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THE NUCLEAR POWER REVOLUTION

Modular High-Temperature Reactors Can Change the World

by Marjorie Mazel Hecht

Sixty years into the atomic age, we are at the threshold of another revolution: the development of fourth-generation modular high-temperature reactors (HTRs) that are meltdown-proof, affordable, mass-producible, quick to construct, and very suitable for use in industrializing the developing sector. The key to these new reactors, as described here, is in their unique fuel: Each tiny fuel particle has its own "containment building."

In the days of "Atoms for Peace," the 1950s and early 1960s, it was assumed that the development of nuclear power would rapidly bring all the world's people into the 20th Century, raising living standards, creating prosperity, allowing every individual to make full use of his creative ability. But this dream was not shared by the Malthusian forces, who, even after the massive slaughter of World War II, were determined to "cull" population further. These oligarchs, like the Olympian Zeus, who punished Prometheus for bringing fire to man, intended to rein in the atom, the 20th-Century "fire." And so they did, creating a counterculture, a fear of science and technology, and an environmentalist movement to be Zeus' army to keep Prometheus bound.[1]

Today, we are at a point when nations, especially impoverished nations, can choose to fulfill the promise of Atoms for Peace, by going nuclear, starting with a modular high temperature reactor small enough, ~200 megawatts, to power a small electric grid and, at the same time, provide process heat for industrial use or desalinating seawater. As the economy grows, more modules can be added.

These fourth-generation reactors are fast to construct and affordable (because of their modularity and mass production), thus slicing through the mountain of statistical gibberish promoted by those Malthusians who disguise themselves as energy economists, such as Amory Lovins. Now that several leading environmentalists have embraced nuclear as a clean energy solution, the hard-core Malthusians, including, prominently, Lovins and Lester Brown, have switched their main anti-nuclear argument to claim that nuclear is "too expensive." But because their mathematical calculations do not include the value of human life, Lovins et al. do not consider the human consequences of *not* going nuclear.

Energy-Flux Density

If we are to support 6.7 billion people at a living standard worthy of the 21st Century, the world must go nuclear now, and in the future, develop fusion power. Fission is millions of times more energy-flux dense than any solar technology, and you can't run a modern industrial economy without this level of energy-flux density.

Energy-flux density refers to the amount of flow of the energy source, at a cross-section of the surface of the power-producing source. No matter what improvements are made in solar technologies, the basic limita-

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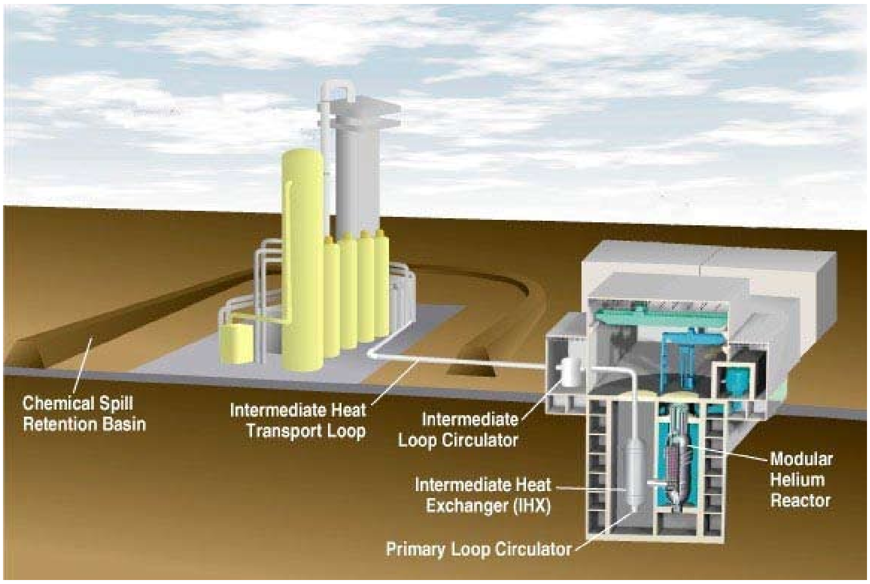
[1] See for example, Rob Ainsworth, "The New Environmental Eugenics: Al Gore's Green Genocide," *EIR,* March 30, 2007, www.larouchepub.com/eiw/public/2007/2007_10-19/2007-13/pdf/36-46_713_ainsworth.pdf; also, Marsha Freeman, "Who Killed U.S. Nuclear Power," *21st Century Science & Technology,* Spring 2001, www.21stcenturysciencetech.com/articles/spring01/nuclear_power.html.



