MHTGR—nuclear engine for world development

by Marjorie Mazel Hecht

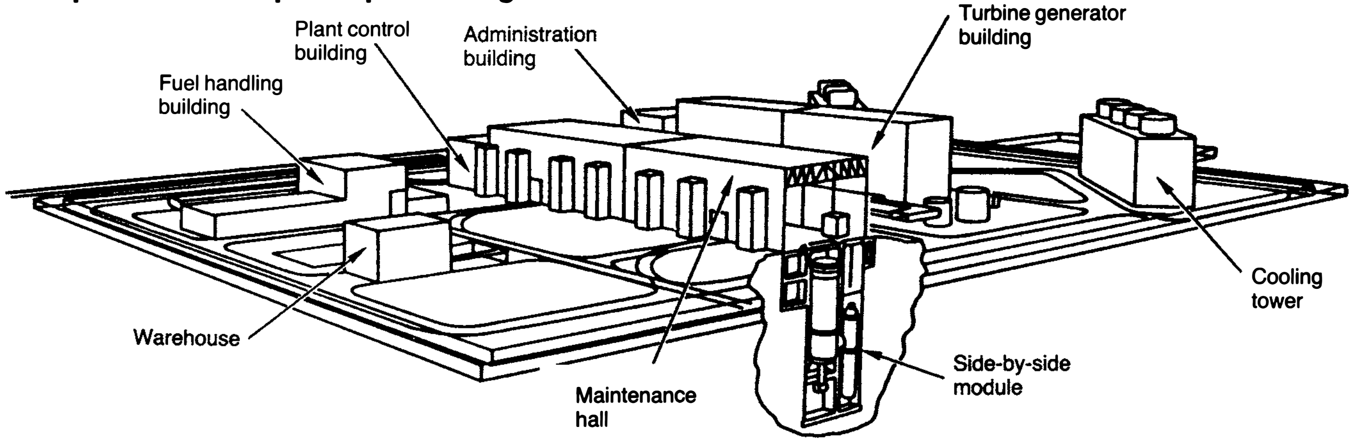
There is a simple and relatively inexpensive way to provide fast delivery of electricity and fresh water, the two major requirements for agro-industrial development: Mass produce the high-temperature gas-cooled nuclear reactor. Known by the acronym MHTGR, the modular high-temperature gas-cooled reactor is a state-of-the-art nuclear reactor that could be built now for placement anywhere in the world—from Eastern Europe to East Africa.

The most visible difference between conventional nuclear reactors and the MHTGR is its fuel and containment design. Instead of the familiar huge, domed containment buildings of conventional nuclear plants, designed to protect the surrounding area from any release of radiation, the containment for the MHTGR is minuscule—the size of a grain of sand. The nuclear fission reaction takes place in the center of this miniature sphere; little particles of enriched uranium are encased ("contained") in a ceramic sphere made out of materials developed in collaboration with the U.S. space program. The fission power of the MHTGR thus comes from tens of thousands of these tiny fuel particles, each in its own "containment building."

The advantages of the MHTGR are many:

- small size units (135 megawatts-electric) that can be grouped at a site;
- standardized, assembly-line design features;
- competitive cost (estimated to be 10-20% cheaper than current coal plants or conventional fission plants);
- higher temperature process heat or steam (1,000°F, compared to the 600°F limit of conventional water-cooled nuclear reactors), making possible a wide range of industrial applications from refining petroleum to making fertilizer and paper;
- passive safety features (the fissile fuel is "contained" in tiny ceramic spheres and the reactor never gets hot enough to breach this containment; no meltdown is possible);
- siting possible in arid areas because cooling water requirements are reduced

FIGURE 1
Proposed MHTGR power plant design



Source: General Atomics

This General Atomics power plant design has four MHTGR modules, each at 135 megawatts-electric, for a total power output of about 540 megawatts. The reactor module, called the nuclear island, is completely separate from the electric power generating system. It is housed in a below-ground concrete silo. Each of the four nuclear islands is an independent confinement structure, with its own exhaust system.

by 30% as a result of higher efficiency.

