranium fuel has inherent challenges. The heat and radiation of the reactor core damage the fuel assemblies, one reason fuel rods are taken out of service after just a few years and after consuming only three to five percent of the energy in the uranium they contain. Buildup of fission products within the fuel rod also undermines the efficiency of the fuel, especially the accumulation of xenon-135, which has a spectacular appetite for neutrons, thus acting as a fission poison by disrupting the neutron economy of the chain reaction. Xenon-135 is short-lived (half-life of 9.2 hours) but it figures importantly in the management of the reactor. For example, as it burns off, the elimination of xenon-135 causes the chain reaction to accelerate, which requires control rods to be reinserted in a carefully managed cycle until the reactor is stabilized. Mismanagement of this procedure contributed to the instability in the Chernobyl core that led to a runaway reactor and the explosion that followed.

Other byproducts of uranium fission include long-lived transuranic materials (elements above uranium

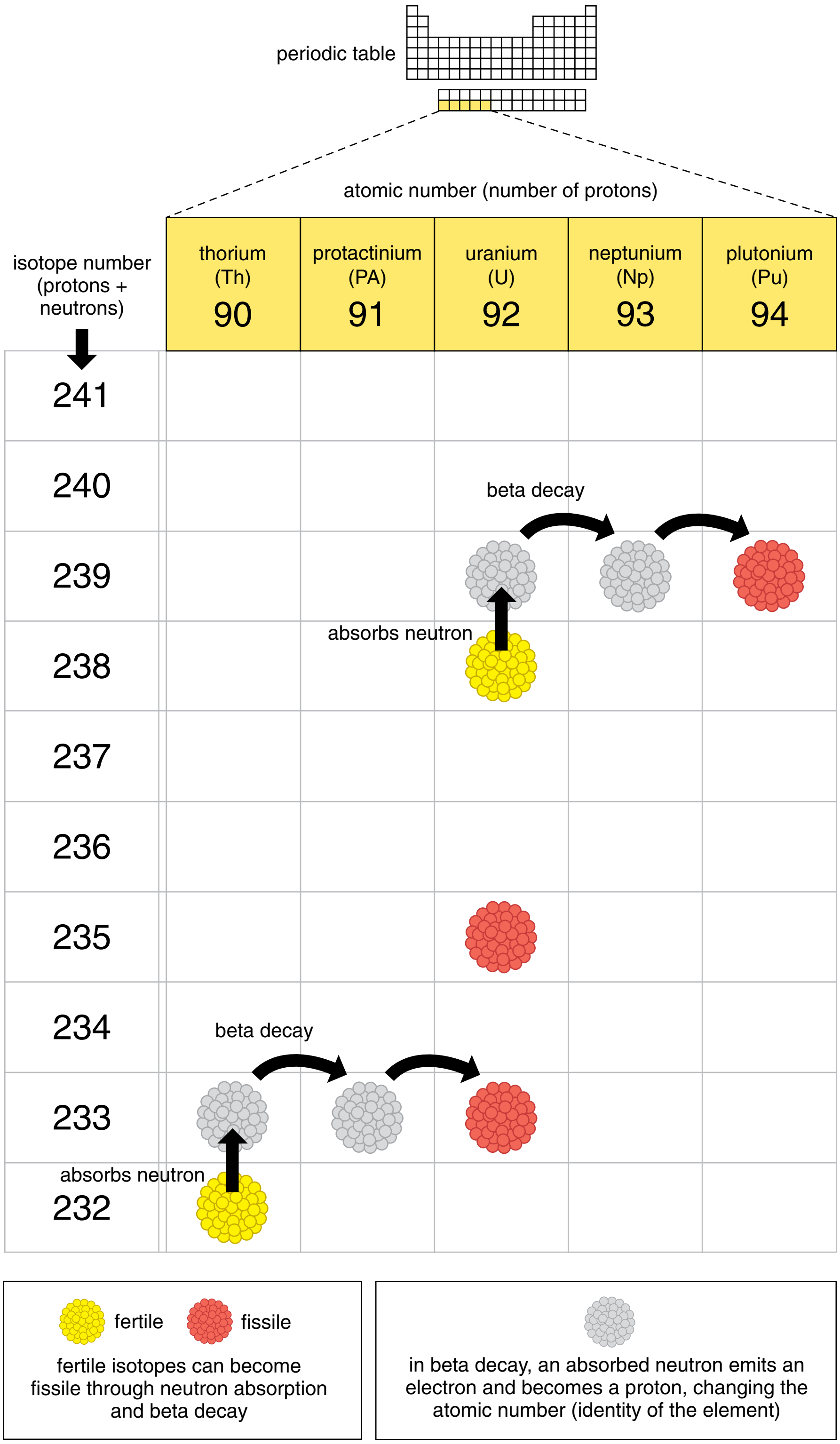

Figure 2. In a reactor core, fission events produce a controlled storm of neutrons that can be absorbed by other elements present. Fertile isotopes are those that can become fissile (capable of fission) after successive neutron captures. Fertile Th-232 captures a neutron to become Th-233, then undergoes beta decay—emission of an electron with the transformation of a neutron into a proton. With the increase in proton number, Th-233 transmutes into Pa-233, then beta decay of Pa-233 forms fissile U-233. Most U-233 in a reactor will absorb a neutron and undergo fission; some will absorb an additional neutron before fission occurs, forming U-234 and so on up the ladder. Comparing the transmutation routes to plutonium in thorium- and uranium-based reactors, many more absorption and decay events are required to reach Pu-239 when starting from Th-232, thus leaving far less plutonium to be managed, and possibly diverted, in the thorium fuel and waste cycles.

in the periodic table), such as plutonium, americium, neptunium and curium. Disposal of these wastes of the uranium era is a problem that is yet to be resolved.