INL

Artist's illustration of a high-temperature gas-cooled reactor coupled with a hydrogen-production plant, for which it provides process heat. The U.S. Next Generation Nuclear Plant program, based at the Idaho National Laboratory, has not yet selected an HTR design (pebble-bed or prismatic), and is on a very slow trajectory, aiming for a commercial plant in 2030. Meanwhile, China and Japan have working experimental HTRs, and South Africa plans to move to construction of the PBMR next year.

tion is that solar power is diffuse, and hence inherently inefficient. At the Earth's surface, the density of solar energy is only 0.0002 of a megawatt.[2]

Chemical combustion, burning coal or oil, for example, produces energy measured in a few electron volts per chemical reaction. The chemical reaction occurs in the outer shell of the atoms involved, the *electrons*. In fission, the *atomic nucleus* of a heavy element splits apart, releasing millions of electron volts, about 200 million electron volts per reaction, versus the few electron volts from a chemical reaction.

Another way to look at it is to compare the development of power sources over time, and the increasing capability of a society to do physical work: human muscle power, animal muscle power, wood burning, coal burning, oil and gas burning, and today, nuclear. The progress of a civilization has depended on increased energy-flux density of power sources. The manual collection of firewood for cooking; tilling, sowing, and reaping by hand; treadle-pumping for irrigation (a favorite of the carbon-offset shysters): These are the so-called "appropriate" technologies that Malthusians advocate for the developing sector, precisely because they preclude an increase in population. In fact, these technologies cannot support the existing populations in the Third

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[2] For a discussion of wind as energy, see Gregory Murphy, "Windmills for Suckers: T. Boone Pickens' Genocidal Plan," *EIR,* Aug. 22, 2008.

The Revolution in Nuclear Power

Part 2 of this feature, to appear next week, will discuss the recent Washington conference on high-temperature reactors, "HTR 2008: Beyond the Grid." Author Gregory Murphy will rebut the George Soros-funded attacks on South Africa's PBMR and the spurious technical arguments being used to try to derail the project.

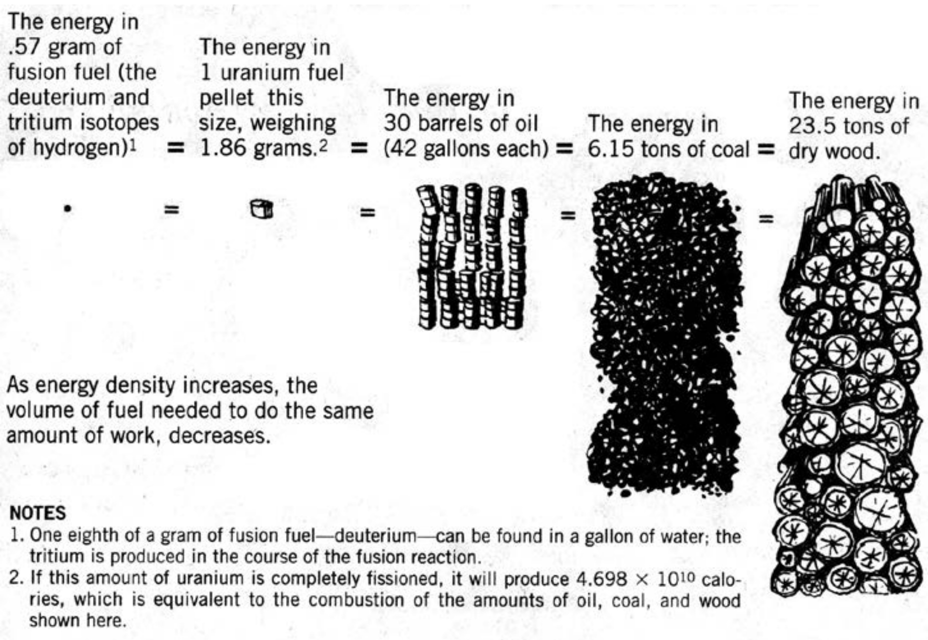
Leading the anti-nuclear charge is Steve Thomas, a professor of energy policy at Britain's Greenwich University, whose July 2008 "white paper" against the PBMR was circulated to green groups and the press. Thomas uses the report of Jülich Research Center scientist Dr. Rainer Moorman to claim that the PBMR is not safe, in light of data Moorman anylyzes from the AVR pebble-bed test reactor. The AVR operated successfully for 21 years at Jülich, and was shut down in 1988 in the wake of hysteria in Germany over Chernobyl.