The MHTGR is especially attractive as the "engine" to power new cities—nuplexes, as they were called in the Atoms for Peace days—because it is simpler to operate and maintain than today's conventional nuclear reactors. As the new cities grow, new MHTGR modules could be added in stages to meet the increasing demand for electrical power. Estimates are that a 100 megawatt-electric plant could meet the electricity needs of a city of 100,000 people.

Another attractive use for the MHTGR is as a source of co-generated process heat for large-scale desalination of seawater. (Desalination projects, of course, would have to be located near the sea.) Since the mid-1960s, the Metropolitan Water District of Southern California has been considering the merits of nuclear energy for desalination and they are now studying the MHTGR as the least expensive way of supplying fresh water to California's growing population.

The most important factor for urgent world development needs is the speed with which the MHTGR could be built. General Atomic Technologies Corporation, one of several U.S. companies involved in research and development for the MHTGR, has estimated that once mass production were under way, it would take only 27 months to put a unit of a multi-unit MHTGR site into power production (assuming that licensing requirements would have already been met by the first prototype).

Because the reactor is modular and factory produced, the site construction proceeds while the reactor components are being produced in a factory off site. When completed, the nuclear reactor and the turbine systems can be transported from the factory by truck or rail and dropped into the underground silos that will house them. A crash program may even make it possible to speed up this timetable.

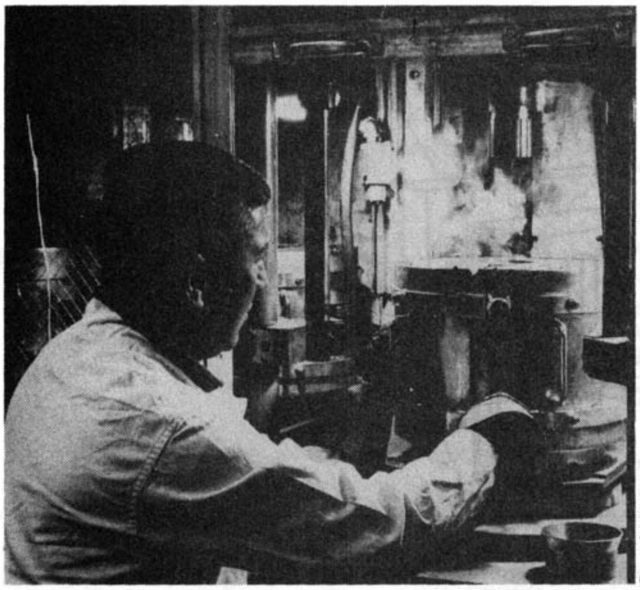
In addition to its civilian applications, the MHTGR has been chosen by the U.S. Department of Energy as one of two reactor technologies for the purpose of defense production (producing the tritium needed for nuclear weapons). The specific design for a MHTGR production reactor is now being negotiated with the Department of Energy and a consortium of private companies—General Atomics, Combustion Engineering, Stone and Webster Engineering, and Burns and Roe. The production reactor, scheduled to be built at the Idaho National Engineering Laboratory by the end of the 1990s, will also produce electricity.

Second-generation nuclear technology

The flexibility of the MHTGR makes it an ideal second-generation nuclear reactor, a necessary bridge between existing water-cooled reactors and the hybrid and fusion reactors of the future (which will have even higher temperatures).

The use of a gas coolant instead of water has the advantage of allowing the power plant to operate at much higher temperatures and hence greater efficiency. Efficiency is measured in terms of a ratio of the fraction of thermal energy that is converted to electrical energy. Conventional water-cooled nuclear plants have a conversion ratio of about 32%, while the high-temperature reactors are 40% or more. With a direct cycle gas turbine instead of steam, the conversion efficiency is 50% or better.

Helium gas is inert and does not react chemically with any part of the fuel or reactor components. Unlike water, which changes from liquid to steam, the helium coolant remains in the gaseous state and does not corrode the reactor parts.



General Atomics

The fuel pebbles for the MHTGR have been developed over the past 20 years in collaboration with NASA's nuclear-power rocket program. The MHGTR reactor never gets hot enough to break the ceramic coating that contains the fusion reaction. Here, fuel components are being tested.

