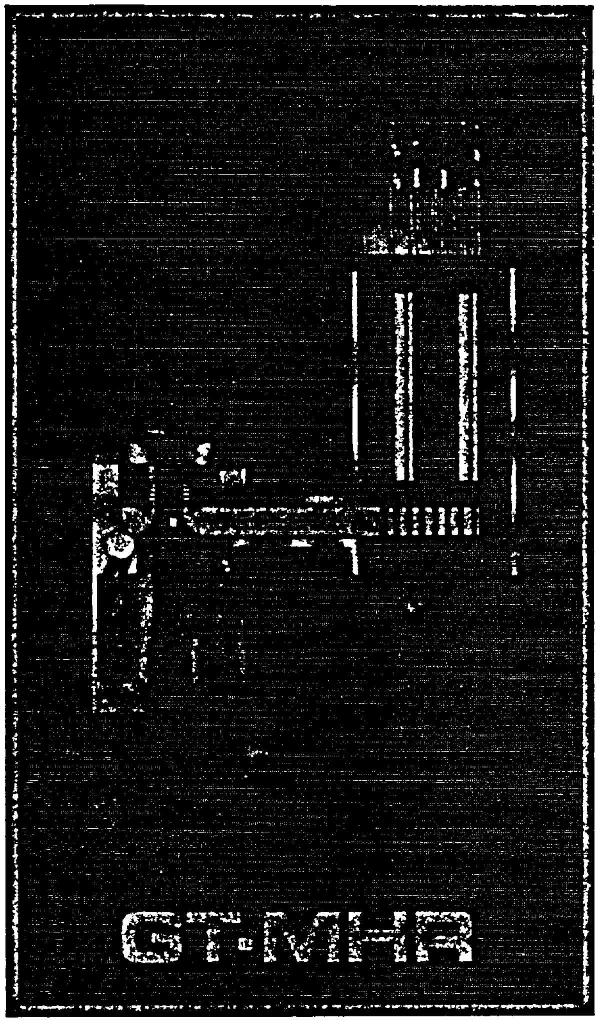



# New Power For The Next Century

A HARVEST OF TECHNOLOGIES

GAS TURBINE MODULAR HELIUM REACTOR

C-19

GENERAL ATOMICS

Steam still generates most of the world's electricity. We burn coal, gas and oil, and use nuclear power to turn water into steam to drive turbines which produce electricity. Even larger quantities of gas and imported oil are being consumed for other energy requirements including transportation. Burning fossil fuels can be very expensive and taxing to the environment. Oil accounts for over half of our entire balance of payments deficit. . . ***more than a billion dollars a week in foreign oil imports.*** . . up the chimney, out the tailpipe and into our atmosphere.

# B A C K G R O U N D

There is a cleaner, more economical, and much safer way to generate electricity. The Gas Turbine - Modular Helium Reactor (GT-MHR) is a new turbine generating system powered by a passively-safe nuclear reactor. It eliminates the need to make steam to produce electricity, and frees us from the pollution and waste of fossil-fuel generating plants. It could also help to reduce our billion dollar a week deficit for foreign oil.

## THE FUTURE

By capitalizing on late 20th century technologies, the GT-MHR achieves high efficiency with a compact operating system and elegant simplicity. The gas turbine power cycle is far superior to the century-old steam plant technology employed in all other nuclear plant designs. The super-safe GT-MHR power plant includes one or more modular units in underground silos, each containing a reactor vessel and a power production vessel.