Murphy dissects the erroneous Moorman analysis, making use of the latest research presented at the HTR 2008 conference. He also reveals some of Thomas's peculiarly racist arguments in his ten-year campaign against the PBMR.

An expanded version of "The Nuclear Power Revolution," including interviews with General Atomics Vice Chairman Linden Blue and PBMR CEO Jaco Kriek, will be posted at the website of *21st Century Science & Technology* magazine, www.21stcenturysciencetech.com.

FIGURE 1

Fuel and Energy Comparisons



As energy density increases, the volume of fuel needed to do the same amount of work, decreases.

NOTES

1. One eighth of a gram of fusion fuel—deuterium—can be found in a gallon of water; the tritium is produced in the course of the fusion reaction.
2. If this amount of uranium is completely fissioned, it will produce 4.698 × 10^{10} calories, which is equivalent to the combustion of the amounts of oil, coal, and wood shown here.

A tiny amount of fission fuel provides millions of times more energy, in quantity, and quality. With a closed nuclear fuel cycle (which reprocesses used nuclear fuel), and development of the breeder reactor, nuclear is not only a renewable resource, but is able to create more new fuel than that used to fuel the reactor.

World—which is exactly why they are glorified by the anti-population lobby.

Although this report will discuss fourth-generation HTRs, to bring every person on Earth into the 21st Century with a good living standard, the nuclear revolution includes the development of all kinds of nuclear plants: large industrial-size plants, fast reactors, breeder reactors, thorium reactors, fission-fusion hybrids, and all sorts of small and even very small reactors. We will also need to fund a serious program to develop fusion reactors. But right now, the modular HTRs are ideal as the workhorses to gear up the global infrastructure-building we need.

The Revolutionary Fuel

There are two types of high-temperature modular gas-cooled reactors under development, which are distinguished by the way in which the nuclear fuel is configured: the *pebble bed* and the *prismatic* reactor. In the pebble bed, the fuel particles are fashioned into pebbles, fuel balls the size of tennis balls, which circulate in the reactor core. In the prismatic reactor, the fuel particles are fashioned into cylindrical fuel rods, that are stacked into a hexagonal fuel block.

South Africa is developing the Pebble Bed Modular Reactor, the PBMR, and China has an operating 10-megawatt HTR of the pebble bed design, with plans to construct a commercial 200-MW unit starting in 2009.

General Atomics, based in San Diego, is developing the Gas Turbine Modular Helium Reactor, GT-MHR, which has a prismatic fuel rod design, and Japan is operating a 30-MW high-temperature test reactor, HTTR, of the prismatic design.

Although the fuel configurations differ, both reactor types start with the same kind of fuel particles, and it is these tiny particles that will revolutionize electricity generation and industry throughout the world. Developed and improved over the past 50 years, these ceramic-coated nuclear fuel particles, three-hundredths of an inch in diameter (0.75 millimeters), make possible a high-temperature reactor that cannot melt down.

At the center of each fuel particle is a kernel of fissile fuel, such as uranium oxycarbide. This is coated with a graphite buffer, and then surrounded by three or more successive containment layers, two layers of pyrolytic carbon and one layer of silicon carbide. The nuclear reaction at the center is contained inside the particle, along with any products of the fission reaction. The ceramic layers that encapsulate the fuel will stay intact up to 2,000°C (3,632°F), which is well above the highest possible temperature of the reactor core, 1,600°C (2,912°F), even if there is a failure of the coolant.

The Chinese tested this in the HTR-10 in September 2004, turning off the helium coolant. The reactor shut down automatically, the fuel temperature remained under 1,600°C, and there was no failure of the fuel containment. This demonstrates both the inherent safety of the reactor design, and the integrity of the fuel particles, stated Frank Wu, CEO of Chinery, the consortium appointed by the Chinese government to head the development project.