Most significant, helium can be heated to higher temperatures than water (in fact, it is the helium coolant referred to as the *high temperature,* not the nuclear fuel.) This high-temperature steam or process heat can be used directly by a wide range of industries and for district heating (steam piped directly into the heating systems of buildings). In the United States, discussions and studies are in progress for desalination (see below) as well as for heavy oil recovery, both of which can be done with the current gas output temperature (under 1,400°F). In Japan, Kawasaki Steel is planning to use the HTGR for steel making, and a Japanese experimental HTGR will start up early in 1990.

As the outlet temperatures become higher (1,800-1,900°F), the MHTGR can be used for various synfuels production, coal gasification, and thermal cracking of water to produce hydrogen for use as a portable fuel.

Having a source of high-temperature process heat along with the MHTGR's electricity production is a tremendous economic advantage. More than 70% of the energy used in U.S. industry, for example, is non-electric, that is, heat or steam. This non-electric energy is now supplied by the burning of fossil fuels and natural gas, finite resources that could be saved for other purposes if MHTGRs supplied the high-temperature heat. To take the example of hydrogen, the current production process uses methane (natural gas) as a chemical feedstock as well as a source of heat in the steam reforming process. Adding an MHTGR to this process would produce the same amount of hydrogen and reduce the the use of natural gas by 40%.

Twenty years ago, the United States had planned to have at least 10 high-temperature gas-cooled reactors in operation in the 1980s, but by the mid-1970s, the orders for these plants were canceled as the U.S. nuclear industry rushed into retreat from the aggressive programs of Atoms for Peace. In the intervening years, the industry has concentrated on research, not development, and much of this research has centered on safety, in particular, passive safety systems that do not depend on human intervention. (All the new designs for advanced fission reactors have this "walkaway" feature: In the worst possible accident scenario, cooling is accomplished by natural convection and other simple physical principles.)

One result of this safety effort is that if something goes wrong with the MHTGR—for example, the highly unlikely worst case where all the coolant and control systems fail—the MHTGR fuel pellets can withstand the maximum temperatures that could be generated (2,912°F). The "containment" wall of the tiny pellets would remain intact, and the reactor heat would dissipate "naturally," even with no human intervention.

The simplified safety system of the MHTGR makes it cost competitive with conventional fission plants, where safety systems account for approximately 25% of the total capital cost of the plant. This is one of the reasons that any crash program for industrialization should make the MHTGR its main power source.

Thirty years of research

Although most of the world's 400 operating nuclear plants are water-cooled, the use of a gas coolant is not a new idea. Gas-cooled reactors have been researched since the beginning of the atomic era, and many gas-cooled nuclear plants exist. The British originated the concept in the late 1940s as a method of producing plutonium for weapons, and soon after decided to use the same system for producing electric power. They built 34 gas-cooled power plants (called Magnox, after the magnesium alloy used to house the fuel elements), beginning in 1956 when the first of four plants came on line at Calder Hall. These plants used pressurized carbon dioxide as a coolant and natural uranium as fuel.

To date, the British gas-cooled plants have contributed 700 reactor years of operating experience. However, the Magnox reactor had an output gas of only 400°C because the metallic uranium fuel elements begin to break down at higher temperatures.

The next generation British reactor, the AGR (advanced gas-cooled reactor) improved the efficiency of the Magnox system by using enriched uranium oxide as fuel, encased in steel instead of magnesium alloy. Its output gas had a temperature of about 650°C, increasing the thermal efficiency to 40%.

The West Germans developed a prototype high-temperature reactor, the AVR, in 1959 at Jülich. The AVR was only 13 megawatts, but it heated helium to 850°C and demonstrated the the pebble bed fuel concept that West Germans have chosen. The pebble bed uses the same type of fuel particle as the U.S. design, but moves the fuel continuously through the reactor core, adding and removing fuel elements while the reactor is on line, thus eliminating the need for shutting down the plant to refuel. In 20 years of operation, the AVR has processed about 2 million fuel elements.

An industry-sponsored 295-megawatt plant, THTR (for thorium high-temperature reactor) was built at Schmehausen in the Ruhr and was connected to the power grid late in 1985. Now there are plans for follow-up reactors both large and small, and the director of the Institute for Reactor Development at Jüelich, Dr. R. Schulten, has estimated that West Germany could, after a start-up period, produce 60 to 70 HTGRs per year!