## WHY IT WORKS

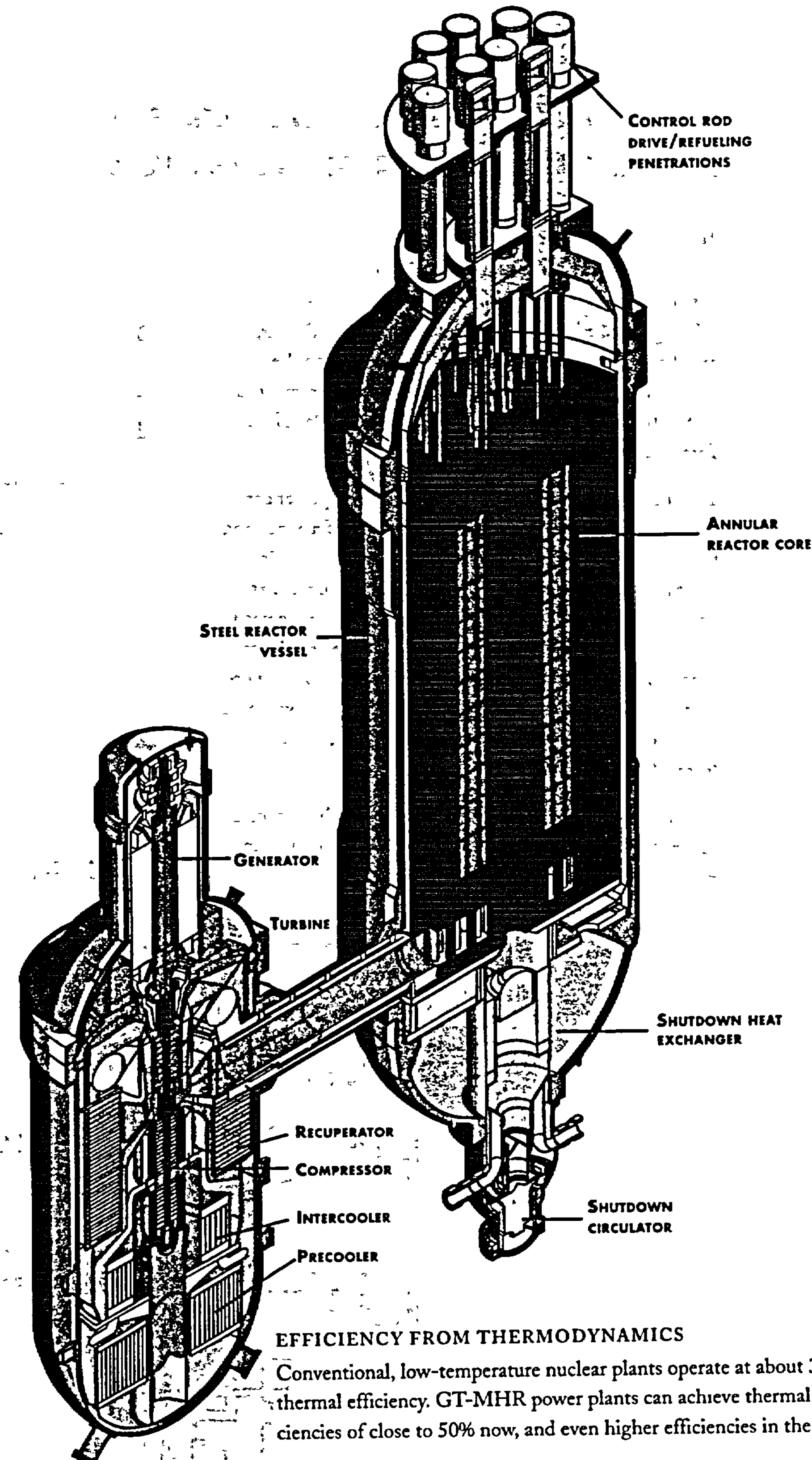
Because helium is naturally inert and single-phase, the helium-cooled reactor can operate at much higher temperatures than today's conventional nuclear plants. The higher the turbine's operating temperature, the more efficient the plant becomes. . . mandated by the laws of thermodynamics. To this is added the efficiency of the helium directly driving the turbine, instead of having to go through a large heat exchanger to produce steam.

## DESIGN SIMPLICITY

The combination of the MHR and the gas turbine represents the ultimate in simplicity, safety and economy. The reactor coolant directly drives the turbine which turns the generator. This allows costly and failure prone steam generating equipment to be eliminated.

- *No* corrosion-caused leaks
- *No* corrosion-caused reduction in operating life
- *No* stress corrosion-caused structural failures

*The GT-MHR combines a meltdown-proof reactor and advanced gas turbine technology in a power plant with a quantum improvement in thermal efficiency. . . approaching 50%. This efficiency makes possible much lower power costs, without the environmental degradation and resource depletion of burning fossil fuels.*




## EFFICIENCY FROM THERMODYNAMICS

Conventional, low-temperature nuclear plants operate at about 32% thermal efficiency. GT-MHR power plants can achieve thermal efficiencies of close to 50% now, and even higher efficiencies in the future.