As for the waste question: The HTRs produce just a tiny amount of spent fuel, the less to store or bury. But the rational question is, why bury it and throw away a resource? Why not reprocess it into new nuclear fuel?

General Atomics had an active research program investigating the reprocessing of spent fuel from the HTR, but when the United States gave up reprocessing in the 1970s under the banner of "nonproliferation," the facility was converted to do other research. As one longtime General Atomics nuclear engineer told me, reprocessing used HTR fuel is absolutely possible—you just have to want to figure out how to do it.

Fission in the HTR

Conventional fission reactors work much like their predecessor technologies. The fission reaction produces heat, the heat boils water to create steam, and the steam turns a turbine, which is attached to a generator to produce electricity. The fourth-generation reactors also use the fission reaction to produce heat, but instead of boiling water, the heat is used to heat helium, an inert gas, which then *directly* turns a turbine, which is connected to a generator to produce electricity. By eliminating the steam cycle, these HTRs increase the reactor efficiency *by 50%,* thus reducing the cost of power production.

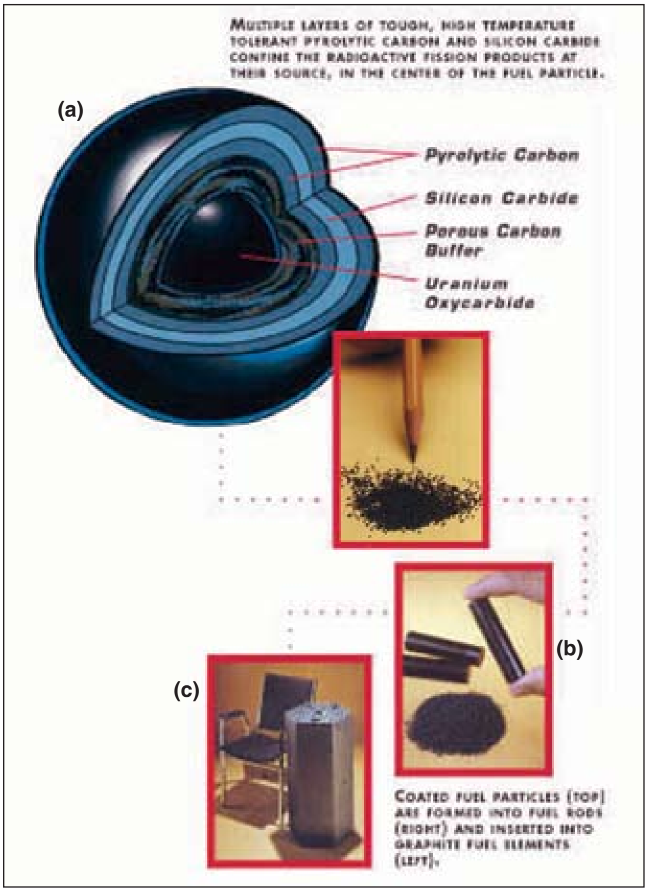
An obvious question is: How does the fission chain reaction occur if all the fission products are contained inside the fuel particles? The key is the neutron.

When the atomic nucleus of uranium splits apart, it produces heat in the form of fast-moving neutral particles (neutrons) and two or more lighter elements. To sustain a controlled fission chain reaction, every nucleus that fissions has to produce at least one neutron that will be captured by another uranium nucleus, causing it to split. The fission process is very fast; ejected neutrons stay free for about 1/10,000 of a second. Then they are either captured by fissionable uranium, or they escape without causing fissioning, to be captured by other elements or by nonfissionable uranium. Free neutrons can travel only about 3 feet.

All nuclear reactors are configured to create the optimum geometry for neutron capture by fissionable uranium. The point of a controlled fission reaction is to engineer the reactor design to capture the right proportion of slow neutrons in order to produce a steady fission reaction. (It is the slower neutrons that cause fissioning; the fast neutrons tend to be captured without causing fissioning.) For this purpose, reactors have *control rods,* made of materials like neutron-absorbing boron, that are raised or lowered to absorb neutrons, and *moderators,* made of a lighter element like carbon (graphite), that slow the neutrons down.[3]

FIGURE 2

The Unique HTR Fuel in a Prismatic Configuration (GT-MHR)



Each tiny fuel particle, three-hundredths of an inch in diameter, has a kernel of fission fuel at the center surrounded by its "containment" layers (a). The fuel particles are mixed with graphite and formed into cylindrical fuel rods, about two inches long (b). The fuel rods are then inserted into holes drilled into the hexagonal graphite fuel element blocks (c), which measure 14 inches wide by 31 inches high. The fuel blocks, which also have helium coolant channels, are then stacked in the reactor core.