In the United States, the test bed HTGR was the 40-megawatts-electric Peach Bottom 1 plant near Philadelphia, built under the U.S. Atomic Energy Commission's Power Reactor Demonstration Program and operated from 1967 through 1974. The Peach Bottom plant was supported by a consortium of 53 utilities—the High Temperature Reactor Development Associates. Its performance compared well to conventional fission reactors, with an 88% availability (time it's on line); fission reactors average 66%.

The next step was the Fort St. Vrain 330 megawatt-electric HTGR built near Denver by GA Technologies for the Public Service Company of Colorado. Fort St. Vrain went critical in early 1974, and has demonstrated much of the technology used in the design of the MHTGR.

The plant's availability has been only 32%, much lower than the 80% (or better) predicted for the MHTGR, largely because of a design flaw (water lubricated circulator bearings instead of oil) that permits water to leak into the helium circulation system. The plant had to be shut down periodically to remove the water.

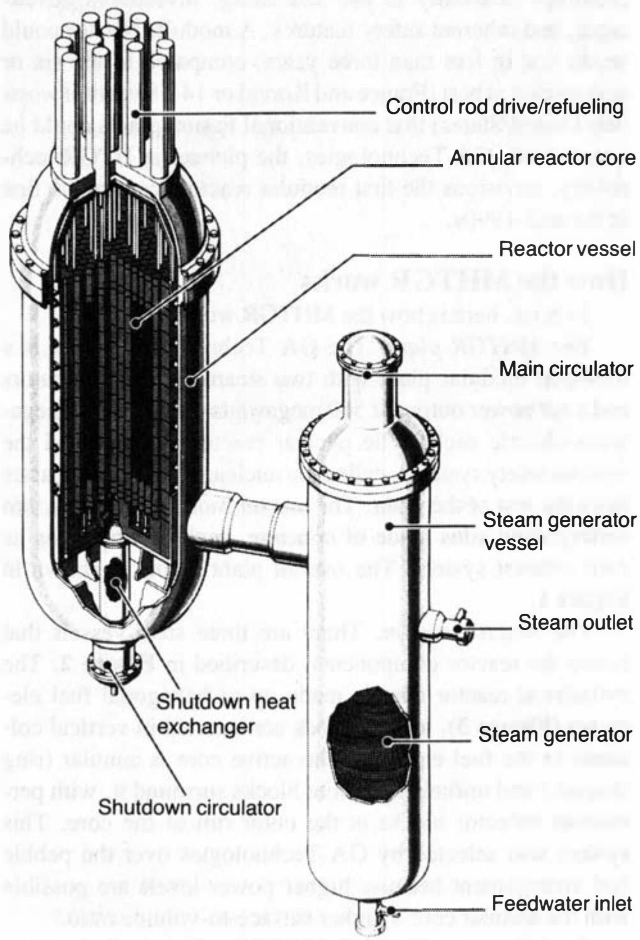
Despite this mechanical problem, the Fort St. Vrain reactor demonstrated proof of concept for the HTGR, proving the inherent safety of the design, the integrity of its fuel pellets, and its incapability of meltdown. There are almost no radioactive emissions from the plant—worker doses are 100 times lower than the already low doses from conventional fission reactors. At Fort St. Vrain, both workers and visitors can walk around the outside of the working reactor with no special protective clothing or equipment needed.

The Fort St. Vrain performance was so impressive in terms of safety and efficiency, that 30 utilities formed the Gas Cooled Reactor Associates in 1978. This industry group worked with the Department of Energy and its predecessors to outline a demonstration project for an 820-megawatt commercial HTGR and five potential regional sites, including a Gulf Coast regional site where an HGTR would provide both electricity and process heat for the Port Arthur, Texas oil refinery. This medium-scale reactor was envisioned for maximum use—day and night—producing a combination of process heat and electricity. The plan was to have the 820-megawatt plant on line by the mid-1990s, paid for by the utilities (75%) and the government (25%, largely for the R&D).