Thorium

When Fermi built Chicago Pile-1, uranium was the obvious fuel choice: Uranium-235 was the only fissile material on Earth. Early on, however, it was understood that burning small amounts of uranium-235 in the presence of much larger amounts of uranium-238 in a nuclear reactor would generate transmuted products, including fissile isotopes such as plutonium-239. The pioneers of nuclear power (Weinberg in his memoir calls his cohorts "the old nukes") were transfixed by the vision of using uranium reactors to breed additional fuel in a cycle that would transform the world by delivering limitless, inexpensive energy. By the same alchem istry of transmutation, the nonfissile isotope thorium-232 (the only naturally occurring isotope of thorium) can be converted to fissile uranium-233. A thorium-based fuel cycle brings with it different chemistry, different technology and different problems. It also potentially solves many of the most intractable problems of the uranium fuel cycle that today produces 17 percent of the electric power generated worldwide and 20 percent of the power generated in the U.S.

Thorium is present in the Earth's crust at about four times the amount of uranium and it is more easily extracted. When thorium-232 (atomic number 90) absorbs a neutron, the product, thorium-233, undergoes a series of two beta decays—in beta decay an electron is emitted and a neutron becomes a proton—forming uranium-233 (atomic number 91). Uranium-233 is fissile and is very well suited to serve as a reactor fuel. In fact, the advantages of the thorium/uranium fuel cycle compared to the uranium/plutonium cycle have mobilized a community of scientists and engineers who have resurrected the research of the Alvin Weinberg era and are attempting to get thorium-based power into the mainstream of research, policy and ultimately, production. Thorium power is sidelined at the moment in the national research laboratories of the U.S., but it is being pursued intensively in India, which has no uranium but massive thorium

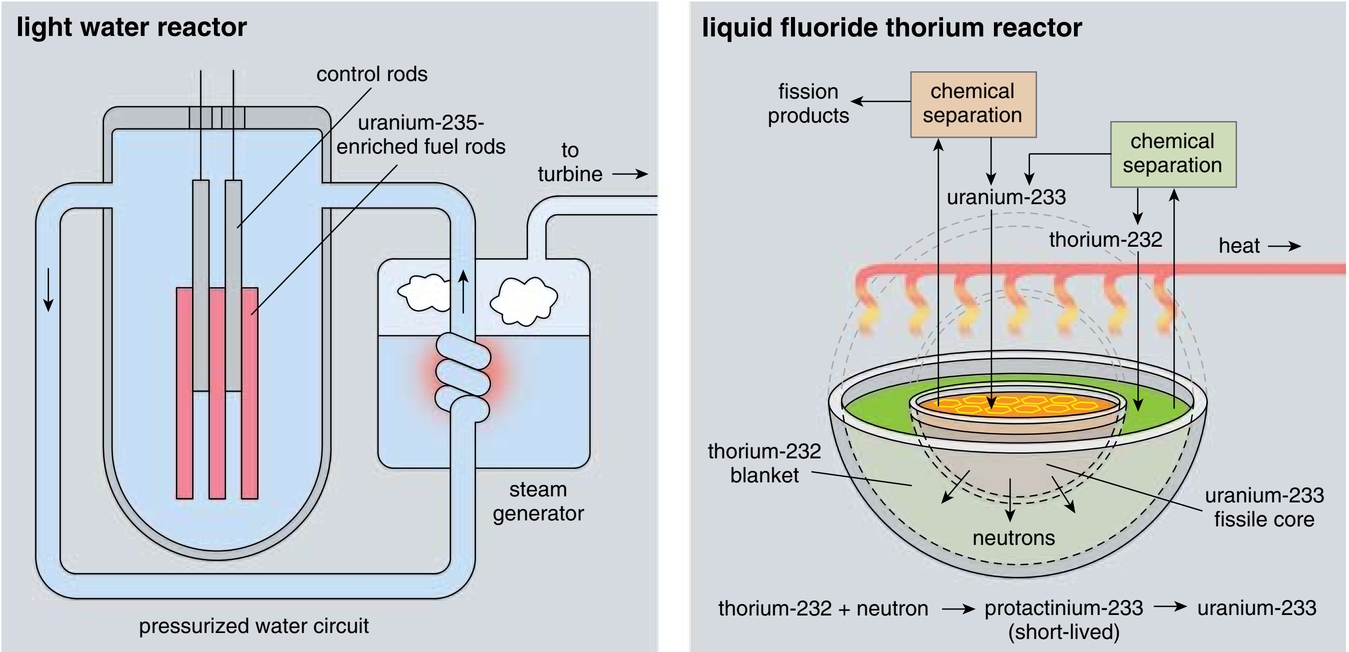

Figure 3. At its most schematic, the uranium-fueled light water reactor (all of the U.S. reactor fleet) consists of fuel rods, control rods, and water moderator and coolant. The liquid fluoride thorium reactor (LFTR) consists of a critical core *(orange)* containing fissile uranium-233 in a molten fluoride salt, surrounded by a blanket of molten fluoride salt containing thorium-232. Excess neutrons produced by fission in the core are absorbed by thorium-232 in the blanket *(green)*, generating uranium-233 by transmutation. The uranium-233 and other fission products are recovered by chemical separation and the newly bred and recovered uranium-233 is directed to the core, where it sustains the chain reaction.

reserves. Perhaps the best known research center for thorium is the Reactor Physics Group of the Laboratoire de Physique Subatomique et de Cosmologie in Grenoble, France, which has ample resources to develop thorium power, although their commitment to a commercial thorium solution remains tentative. (French production of electricity from nuclear power, at 80 percent, is the highest in the world, based on a large infrastructure of traditional pressurized water plants and their own national fuel-reprocessing program for recycling uranium fuel.)