In conventional nuclear reactors, water is the usual moderator, and the fission products stay inside the reactor core's fuel assembly. In the HTR, each tiny fuel particle contains the fission products produced by its uranium fuel kernel; only the neutrons leave the fuel particles.

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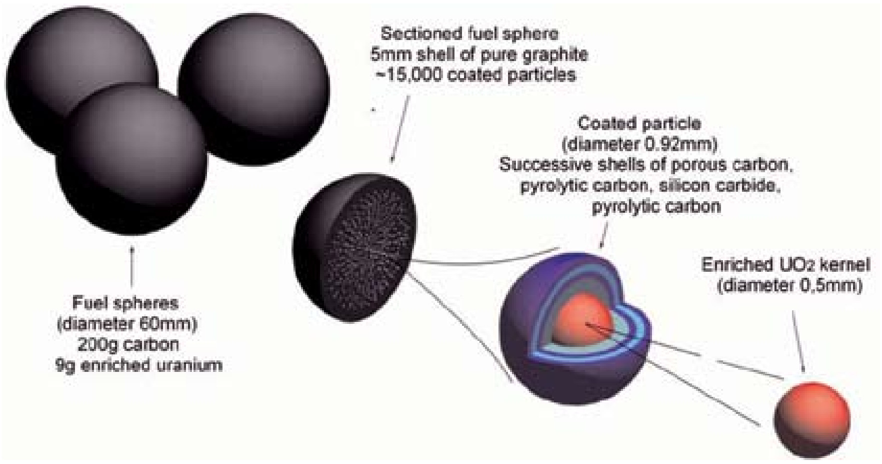
[3] For more detail, see "Inside the Fourth-Generation Reactors," *21st Century Science & Technology,* Spring 2001.

FIGURE 3

HTR Fuel Formed into Pebbles (PBMR)



The PBMR fuel particles are similar to those in Figure 2, with a kernel of fission fuel (uranium oxide) at the center (at right). But instead of being fashioned into rods, the particles are coated with containment layers and then inserted into a graphite sphere to form "pebbles" the size of tennis balls (at left). Each pebble contains about 15,000 fuel particles. Each pebble travels around the reactor core about ten times in its lifetime.

Helium Gas Heats and Cools

The beauty of the high-temperature reactor, and the reason that it can attain such a high temperature (1,562° F, or 850°C, compared with the 600°F of conventional nuclear plants) lies in the choice of helium, the inert gas that carries the heat produced by the reactor. Helium has three key advantages:

- Helium remains as a gas, and thus the hot helium can directly turn a gas turbine, enabling conversion to electricity without a steam cycle.
- Helium can be heated to a higher temperature than water, so that the outlet temperature of the HTR can be higher than in conventional water-cooled nuclear reactors.
- Helium is inert and does not react chemically with the fuel or the reactor components, so there is no corrosion problem.

The helium circulates through the nuclear core, conveying the heat from the reactor through a connecting duct to the turbine. Then it passes through a compressor system, where it is cooled to 915°F (490°C), and reenters the nuclear core. The use of helium as both the coolant and the gas that turns the turbine simplifies the reactor by eliminating much of the equipment (and expense) of conventional reactors.

The high heat that is produced can be coupled with many industrial processes, such as desalination of seawater, hydrogen production, and coal liquefaction. These reactors are also small enough to be located on site for some industries, producing both electricity and process heat. The LaRouche plans for the Eurasian Land-Bridge and the World Land-Bridge, for example, envision these HTR reactors as the hub of new industrial cities across Eurasia and the harsh Arctic environment of eastern Russia, linked by high-speed and magnetically levitated railways.

Direct Conversion to Electricity

The HTRs, as noted above, gain efficiency by eliminating the steam cycle of conventional nuclear reactors (the heating of water to turn it into steam, which then turns a turbine). Instead, the helium gas carries the heat of the nuclear reaction to *directly* turn a gas turbine.