But this specific reactor plan was felled by the anti-nuclear and anti-industry virus that infected the United States in the 1970s and grew worse through the Carter and Reagan

FIGURE 2

A schematic view of the High-Temperature Gas-cooled Reactor



Source: General Atomics

This General Atomics design for an MHTGR has three steel vessels: a reactor vessel, a steam generator/circulator vessel, and a connecting vessel. The reactor vessel is 72 feet long and 22.5 feet in diameter, with the control rod drive mechanism (and the reserve boron pellets) on top and the shutdown systems (heat exchanger and cooling circulator) at the bottom of the vessel. Refueling and inspection of the inside of the reactor take place through the ports provided by the standpipes for the control rods. The steam generator vessel, which is 85 feet long and 14 feet in diameter, has the main helium circulator at its top. Feedwater enters the generator at the bottom, and the superheated steam exits through a nozzle at the side.

administrations. The idea stayed alive, however, and by the mid-1980s, the focus became smaller, modular reactors that could be serially produced. Thus, the MHTGR was born. The concept quickly took hold because of the reactor's great promise—flexibility in use and siting, investment advantages, and inherent safety features. A modular reactor could be on line in less than three years, compared to the six or seven years at best (France and Korea) or 14-18 years at worst (the United States) that conventional fission plants could be constructed. GA Technologies, the pioneer in HTGR technology, envisions the first modular reactors coming on line in the mid-1990s.

How the MHTGR works

In brief, here is how the MHTGR works:

The MHTGR plant. The GA Technologies design is a four-unit modular plant with two steam turbine generators and a net power output of 540 megawatts-electric (135 megawatts-electric each). The nuclear reactor modules and the various safety systems, called the nuclear island, are separate from the rest of the plant. The reactor modules are sunk into underground silos made of concrete, each of which has its own exhaust system. The overall plant layout is shown in **Figure 1.**

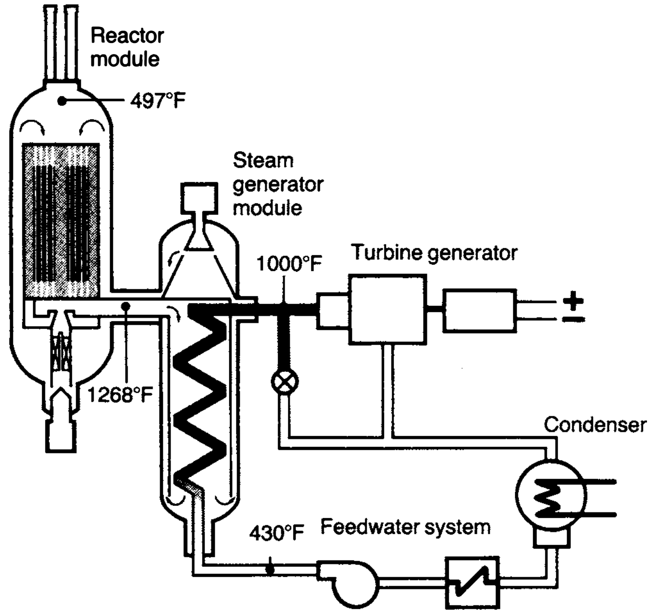
The reactor system. There are three steel vessels that house the reactor components, described in **Figure 2.** The cylindrical reactor core is made up of hexagonal fuel elements (**Figure 3**), and fuel rods are inserted in vertical columns in the fuel element. The active core is annular (ring shaped,) and unfueled graphite blocks surround it, with permanent reflector blocks at the outer rim of the core. This system was selected by GA Technologies over the pebble bed arrangement because higher power levels are possible with the annular core's higher surface-to-volume ratio.

Fuel elements. The U.S. MHTGR reference design uses prismatic fuel elements, with tiny fuel particles fashioned into finger-sized rods and then stacked in a column and inserted into the fuel blocks. The fuel particles themselves are the same as those used in the West German pebble bed design. There is a central kernel of fissionable uranium oxycarbide (20% enriched U-235), about 350 microns in diameter, surrounded by three ceramic layers—pyrolytic carbon, silicon carbide, and pyrolytic carbon. These coatings, which bring the outer diameter of the fuel pebble to 800 microns (less than 1 millimeter), were developed collaboratively with the National Aeronautics and Space Administration, which used similar fuel particles in the nuclear rocket NERVA program in the early 1960s. More than trillions of fuel particles have been tested by GA Technologies over the past 20 years.