The key to thorium-based power is detaching from the well-established picture of what a reactor should be. In a nutshell, the liquid fluoride thorium reactor (LFTR, pronounced "lifter") consists of a core and a "blanket," a volume that surrounds the core. The blanket contains a mixture of thorium tetrafluoride in a fluoride salt containing lithium and beryllium, made molten by the heat of the core. The core consists of fissile uranium-233 tetrafluoride also in molten fluoride salts of lithium and beryllium within a graphite structure that serves as a moderator and neutron reflector. The uranium-233 is produced in the blanket when neutrons generated in the core are absorbed by thorium-232 in the surrounding blanket. The thorium-233 that results then beta decays to short-lived protactinium-233, which rapidly beta decays again to fissile uranium-233. This fissile material is chemically separated from the blanket salt and transferred to the core to be burned up as fuel, generating heat through fission and neutrons that produce more uranium-233 from thorium in the blanket.

Advantages of Liquid Fuel

Liquid fuel thorium reactors offer an array of advantages in design, operation, safety, waste management, cost and proliferation resistance over the traditional configuration of nuclear plants. Individually, the advantages are intriguing. Collectively they are compelling.

Unlike solid nuclear fuel, liquid fluoride salts are impervious to radiation damage. We mentioned earlier that fuel

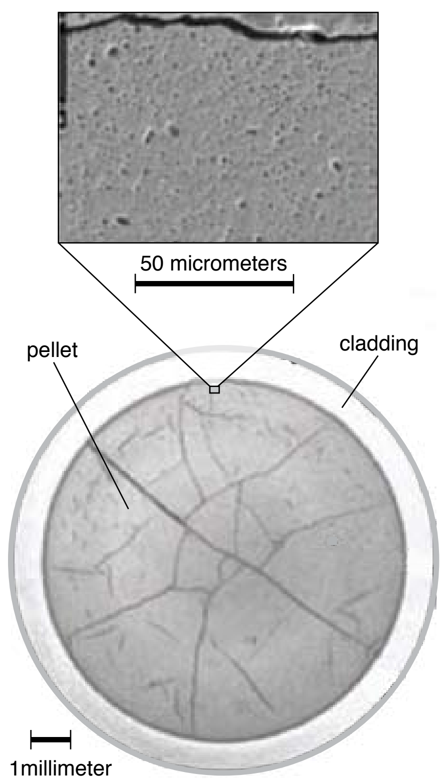

Figure 4. Uranium fuel rods are removed after just four percent or so of their potential energy is consumed. Noble gases such as krypton and xenon build up, along with other fission products such as samarium that accumulate and absorb neutrons, preventing them from sustaining the chain reaction. The solid is stressed by internal temperature differences, by radiation damage that breaks the covalent bonds of uranium dioxide, and by fission products that disturb the solid lattice structure. As the solid fuel swells and distorts, the irradiated zirconium cladding tubes must contain the fuel and all fission products within it, both in the reactor and for centuries thereafter in a waste storage repository.