Like conventional nuclear reactors, the first high-temperature reactors—Peach Bottom in Pennsylvania and Fort St. Vrain in Colorado, for example—used a steam cycle. The Chinese HTR-10 also uses a steam cycle, but plans are to switch to a direct conversion system in its later models.

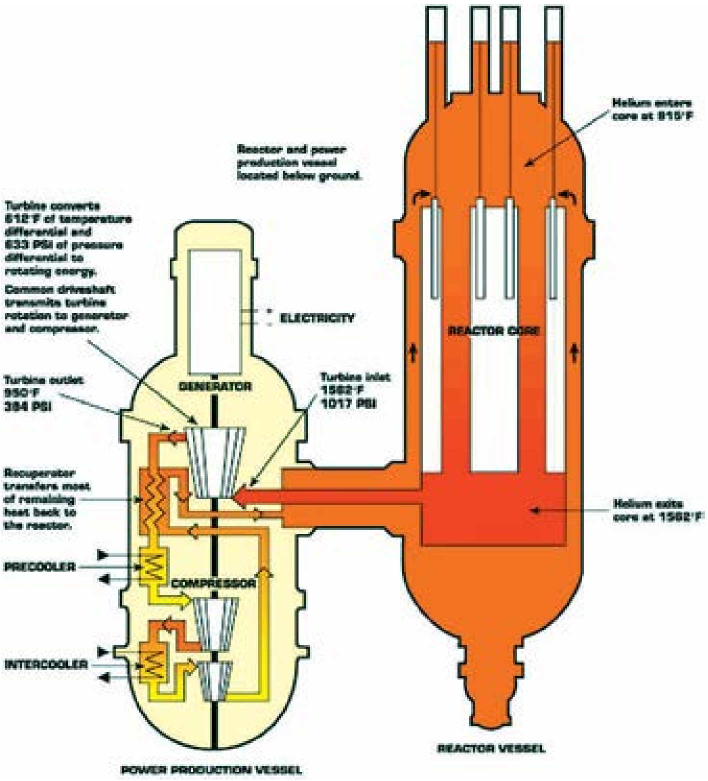
It only became possible to use the Brayton direct-cycle gas turbine with the HTRs after advances in industrial gas turbine use, and work carried out at the Massachusetts Institute of Technology during the 1980s specifically for coupling HTRs with a Brayton cycle. There were also advances in related systems, such as the recuperators and magnetic bearings. Taken together, these advances give the HTRs an overall efficiency of about 48%, which is 50% more than the efficiency of conventional nuclear reactors.

Multiple Safety Systems: Meltdown Proof

The modular HTRs are inherently safe, because they are designed to shut down on their own, without any human intervention. Even in the unlikely event that all the cooling systems failed, the reactor would shut down safely, dissipating the heat from the core without any release of radioactivity.

FIGURE 4

Schematic View of the GT-MHR



The reactor vessel (right) and the power conversion vessel are located below ground, and the support systems for the reactor are above ground. Layers of the hexagonal fuel elements are stacked in the reactor core. The helium gas passes from the reactor to the gas turbine through the inside of the connecting coaxial duct, and returns via the outside.

The built-in safety systems include the unique fuel particle containment: The fission products stay inside these “containment” walls.

Another safety feature is the reactor’s “negative temperature coefficient” operating principle: If the operating temperature of the reactor goes up above normal, the neutron speed goes up, which means that more neutrons get captured without fissioning. In effect, this shuts down the chain reaction. Additionally, there are certain amounts of “poisons” present in the reactor core (the element erbium, for example), which will help the process of capturing neutrons without fissioning, if the operating temperature goes up.

The first line of safety in regulating the fission reactor is, of course, the control rods, which are used to slow down or speed up the fissioning process. But if the control rods were to fail, the reactor is designed to automatically drop spheres of boron into the core; boron absorbs neutrons without fissioning, and thus would stop the reaction.

Additionally, there are two external cooling systems, a primary coolant system and a shutdown coolant system. If both of these should fail, there are cooling panels on the inside of the reactor walls, which use natural convection to remove the core heat to the ground. Because the reactor is located below ground, the natural conduction of heat will ensure that the reactor core temperature stays below 1,600°C, well below the temperature at which the fuel particles will break apart.

The graphite moderator also helps dissipate heat in a shutdown.