- 50% more electrical power from the same number of fissions.
- Dramatically lower high-level radioactive waste per unit of energy – today's reactors produce 50% more high-level waste than will the GT-MHR.
- Much less thermal discharge to the environment. Plants can use air cooling.

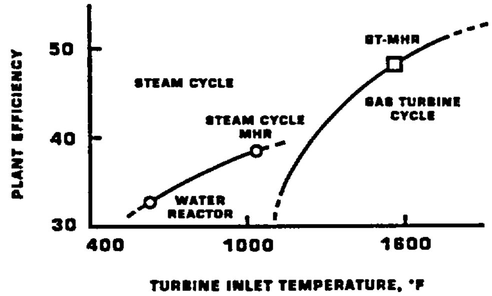
## *THE SIMPLICITY OF THE GAS TURBINE AND THE HELIUM REACTOR PROVIDE THE NEXT GREAT STEP IN NUCLEAR POWER*

PLANT DESCRIPTION

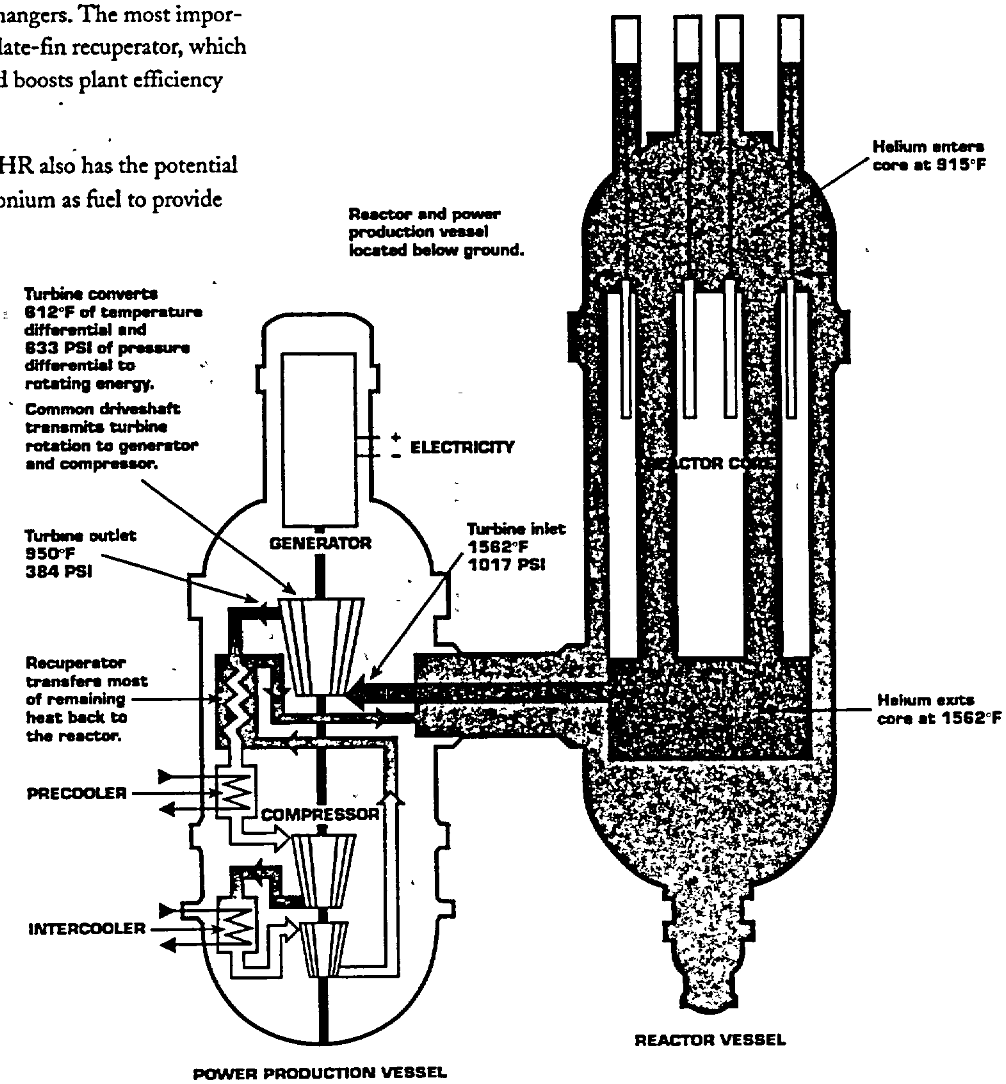
The entire GT-MHR power plant is essentially contained in two interconnected pressure vessels enclosed within a below-ground concrete containment structure. The larger vessel contains the reactor system and is based on the steam-cycle MHR which has been under development as part of the U.S. Department of Energy's Modular High Temperature Gas-cooled Reactor program.