The fuel rods also include coated particles that have a kernel of thorium oxide (Th-232), a fertile, nonfissionable material. The thorium oxide absorbs the neutrons from the fissioning uranium oxide and is converted into fissionable uranium-233, thus enhancing the conversion ratio of the fuel.

FIGURE 3

How the MHTGR works: a schematic flow diagram



Source: General Atomics

The helium coolant moves downward through the reactor core, where it is heated by the nuclear reactions. The hot helium then flows through the connecting duct to the steam generator, where its heat is transferred to the water to make steam. Cooled helium then moves up the side of steam generator in the annulus between the generator bundle and the vessel; it is recompressed by the circulator and then driven into the annulus ring of the connecting duct. To complete the circuit, the cool gas entering the reactor vessel flows up between the core and the reactor to the top of the core.

Inside the core are graphite fuel blocks, hexagonal in cross section. The fuel elements are stacked in columns forming a ring that is 11.5 feet in diameter and 25 feet long. The active core region is surrounded by unfueled graphite blocks. Control rods travel up and down in vertical channels in the core.

At present, the MHTGR fuel cycle is planned as "once through"—no recycling—a requirement of the Carter administration, which prevented any reprocessing of spent nuclear fuel (instead creating mountains of nuclear "waste" that is actually 99% recoverable as new nuclear fuel and valuable isotopes). Refueling will take place when the reactor is shut down. In the three-year fuel cycle, half the core is refueled every 18 months.

The helium coolant and steam generation. The helium gas flows down through the coolant channels in the fuel elements, mixes in a space below the core, and then transports the reactor heat through the inner chamber of the connecting duct to the conventional steam generator. It flows down through the helically shaped coils of the generator and then up the annular duct between the generator and the vessel. The compressed helium then goes back to the reactor vessel via the outside chamber of the connecting duct. In this continuous cycle, the helium coolant surrounds all three of the reactor vessels.

Feedwater flows into the bottom of the steam generator vessel and superheated steam exits at a nozzle on the side of the vessel.

Safety systems. Control rods at the top of the reactor vessel are used to regulate the fission reaction, and are lowered into vertical channels in the center and circumference of the core. Should the control rods fail, gravity-released spheres of boron are automatically dropped into the core to stop the fissioning.

There is a primary coolant system and a shutdown coolant system, but even if both these systems fail, the reactor is designed to cool down on its own. First, a passive back-up system is available, the reactor cavity cooling system (cooling panels on the inside of the reactor walls), which uses natural convection to remove core heat to an external sink. And even if this cooling system fails, the natural conduction of heat to the underground silo structure and surrounding ground will ensure that the core temperature does not go above 2,912°F (1,600°C). This limit is well below the temperature at which the fuel particles will break apart and release fission—3,632° (2,000°C). The graphite fuel blocks retain their strength up to temperatures of 4,500°F.

What all the detailed assessments of the MHTGR's geometry and power level have shown is that no release of radioactivity is possible even if there is a loss of all active cooling systems, a failure of the passive cooling system, and a massive failure of the vessel. To quote from an April 1988 evaluation of the MHTGR by General Atomics, "The examination of these events has shown that the residual risk to the public from events beyond the licensing basis is negligible. No events have been identified that can defeat the fuel particle retention."

Providing abundant fresh water

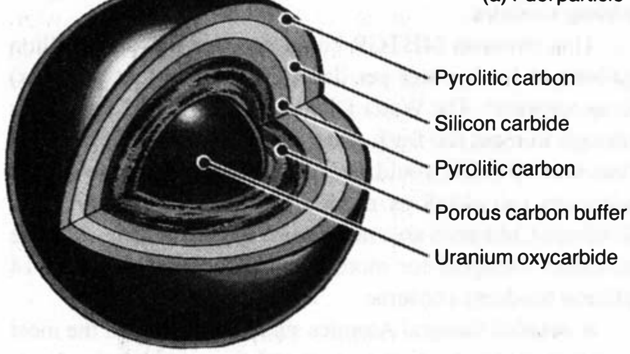
The design of the MHTGR—with its unique safety features and high temperature—makes it an ideal choice for electricity production and co-generation for desalination in a populous area. The Metropolitan Water District of Southern California has been exploring a nuclear-based co-generation plant since the 1960s. Initial plans were for an offshore island plant near Huntington Beach, but this was dropped for economic reasons. Now, since both the nuclear and the desalination technologies have improved in efficiency, the Water District is evaluating and encouraging the MHTGR as the most economical way to desalt water on the large scale it needs.