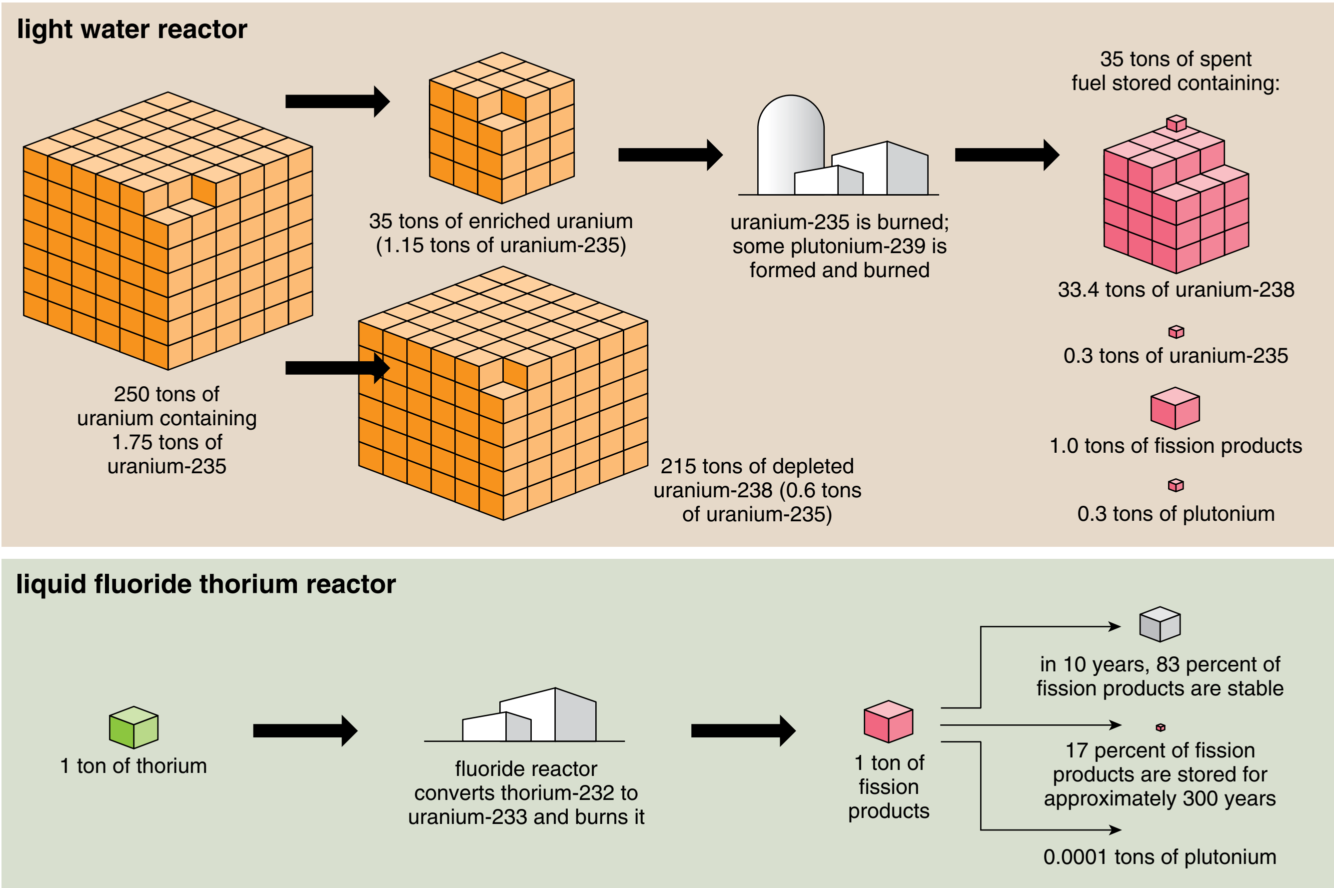

Figure 5. Among the many differences between the thorium/uranium fuel cycle and the enriched uranium/plutonium cycle is the volume of material handled from beginning to end to generate comparable amounts of electric power. Thorium is extracted in the same mines as rare earths, from which it is easily separated. In contrast, vast amounts of uranium ore must be laboriously and expensively processed to get usable amounts of uranium enriched in the fissile isotope uranium-235. On the other end of the fuel cycle, the uranium fuel cycle generates many times the amount of waste by mass, which must be stored in geological isolation for hundreds of centuries. The thorium fuel cycle generates much less waste, of far less long-term toxicity, which has to be stored for just three centuries or so.

rods acquire structural damage from the heat and radiation of the nuclear furnace. Replacing them requires expensive shutdown of the plant about every 18 months to swap out a third of the fuel rods while shuffling the remainder. Fresh fuel is not very hazardous, but spent fuel is intensely radioactive and must be handled by remotely operated equipment. After several years of storage underwater to allow highly radioactive fission products to decay to stability, fuel rods can be safely transferred to dry-cask storage. Liquid fluoride fuel is not subject to the structural stresses of solid fuel and its ionic bonds can tolerate unlimited levels of radiation damage, while eliminating the (rather high) cost of fabricating fuel elements and the (also high) cost of periodic shutdowns to replace them.

More important are the ways in which liquid fuel accommodates chemical engineering. Within uranium oxide fuel rods, numerous transuranic products are generated, such as plutonium-239, created by the absorption of a neutron by uranium-238, followed by beta decay. Some of this plutonium is fissioned, contributing as much as one-third of the energy production of uranium reactors. All such transuranic elements could eventually be destroyed in the neutron flux, either by direct fission or transmutation to a fissile element, except that the solid fuel must be removed long before complete burnup is achieved. In liquid fuel, transuranic fission products can remain in the fluid fuel of the core, transmuting by neutron absorption until eventually they nearly all undergo fission.

In solid fuel rods, fission products are trapped in the structural lattice of the fuel material. In liquid fuel, reaction products can be relatively easily removed. For example, the gaseous fission poison xenon is easy to remove because it bubbles out of solution as the fuel salt is pumped. Separation of materials by this mechanism is central to the main feature of thorium power, which is formation of fissile uranium-233 in the blanket for export to the core. In the fluoride salt of the thorium blanket, newly formed uranium-233 forms soluble uranium tetrafluoride (UF_4). Bubbling fluorine gas through the blanket solution converts the uranium tetrafluoride into gaseous uranium hexafluoride (UF_6), while not chemically affecting the less-reactive thorium tetrafluoride. Uranium hexafluoride comes out of solution, is captured, then is reduced back to soluble UF_4 by hydrogen gas in a reduction column, and finally is directed to the core to serve as fissile fuel.

Other fission products such as molybdenum, neodymium and technetium can be easily removed from liquid fuel by fluorination or plating techniques, greatly prolonging the viability and efficiency of the liquid fuel.

Liquid fluoride solutions are familiar chemistry. Millions of metric tons of liquid fluoride salts circulate through hundreds of aluminum chemical plants daily, and all uranium used in today's reactors has to pass in and out of a fluoride form in order to be enriched. The LFTR technology is in many ways a straightforward extension of contemporary nuclear chemical engineering.

Waste Not

Among the most attractive features of the LFTR design is its waste profile. It makes very little. Recently, the problem of nuclear waste generated during the uranium era has become both more and less urgent. It is more urgent because as of early 2009, the Obama administration has ruled that the Yucca Mountain Repository, the site designated for the permanent geological isolation of existing U.S. nuclear waste, is no longer to be considered an option. Without Yucca Mountain as a strategy for waste disposal, the U.S. has no strategy at all. In May 2009, Secretary of Energy Steven Chu, Nobel laureate in physics, said that Yucca Mountain

> is off the table. What we're going to be doing is saying, let's step back. We realize that we know a lot more today than we did 25 or 30 years ago. The [Nuclear Regulatory Commission] is saying that the dry-cask storage at current sites would be safe for many decades, so that gives us time to figure out what we should do for a long-term strategy.