The second, smaller vessel contains the entire power conversion system. The turbo-machine consists of a generator, turbine and two compressor sections mounted on a single shaft rotating on magnetic bearings. The active magnetic bearings control shaft stability while eliminating the need for lubricants within the primary system. The vessel also contains three compact heat exchangers. The most important of these is a 95% effective plate-fin recuperator, which recovers turbine exhaust heat and boosts plant efficiency from 34% to 48%.

As an added benefit, the GT-MHR also has the potential to consume weapons-grade plutonium as fuel to provide electrical energy.




HIGH TEMPERATURES MEAN HIGH THERMAL EFFICIENCY.

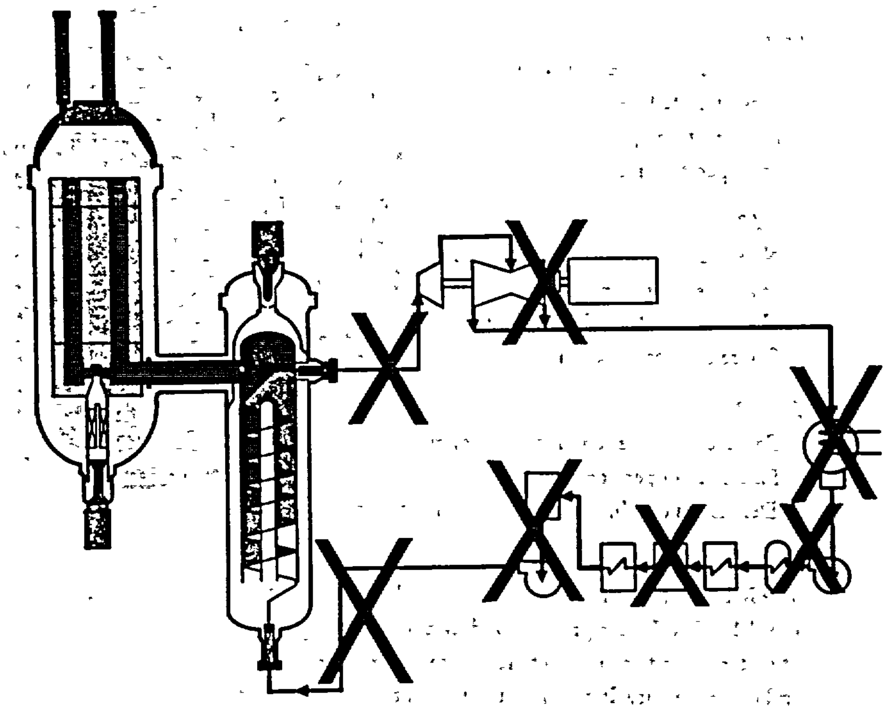



SCHEMATIC FLOW DIAGRAM

## HIGH EFFICIENCY AND PLANT SIMPLICITY PRODUCE LOW-COST ELECTRICITY AND MINIMIZE WASTE

ECONOMICS

- Dramatic system simplification combined with high efficiency results in impressively low power costs, even competing with those of natural gas-fired, combined-cycle systems.
- Fewer systems and fewer parts significantly reduce the complexities of conventional reactor systems.
- Modularized, factory-controlled, serial production ensures industrial-type economy based on established learning curves, rather than elusive economies of scale.
- Simple systems based on passive and inherent safety characteristics and slow transient responses mean simpler licensing and reduced staffing needs.



SYSTEMS THAT ARE ELIMINATED BY GT-MHR

CONSERVATION

The GT-MHR technology can help reduce fossil-fuel usage four ways:

- Nuclear-generated electricity saves fossil fuels.
- High temperature characteristics make the MHR ideal for supplying high-grade thermal energy for oil and gas-intensive industrial processes.
- Waste heat is at the ideal temperature for use in district heating.
- Inexpensive electricity can be used to charge electric vehicles, further saving gas and oil. Ultimately, the MHR's high temperature capability will make hydrogen and methanol economically attractive for transportation uses.