Envisioned are two 135-megawatts-electric MHTGR modules coupled to a steam power conversion system with a backpressure turbine that will make use of waste heat for

FIGURE 4

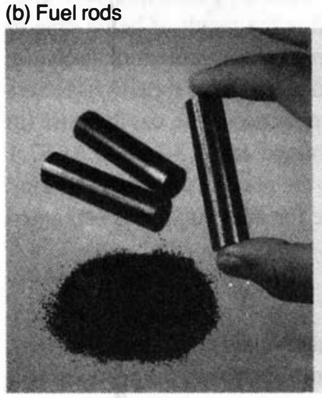
MHTGR's fuel components

(a) Fuel particle



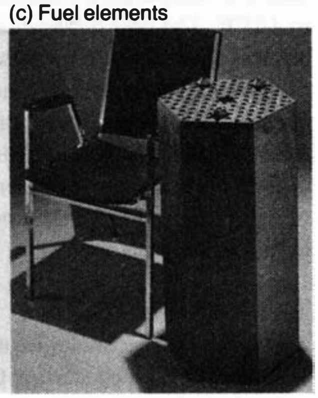
The tiny fuel pellet is about 800 microns in diameter (0.03 inch). Each pellet consists of a kernel of fissile uranium oxycarbide (about 350 microns in diameter) that is coated with a graphite buffer and then encapsulated by three successive layers of pyrolytic carbon, silicon carbide, and pyrolytic carbon. This coating contains the fission reaction within the fuel kernel and graphite buffer. Slightly larger particles, similarly coated, contain a kernel of thorium oxide.

(b) Fuel rods



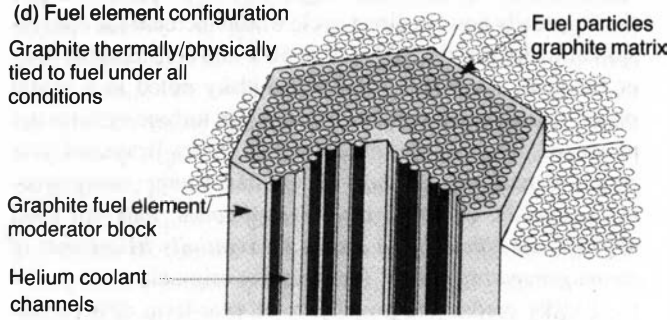
Both the thorium and uranium particles are mixed with a graphite material and formed into fuel rods that are 0.5 inch in diameter and 2 inches long.

(c) Fuel elements



The fuel rods are inserted into holes that are drilled into the hexagonal graphite fuel element blocks, which are 14 inches in diameter and 31 inches long.

(d) Fuel element configuration



This schematic shows the fuel rods and helium coolant channels in a graphite fuel element.

Source: General Atomics

desalinating. The Water District notes that the modular design gives them the capability to distribute the financial commitment over time—instead of requiring a big amount of capital all at once—and flexibility to meet future needs by adding modules.

This two-unit MHTGR could produce up to 75 million gallons of fresh water per day (85,000 acre-feet per year) from seawater. The Water District has calculated that this is enough to meet the fresh water needs of 350,000 people; a four-unit MHTGR would meet nearly half of the water supply additions calculated as needed by the 21st century. This Southern California area now uses a system of long-distance aqueduct transport for more than 60% of the water its 14 million residents consume.

A detailed General Atomics study has looked at the most appropriate desalination system and the costs involved, selecting a low-temperature horizontal-tube multi-effect distillation method. The equipment for this desalination system is commercially available (it was developed and is being used now in Israel) and would fit with minor modifications into the MHTGR configuration. The cost is lower by a factor of two to three, the study showed, if the desalination process uses low-temperature exhaust from the steam turbine—155° to 165°F. The cost differential is the result of being able to use less expensive tubing materials for desalination (because of the lower temperatures) and at the same time to have less of an impact on the power production. The capital cost (in January 1988 dollars) is estimated at $1.8 billion to $2.1 billion, depending on whether the plant is the first of its kind or a replica, and the total time for construction is estimated at four to six years.