In addition to the successful Chinese HTR-10 test shutdown, a similar test was carried out on the AVR, the German prototype for the pebble bed, at Jülich. In one test, reactor staff shut down the cooling systems while the reactor was operating. The AVR shut itself down in just a few minutes, with no damage to the nuclear fuel. In other words, no meltdown was possible.

The HTR: A Manhattan Project Idea

The idea of a high-temperature gas-cooled reactor dates back to the Manhattan Project and chemist Farrington Daniels, who designed a nuclear reactor, then called a “pile,” which had “pebbles” of fission fuel whose heat was removed by a gas. Daniels patented his idea in 1945, calling it a “pebble bed reactor,” and the Oak Ridge National Laboratory began to work on the concept. But Daniels’ idea was dropped, in favor of the pressurized water reactor, and the group working with Daniels went on to design the first nuclear reactor for the *Nautilus* submarine.[4]

Later, Great Britain, Germany, and the United States developed high-temperature gas-cooled reactors. In Germany, Prof. Rudolf Schulten began working on a pebble-bed type reactor, and designed the 40-megawatt AVR pebble-bed reactor at Jülich, which operated successfully from 1966 to 1988, producing power for the grid and yielding a wealth of research data. Both this

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[4] Manhattan Project veteran Alvin M. Weinberg, who headed Oak Ridge National Laboratory, describes this in his autobiography, *The First Nuclear Era: The Life and Times of a Technological Fixer* (Woodbury, N.Y.: American Institute of Physics Press, 1994).

EIRNS

EIR*'s Mary Burdman holding a Chinese fuel pebble on a visit to the HTR-10 in 2001.*

Chinese technicians in the control room of the experimental HTR-10, which has a pebble-bed design. China plans to construct a commercial-size 200-megawatt HTR starting in 2009.

and a subsequent larger HTR were shut down in 1988, as the anti-nuclear movement rode the wave of Chernobyl fear. South Africa's PBMR, as well as the Chinese HTR-10, make use of the Schulten pebble-bed system, with innovations particular to each of the two new designs.

In Europe, 13 countries collaborated on the experimental high-temperature gas reactor called Dragon, built in England in 1962. The 20-MW Dragon operated successfully from 1964 to 1975, testing materials and fuels, and its experimental results were used by later HTR projects, including the THTR and the Fort St. Vrain HTR.

In the United States, Peach Bottom 1 in Pennsylvania was the first commercial HTR, put into planning in 1958, just a year after the first U.S. nuclear plant went on line at Shippingport, Pennsylvania. Built by General Atomics and operated by the Philadelphia Electric Company, the prototype HTR operated successfully from 1966 to 1974, producing power for the grid and operating information on HTRs. As General Atomics' Linden Blue characterized it, Peach Bottom worked "like a Swiss watch." Unit 1 at Peach Bottom was followed by two conventional boiling water reactors at the same site.

General Atomics next built a larger HTR, the 330-megawatt Fort St. Vrain plant in Colorado, which operated from 1977 until 1989, using a uranium-thorium fuel. Unfortunately, mechanical problems with the bearings—a non-nuclear problem—made the plant too expensive to operate, and it was shut down. Later, Fort St. Vrain was transformed into a natural gas power plant.

General Atomics continued its HTR research through the 1980s, and in 1993, began a joint project with the Russians to develop the GT-MHR, with a focus on using the reactor to dispose of surplus Russian weapons-grade plutonium, by burning it as fuel. The HTR is particularly suitable for this purpose, because of the high burnup of fuel. Later in the 1990s, the French company Framatome and Japan's Fuji Electric joined the program.

Today the conceptual design for the GT-MHR is complete and work continues to advance on the engineering, but construction cannot start until sufficient funds are available. The site selected for the reactor is Tomsk-7 in Russia, a Soviet-era "secret city" for production of plutonium and weapons, today known as Seversk.

In 2006, the University of Texas at the Permian Basin selected the GT-MHR design as the focus for a new nuclear research reactor, to be built in West Texas near Odessa.[5] General Atomics, Thorium Power, and the local communities contributed funds for the initial conceptual design. Now the university has signed a Cooperative Research and Development Agreement with Los Alamos National Laboratory, to develop a "pipeline of new nuclear reactor engineers" (a Bachelors degree program) to be ready immediately for working in power plants, national laboratories, or one of the U.S. nuclear agencies. According to the agreement, Los Alamos will send its scientists and engineers to the campus to teach and lead research, along with R&D equipment. The university's engineering staff will work with Los Alamos on research and joint seminars.