THE ENVIRONMENT

- The GT-MHR is free of the emissions associated with burning fossil fuels.
- Radioactive emissions from helium-cooled reactor plants are lower than those from comparably sized coal-fired plants.
- The MHR spent fuel characteristics result in substantially reduced proliferation risks.
- Worker radiation doses are only a fraction of those from today's nuclear power plants.
- MHR thermal discharge to the environment is low, due to the system's high efficiency.

## *THE ROBUST, CERAMIC FUEL RETAINS ITS INTEGRITY EVEN UNDER THE MOST SEVERE ACCIDENT CONDITIONS AND SIMPLIFIES THE SAFETY EQUATION*

A SIMPLER, MORE RATIONAL WAY TO THINK ABOUT NUCLEAR SAFETY: FOUR LEVELS OF SAFETY*

*Level 0.*

No hazardous materials or confined energy sources.

*Level 1:*

No need for active systems in event of subsystem failure.
Immune to major structural failure and operator error.

*Level 2.*

No need for active systems in event of subsystem failure.
No immunity to major structural failure or operator error.

*Level 3:*

Positive response required to subsystem malfunction or operator error.
Defense in depth. No immunity to major structural failure.

The MHR is the only reactor that meets the criterion of Level 1 safety. Its design is derived from natural properties of materials and optimum choice of reactor size, geometry and power density. It can withstand the total loss of coolant without the possibility of a meltdown – going beyond simply saying "it is safe enough."

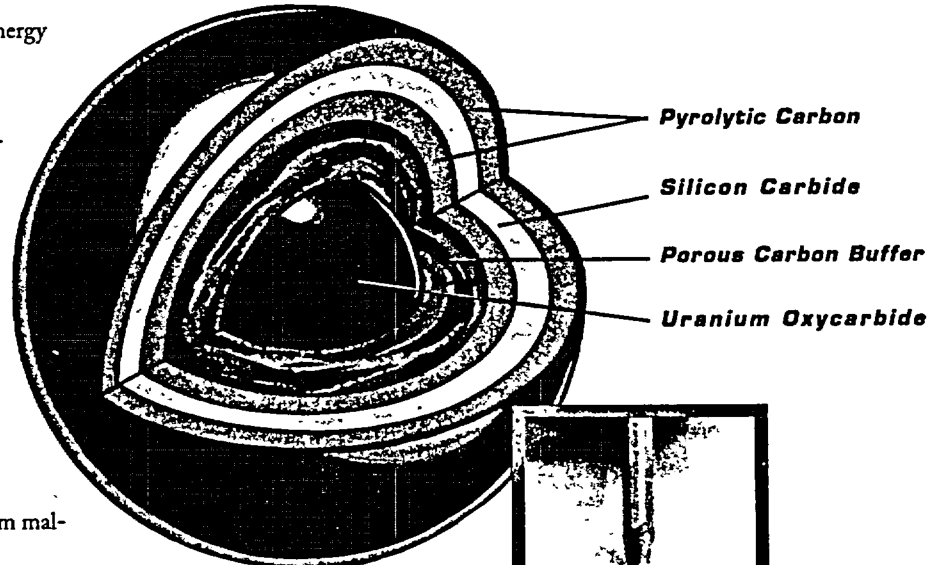
The Chernobyl and Three Mile Island reactors fall in the Level 3 category.

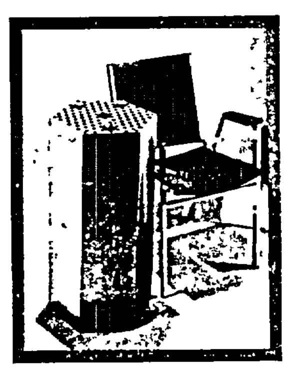
The Chernobyl power runaway was initiated by human error which resulted in loss of coolant, which led to structural failure.

The Three Mile Island core melt accident was caused by human error which resulted in loss of coolant. Core melt caused radioactivity release from the reactor vessel, but containment effectively confined radioactive release.