The waste problem has become somewhat less urgent because many stakeholders believe Secretary Chu is correct that the waste, secured in huge, hardened casks under adequate guard, is in fact not vulnerable to any foreseeable accident or mischief in the near future, buying time to develop a sound plan for its permanent disposal. A sound plan we must have. One component of a long-range plan that would keep the growing problem from getting worse while meeting growing power needs would be to mobilize nuclear technology that creates far less waste that is far less toxic. The liquid fluoride thorium reactor answers that need.

Thorium and uranium reactors produce essentially the same fission (breakdown) products, but they produce a quite different spectrum of actinides (the elements above actinium in the periodic table, produced in reactors by neutron absorption and transmutation). The various isotopes of these elements are the main contributors to the very long-term radiotoxicity of nuclear waste.

The mass number of thorium-232 is six units less than that of uranium-238, thus many more neutron captures are required to transmute thorium to the first transuranic. Figure 6 shows that the radiotoxicity of wastes from a thorium/uranium fuel cycle is far lower than that of the currently employed uranium/plutonium cycle—after 300 years, it is about 10,000 times less toxic.

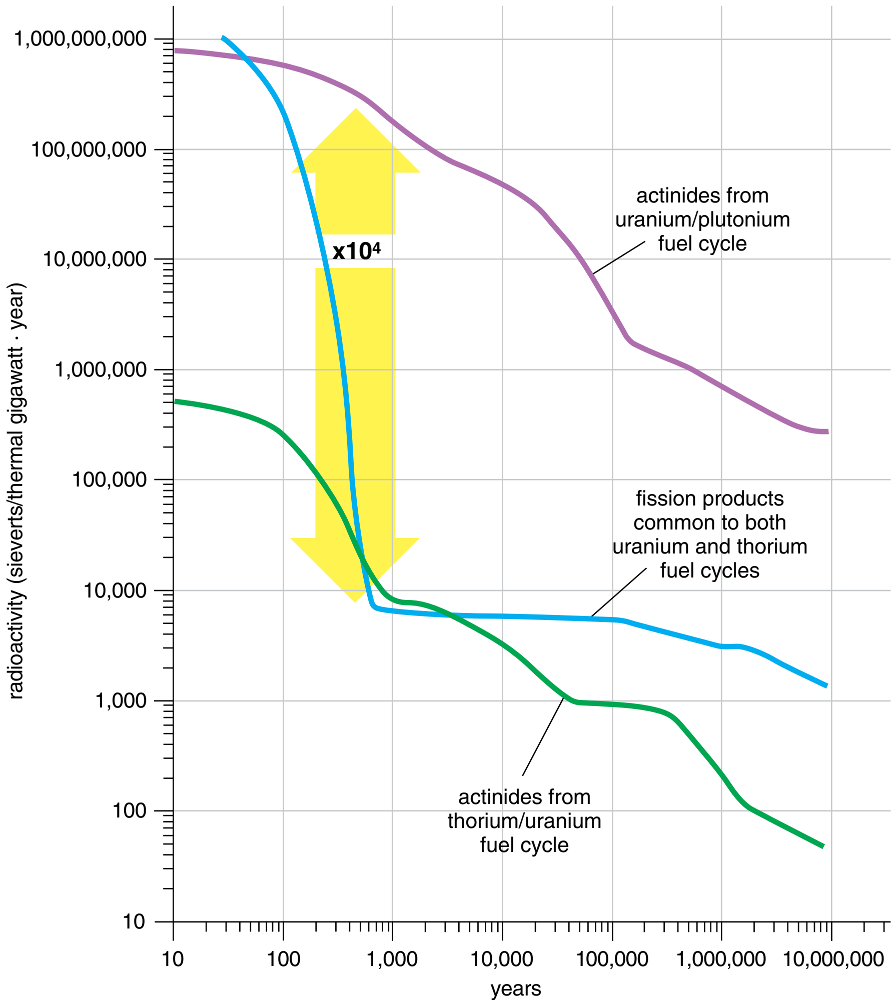

Figure 6. Switching to liquid fluoride thorium reactors would go a long way toward neutralizing the nuclear waste storage issue. The relatively small amount of waste produced in LFTRs requires a few hundred years of isolated storage versus the few hundred thousand years for the waste generated by the uranium/plutonium fuel cycle. Thorium- and uranium-fueled reactors produce essentially the same fission products, whose radiotoxicity is displayed in blue on this diagram of radiation dose versus time. The purple line is actinide waste from a light-water reactor, and the green line is actinide waste from a LFTR. After 300 years the radiotoxicity of the thorium fuel cycle waste is 10,000 times less than that of the uranium/plutonium fuel cycle waste. The LFTR scheme can also consume fissile material extracted from light-water reactor waste to start up thorium/uranium fuel generation.

By statute, the U.S. government has sole responsibility for the nuclear waste that has so far been produced and has collected $25 billion in fees from nuclear-power producers over the past 30 years to deal with it. Inaction on the waste front, to borrow the words of the Obama administration, is not an option. Many feel that some of the $25 billion collected so far would be well spent kickstarting research on thorium power to contribute to future power with minimal waste.