The project is named HT^{3}R (pronounced "heater"), which stands for high-temperature teaching and test reactor. Dr. James Wright, who manages HT^{3}R, told this writer that the initial efforts will be "geared toward developing any non-nuclear simulation or calculation that will move the HTGR technology forward to commercial deployment." Wright said that they would like

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[5] Interview with James Wright, "Texas University to Build HTR Reactor," www.21stcenturysciencetech.com/2006_articles/ spring%202006/ Nuclear_Report.pdf.

to "eventually find a way to participate in an advanced reactor test facility like the HT^{3}R, but we are not necessarily tied to any particular design. Again, our goal is to move the HTGR technology to commercial deployment as fast as possible." In Wright's personal view, such a first reactor could be built without Federal involvement or money, "if the economics are right."

Will the U.S. Catch Up?

The Department of Energy's Next Generation Nuclear Plant program plans to put a commercial-size HTR on line . . . by the year 2030. So far, two industry groups have received a small amount of funding for design studies, and there is a target date of 2021 for a demonstration reactor of a type (pebble bed or prismatic) to be determined. But even that slow timetable is not sure, given the budget limits and lack of political priority.[6] This HTR project, called the Very High Temperature Reactor, is based at Idaho National Laboratory, and is planned for coupling with a hydrogen production plant. At the slow rate it is going, the United States, a former nuclear pioneer, may find itself importing this next-generation technology from a faster advancing nation.

PBMR

The planned PBMR facility at Koeberg, South Africa, in an artist's illustration. Once the regulatory and environmental permissions are granted, the PBMR should start contruction in 2009. Koeberg is now the site of two large boiling water nuclear reactors.

The other problem is that the Next-Gen program has taken a backseat to the Bush Administration's Nuclear Energy Partnership (GNEP) program. The political thrust of the Department of Energy's GNEP is to prevent other nations (especially unfavored nations) from developing the full nuclear fuel cycle, by controlling the enrichment and supply of nuclear fuel. In line with the goal of non-proliferation, GNEP's focus is on building a fast (breeder) reactor that is "proliferation proof"—one that would burn up plutonium, preventing any diversion for bomb making. Non-proliferation, an obsession with both the Bush Administration and the Democrats, in reality is just a euphemism used for years by the Malthusian anti-nuclear movement to kill *civilian* nuclear power.[7]

It would make sense under the Next-Gen program for the United States to build a prototype GT-MHR, because the South Africans are building a PBMR, and this would give the world working models of each type. But at the present pace and budget, without a major commitment on the level of the Manhattan Project, a U.S. demonstration reactor is barely on the horizon.

The problem is not with the technology. Speaking at a press conference on the HTR in Washington, D.C., on Oct. 1, Dr. Regis Matzie, Senior Vice President & Chief Technology Officer at Westinghouse, who chaired the HTR 2008 conference, stated flatly, "We don't have a national priority" on building an HTR, and other countries which do—South Africa and China, for example—can move faster. At the same press conference, Linden Blue summed up the current HTR situation philosophically. With any new technology he said, you have an initial period of ridicule; then the technology is viciously attacked; and finally, the technology is adopted as self-evident. Soon after that, Blue said, everyone will be commenting on that first HTR, "What took you so long?"

The nuclear power revolution is now within our grasp, here in the United States, in South Africa, in China, in Japan, in Europe. The cost of developing the HTR is minuscule, in comparison with the trillions of dollars being sunk into the unproductive and losing gamblers on Wall Street. The cost of *not* developing these fourth-generation reactors will be measured in lives lost, and perhaps civilizations lost.

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[6] This program is discussed in Marsha Freeman, "It's Time for Next Generation Nuclear Plants," *21st Century Science & Technology,* Fall 2007, www.21stcenturysciencetech.com/Articles%202007/NextGen.pdf.

[7] See "The Neo-cons Not Carter Killed Nuclear Energy," *21st Century Science & Technology,* Spring-Summer 2006, www.21stcenturysciencetech.com/2006_articles/ spring%202006/Wohlstetter.pdf; and "Bush Nuclear Program: Technological Apartheid," *EIR,* July 6, 2007.