*Definition developed by Professor Lawrence Lidsky, Massachusetts Institute of Technology

**MULTIPLE LAYERS OF TOUGH, HIGH TEMPERATURE TOLERANT PYROLYTIC CARBON AND SILICON CARBIDE CONFINE THE RADIOACTIVE FISSION PRODUCTS AT THEIR SOURCE, IN THE CENTER OF THE FUEL PARTICLE.**



**COATED FUEL PARTICLES (TOP) ARE FORMED INTO FUEL RODS (RIGHT) AND INSERTED INTO GRAPHITE FUEL ELEMENTS (LEFT).**

*The MHR is the on.*

## WHAT A LARGE NEGATIVE TEMPERATURE COEFFICIENT MEANS TO SAFETY

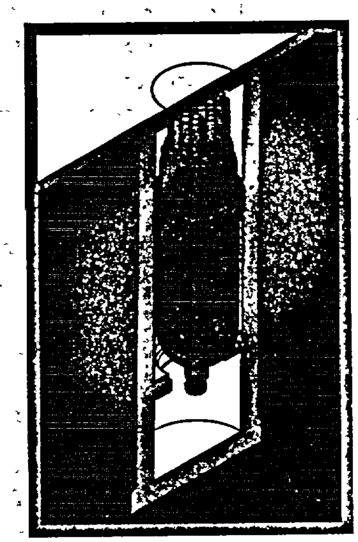
The picture has captured a power pulse in a TRIGA research reactor where the power increased 4,000 times over its normal operating range. This intentional power increase lasted only about one hundredth of a second because the reactor has a very large negative temperature coefficient which naturally shuts the reactor down... guaranteed by the laws of nature.

Like other U.S. power reactors, the GT-MHR has a negative temperature coefficient.

By contrast, Chernobyl had a positive reactivity coefficient; its temperature increase acted to intensify the fission reaction, thus causing a runaway.

### SAFETY: THE EFFECTS OF DECAY HEAT

Decay heat, resulting from the decay of fission products, is a phenomenon in all reactors. The heating does not stop when the power is shut off, so having a negative temperature coefficient is good but not enough.



The decay heat at Three Mile Island caused the reactor fuel to melt, even after the fission reaction had essentially stopped, because of the loss of cooling water.

The Modular Helium Reactor's decay heat will not cause a meltdown even if the coolant is lost. The reactor's low power density and geometry assure that decay heat will be dissipated passively by conduction and radiation without ever reaching a temperature that can threaten the integrity of the ceramically-coated fuel particles... even under the most severe accident conditions.

*reactor that meets the criterion of Level 1 safety.*

## THE TURBOMACHINERY AND HEAT EXCHANGER TECHNOLOGIES REQUIRED FOR THE GT-MHR HAVE ALREADY BEEN DEVELOPED BY INDUSTRY

### AIRCRAFT INDUSTRY EXPERIENCE

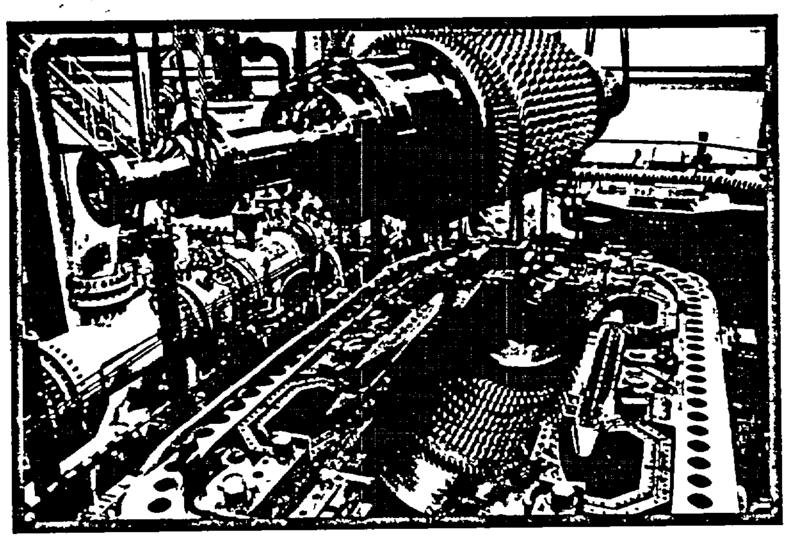
The MHR gas turbine uses the same technology as the modern jet engine. However, in the case of the MHR, its design requirements are less demanding. Temperatures, stresses and blade tip speeds are all far below those proven in millions of hours of aircraft engine operation. Although most of the components represent current state-of-the-art technology, additional design work is needed to integrate them into the most economical and reliable package. Supercomputers will aid in analyzing the dynamics of the gas turbine power-producing module before the prototype hardware is built. This design approach is very similar to that which went into the Boeing 747-400. . . which had to work the first time.