Safety First

It has always been the dream of reactor designers to produce plants with inherent safety—reactor assembly, fuel

Theodore Clutter/Photo Researchers

Figure 7. Nuclear power plants provide 20 percent of U.S. electricity and 70 percent of low-emissions energy supply. Every 750 megawatts of installed nuclear reactor capacity could avoid the release of one million metric tons of CO_2 per year versus similar electricity output obtained from natural gas.

and power-generation components engineered in such a way that the reactor will, without human intervention, remain stable or shut itself down in response to any accident, electrical outage, abnormal change in load or other mishap. The LFTR design appears, in its present state of research and design, to possess an extremely high degree of inherent safety. The single most volatile aspect of current nuclear reactors is the pressurized water. In boiling light-water, pressurized light-water, and heavy-water reactors (accounting for nearly all of the 441 reactors worldwide), water serves as the coolant and neutron moderator. The heat of fission causes water to boil, either directly in the core or in a steam generator, producing steam that drives a turbine. The water is maintained at high pressure to raise its boiling temperature. The explosive pressures involved are contained by a system of highly engineered, highly expensive piping and pressure vessels (called the "pressure boundary"), and the ultimate line of defense is the massive, expensive containment building surrounding the reactor, designed to withstand any explosive calamity and prevent the release of radioactive materials propelled by pressurized steam.

A signature safety feature of the LFTR design is that the coolant—liquid fluoride salt—is not under pressure. The fluoride salt does not boil below 1400 degrees Celsius. Neutral pressure reduces the cost and the scale of LFTR plant construction by reducing the scale of the containment requirements, because it obviates the need to contain a pressure explosion. Disruption in a transport line would result in a leak, not an explosion, which would be captured in a noncritical configuration in a catch basin, where it would passively cool and harden.

Another safety feature of LFTRs, shared with all of the new generation of LWRs, is its *negative temperature coefficient of reactivity*. Meltdown, the bogey of the early nuclear era, has been effectively designed out of modern nuclear fuels by engineering them so that power excursions—the industry term for runaway reactors—are self-limiting. For example, if the temperature in a reactor rises beyond the intended regime, signaling a power excursion, the fuel itself responds with thermal expansion, reducing the effective area for neutron absorption—the temperature coefficient of reactivity is negative—thus suppressing the rate of fission and causing the temperature to fall. With appropriate formulations and configurations of nuclear fuel, of which there are now a number from which to choose among solid fuels, runaway reactivity becomes implausible.

In the LFTR, thermal expansion of the liquid fuel and the moderator vessel containing it reduces the reactivity of the core. This response permits the desirable property of load following—under conditions of changing electricity demand (load), the reactor requires no intervention to respond with automatic increases or decreases in power production.

As a second tier of defense, LFTR designs have a freeze plug at the bottom of the core—a plug of salt, cooled by a fan to keep it at a temperature below the freezing point of the salt. If temperature rises beyond a critical point, the plug melts, and the liquid fuel in the core is immediately evacuated, pouring into a subcritical geometry in a catch basin. This formidable safety tactic is only possible if the fuel is a liquid. One of the current requirements of the Nuclear Regulatory Commission (NRC) for certification of a new nuclear plant design is that in the event of a complete electricity outage, the reactor remain at least stable for several days if it is not automatically deactivated. As it happens, the freeze-plug safety feature is as old as Alvin Weinberg's 1965 Molten Salt Reactor Experiment design, yet it meets the NRC's requirement; at ORNL, the "old nukes" would routinely shut down the reactor by simply cutting the power to the freeze-plug cooling system. This setup is the ultimate in safe power-outage response. Power isn't needed to shut down the reactor, for example by manipulating control elements. Instead power is needed to *prevent* the shutdown of the reactor.

Cost Wise

In terms of cost, the ideal would be to compete successfully against coal without subsidies or market-modifying legislation. It may well be possible. Capital costs are generally higher for conventional nuclear versus fossil-fuel plants, whereas fuel costs are lower. Capital costs are outsized for nuclear plants because the construction, including the containment building, must meet very high standards; the facilities include elaborate, redundant safety systems; and included in capital costs are levies for the cost of decommissioning and removing the plants when they are ultimately taken out of service. The much-consulted MIT study *The Future of Nuclear Power*, originally published in 2003 and updated in 2009, shows the capital costs of coal plants at $2.30 per watt versus $4 for light-water nuclear. A principal reason why the capital costs of LFTR plants could depart from this ratio is that the LFTR operates at atmospheric pressure and contains no pressurized water. With no water to flash to steam in the event of a pressure breach, a LFTR can use a much more close-fitting containment structure. Other expensive high-pressure coolant-injection systems can also be deleted. One concept for the smaller LFTR containment structure is a hardened concrete facility below ground level, with a robust concrete cap at ground level to resist aircraft impact and any other foreseeable assaults.

Other factors contribute to a favorable cost structure, such as simpler fuel handling, smaller components, markedly lower fuel costs and significantly higher energy efficiency. LFTRs are high-temperature reactors, operating at around 800 degrees Celsius, which is thermodynamically favorable for conversion of thermal to electrical energy—a conversion efficiency of 45 percent is likely, versus 33 percent typical of coal and older nuclear plants. The high heat also opens the door for other remunerative uses for the thermal energy, such as hydrogen production, which is greatly facilitated by high temperature, as well as driving other industrial chemical processes with excess process heat. Depending on the siting of a LFTR plant, it could even supply heat for homes and offices.

Thorium must also compete economically with energy-efficiency initiatives and renewables. A mature decision process requires that we consider whether renewables and efficiency can realistically answer the rapidly growing energy needs of China, India and the other tiers of the developing world as cheap fossil fuels beckon—at terrible environmental cost. Part of the cost calculation for transitioning to thorium must include its role in the expansion of prosperity in the world, which will be linked inexorably to greater energy demands. We have a pecuniary interest in avoiding the enviromental blowback of a massive upsurge in fossil-fuel consumption in the developing world. The value of providing an alternative to that scenario is hard to monetize, but the consequences of not doing so are impossible to hide from.