The immediate future

None of the technologies mentioned here is a pipe dream; all can be developed starting tomorrow—if the political will exists to do it.

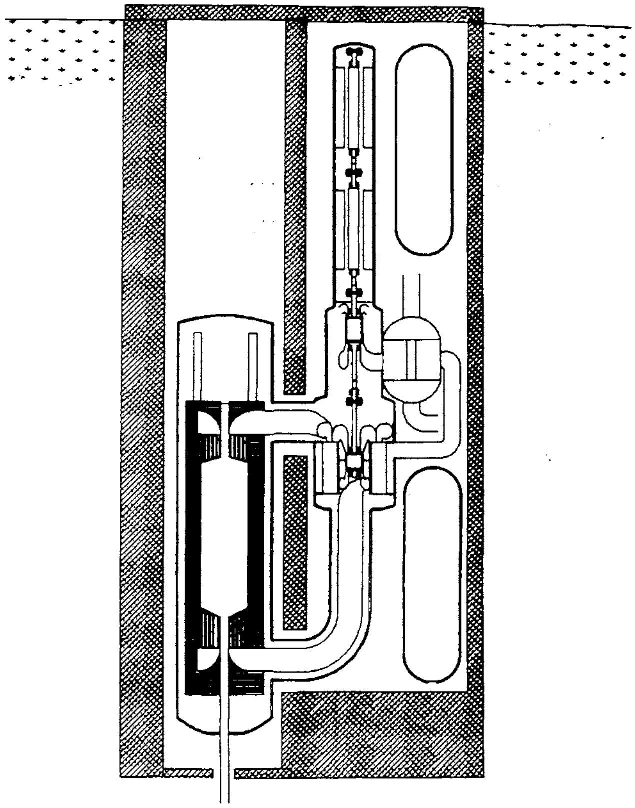
Even more advanced technologies are ready and waiting. The current plans for the MHTGR call for a conventional steam turbine cycle, but a more advanced direct cycle gas turbine (**Figure 5**) has been thoroughly studied at the Massachusetts Institute of Technology, and its proponents argue that it is ready now. A direct cycle would increase the conversion efficiency of the MHTGR to 50% and considerably lower the cost. As MIT's Lawrence Lidsky noted in a recent paper, "Although it remains true that gas turbine systems are advanced, it is now possible to build a Direct-Brayton-Cycle power plant using a modular HTGR heat source, *using existing materials, within existing design codes, that will yield 45-50% net efficiency at a cost substantially below that of steam generating plants*" (emphasis in original).

Lidsky credits the possibility of near-term direct cycle plants to three developments: smaller, modular plant designs, high-effectiveness steam recuperators that depend on recent advances in compact heat exchanger technology, and reliable high-efficiency solid-state power electronics. In addition, Lidsky notes, the latest fuel particle coatings prevent contamination of the machinery.

It is not too late to revive the dream of Atoms for Peace and to fulfill it with an even more advanced technology than that envisioned in the Eisenhower years. A crash program to make the MHTGR the engine for world development would shake U.S. industry out of its forced and premature retirement. Within months, assembly-line-produced MHTGRs could begin producing electrical power—and fresh water—across the globe.

FIGURE 5

An MHTGR with a direct-cycle gas turbine



Source: J.E. Staudt and L.M. Lidsky, "Design Study of an MGR Direct Brayton-Cycle Power Plant," Massachusetts Institute of Technology Report MITNPI-TR-018, May 1987.

The near-term development of a direct-cycle gas turbine with the MHTGR is now possible using existing materials, according to studies done at the Massachusetts Institute of Technology. This system has the advantage of producing a 45-50% net efficiency at much lower costs than those of steam-generating plants. The simplest Brayton cycle is used, which has good recuperator effectiveness. The reference design for the MIT work was the pebble bed MHTGR, not the prismatic core, but this is not a significant difference. Shown here is the machinery module containing the power plant machinery and heat exchangers.