Perhaps the most compelling idea on the drawing board for pushing thorium-based power into the mainstream is mass production to drive rapid deployment in the U.S. and export elsewhere. Business economists observe that commercialization of any technology leads to lower costs as the number of units increases and the experience curve delivers benefits in work specialization, refined production processes, product standardization and efficient product redesign. Given the diminished scale of LFTRs, it seems reasonable to project that reactors of 100 megawatts can be factory produced for a cost of around $200 million. Boeing, producing one $200 million airplane per day, could be a model for LFTR production.

Modular construction is an important trend in current manufacturing of traditional nuclear plants. The market-leading Westinghouse AP1000 advanced pressurized-water reactor can be built in 36 months from the first pouring of concrete, in part because of its modular construction. The largest module of the AP1000 is a 700-metric-ton unit that arrives at the construction site with rooms completely wired, pipe-fitted and painted. Quality benefits from modular construction because inspection can consist of a set of protocols executed by specialists operating in a dedicated environment.

One potential role for mass-produced LFTR plants could be replacing the power generation components of existing fossil-fuel fired plants, while integrating with the existing electrical-distribution infrastructure already wired to those sites. The savings from adapting existing infrastructure could be very large indeed.

Louie Psihoyos/Corbis

Figure 8. Boeing produces one $200 million plane per day in massive production lines that could be a model for mass production of liquid fluoride thorium reactors. Centralized mass production offers the advantages of specialization among workers, product standardization, and optimization of quality control, as inspections can be conducted by highly trained workers using intalled, specialized equipment.

Nonproliferation

Cost competitiveness is a weighty consideration for nuclear power development, but it exists on a somewhat different level from the life-and-death considerations of waste management, safety and nonproliferation. Escalating the role of nuclear power in the world must be anchored to decisively eliminating the illicit diversion of nuclear materials.

When the idea of thorium power was first revived in recent years, the

Connie Ricca/Corbis

Figure 9. Thorium is more common in the earth's crust than tin, mercury, or silver. A cubic meter of average crust yields the equivalent of about four sugar cubes of thorium, enough to supply the energy needs of one person for more than ten years if completely fissioned. Lemhi Pass on the Montana-Idaho border is estimated to contain 1,800,000 tons of high-grade thorium ore. Five hundred tons could supply all U.S. energy needs for one year. Due to lack of current demand, the U.S. government has returned about 3,200 metric tons of refined thorium nitrate to the crust, burying it in the Nevada desert. Image at right courtesy of the National Nuclear Security Administration/Nevada Site Office.

focus of discussion was its inherent proliferation resistance (see the September–October 2003 issue of *American Scientist;* Mujid S. Kazimi, "Thorium Fuel for Nuclear Energy"). The uranium-233 produced from thorium-232 is necessarily accompanied by uranium-232, a proliferation prophylactic. Uranium-232 has a relatively short half-life of 73.6 years, burning itself out by producing decay products that include strong emitters of high-energy gamma radiation. The gamma emissions are easily detectable and highly destructive to ordnance components, circuitry and especially personnel. Uranium-232 is chemically identical to and essentially inseparable from uranium-233.

The neutron economy of LFTR designs also contributes to securing its inventory of nuclear materials. In the LFTR core, neutron absorption by uranium-233 produces slightly more than two neutrons per fission—one to drive a subsequent fission and another to drive the conversion of thorium-232 to uranium-233 in the blanket solution. Over a wide range of energies, uranium-233 emits an average of 2.4 neutrons for each one absorbed. However, taking into account the overall fission rate per capture, capture by other nuclei and so on, a well-designed LFTR reactor should be able to direct about 1.08 neutrons per fission to thorium transmutation. This delicate poise doesn't create excess, just enough to generate fuel indefinitely. If meaningful quantities of uranium-233 are misdirected for nonpeaceful purposes, the reactor will report the diversion by winding down because of insufficient fissile product produced in the blanket.

Only a determined, well-funded effort on the scale of a national program could overcome the obstacles to illicit use of uranium-232/233 produced in a LFTR reactor. Such an effort would certainly find that it was less problematic to pursue the enrichment of natural uranium or the generation of plutonium. In a world where widespread adoption of LFTR technology undermines the entire, hugely expensive enterprise of uranium enrichment—the necessary first step on the way to plutonium production—bad actors could find their choices narrowing down to unusable uranium and unobtainable plutonium.

Prospects

What kind of national effort will be required to launch a thorium era? We are watching a rehearsal in the latter half of 2010 with the unfolding of the Department of Energy's (DOE) flagship $5 billion Next Generation Nuclear Plant (NGNP) project. Established by the Energy Policy Act of 2005, NGNP was charged with demonstrating the generation of electricity and possibly hydrogen using a high-temperature nuclear energy source. The project is being executed in collaboration with industry, Department of Energy national laboratories and U.S. universities. Through fiscal year 2010, $528 million has been spent. Proposals were received in November 2009 and designs are to be completed by September 30, 2010. Following a review by the DOE's Nuclear Energy Advisory Committee, Secretary Chu will announce in January 2011 whether one of the projects will be funded to completion, with the goal of becoming operational in 2021.

There are two major designs under consideration, the pebble bed and prismatic core reactors, which are much advanced versions of solid-fuel designs from the 1970s and 1980s. In both designs, tiny, ceramic-coated particles of enriched uranium are batched in spheres or pellets, coupled with appropriate designs for managing these fuels in reactors. These fuel designs feature inherent safety features that eliminate meltdown, and in experiments they have set the record for fuel burnup in solid designs, reaching as high as 19 percent burnup before the fuel must be replaced. Thorium is not currently under consideration for the DOE's development attention.

If the DOE is not promoting thorium power, who will? Utilities are constrained by the most prosaic economics when choosing between nuclear and coal, and they are notoriously risk averse. The utilities do not have an inherent motive, beyond an unproven profit profile, to make the leap to thorium. Furthermore, the large manufacturers, such as Westinghouse, have already made deep financial commitments to a different technology, massive light-water reactors, a technology of proven soundness that has already been certified by the NRC for construction and licensing. Among experts in the policy and technology of nuclear power, one hears that large nuclear-plant technology has already arrived—the current so-called Generation III+ plants have solved the problems of safe, cost-effective nuclear power, and there is simply no will from that quarter to inaugurate an entirely new technology, with all that it would entail in research and regulatory certification—a hugely expensive multiyear process. And the same experts are not overly oppressed by the waste problem, because current storage is deemed to be stable. Also, on the horizon we can envision burning up most of the worst of the waste with an entirely different technology, fast-neutron reactors that will consume the materials that would otherwise require truly long-term storage.

But the giant preapproved plants will not be mass produced. They don't offer a vision for massive, rapid conversion from fossil fuels to nuclear, coupled with a nonproliferation portfolio that would make it reasonable to project the technology to developing parts of the world, where the problem of growing fossil-fuel consumption is most urgent.

The NGNP project is not the answer. There is little prospect that it can gear up on anything close to the timescale needed to replace coal and gas electricity generation within a generation or two. Yet its momentum may crowd out other research avenues, just as alternative nuclear technologies starved support of Alvin Weinberg's Molten Salt Reactor Project. We could be left asking, What if? Or we can take a close look at thorium as we rethink how we will produce the power consumed by the next generation. These issues and others are being explored at the online forum http://energyfromthorium.com, an energetic, international gathering of scientists and engineers probing the practical potential of this fuel.

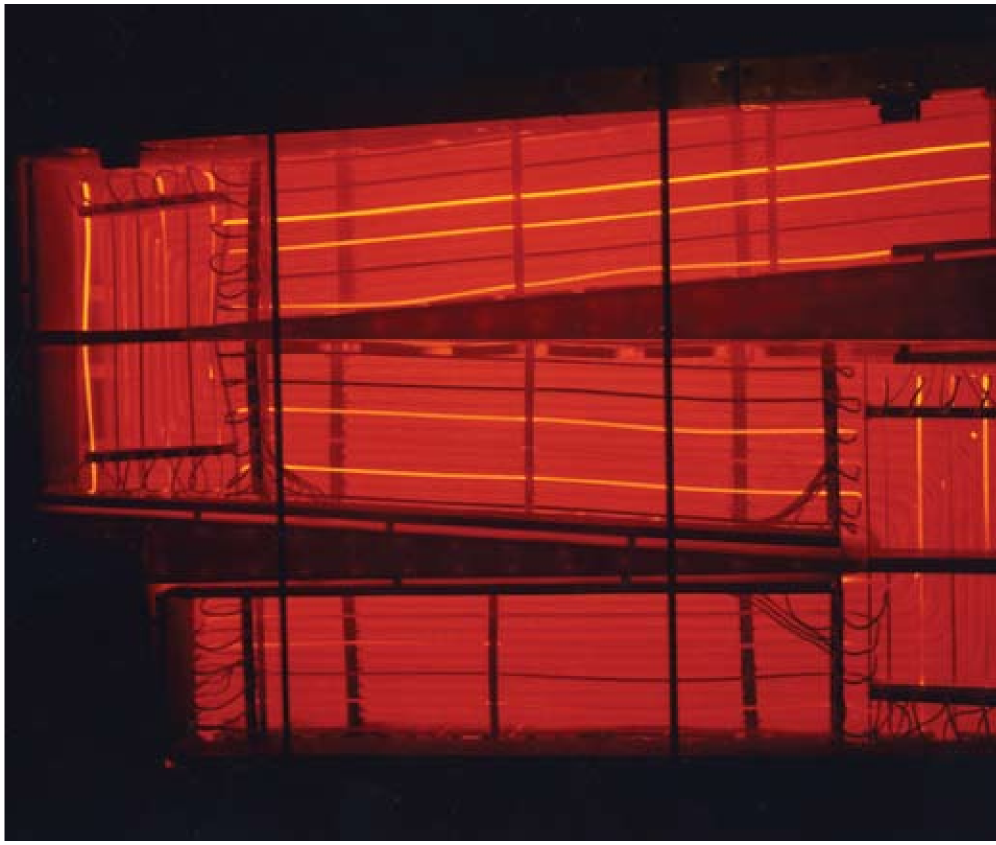

Figure 10. The Molten Salt Reactor Experiment at Oak Ridge National Laboratory operated successfully over four years through 1969. To conduct engineering tests, the thorium blanket was not installed; the uranium-233 needed to fuel the core came from other reactors, bred from thorium-232. No turbine generator was attached. Xenon gas was continually removed to prevent unwanted neutron absorptions. Online refueling was demonstrated. Graphite structures and noncorroding Hastelloy metal for vessels, pipes and pumps proved their suitability. Oak Ridge also developed chemistry for separation of thorium, uranium and fission products in the fluid fluoride salts. Image courtesy of Oak Ridge National Laboratory, U.S. Department of Energy.

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