Even more intriguing, the gas turbine uses the same technology which powers the 747. . . the modern jet engine. Just as it replaced the reciprocating engine for modern world-spanning travel, so will the gas turbine replace the steam turbine to generate electricity.

### RECUPERATOR EXPERIENCE

New plate-fin recuperators are highly efficient and compact heat exchangers. The GT-MHR recuperators will draw on extensive experience from the fossil-fuel power industry, including the construction of sixty such units for large gas turbine plants.

RECUPERATOR



LARGE HELIUM TURBINE

## OVER 30 YEARS OF EXPERIENCE PROVIDE AN EXTENSIVE DATA BASE

*England - Dragon -1964 to 1976* — This helium-cooled test reactor provided early successful demonstration of the high temperature gas-cooled reactor.

*Germany - AVR - 1966 to 1988* — This prototype helium reactor operated successfully for over 20 years and provided demonstration of 1740°F gas outlet temperature and key safety features, including safe shutdown with total loss of coolant circulation and without control rod insertion.

*U.S. - Peach Bottom - 1967 to 1974* — This prototype helium reactor achieved a remarkable 86% availability during the electricity production phase.

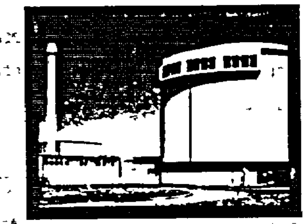
*U.S. - Fort St. Vrain - 1979 to 1989* — This reactor used water-lubricated circulator bearings which resulted in frequent water ingress into the reactor system and caused significant down time. In spite of a poor operating record, the Fort St. Vrain coated fuel and reactor core worked extremely well. Because of the non-corrosive nature of helium, workers were exposed to radiation doses only about 1% that of average water reactors. Fort St. Vrain generated about 5 billion kWh.

*Germany - Oberhausen 2 - 1975 to 1987* — This 50 MW electric turbine plant represented the evolutionary step from fossil-fired gas turbines with air as the working fluid towards the realization of nuclear powered helium gas turbines. Helium was used as the working fluid in a closed-cycle process for electricity and heat production. The plant incorporated heat exchangers (recuperator, precooler, intercooler) of comparable size to those required for a 600 MW thermal GT-MHR.

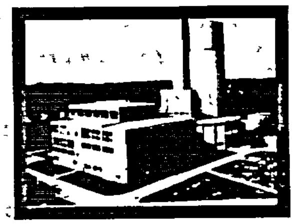
*Germany - THTR - 1985 to 1988* — This helium-cooled nuclear power plant generated about 3 billion kWh. Political resistance in the post-Chernobyl era precipitated early shutdown.

*Russia* — Various successful demonstrations of fuel fabrication and fuel irradiation performance.

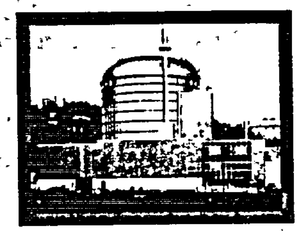
*Japan* — A high temperature helium-cooled test reactor is now under construction.



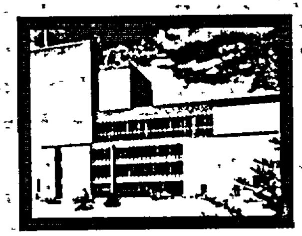
**Dragon**



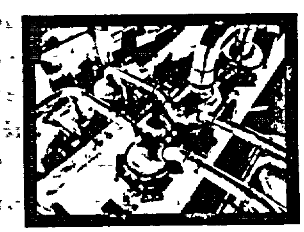
**AVR**



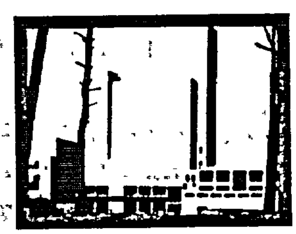
**Peach Bottom**



**Fort St. Vrain**



**Oberhausen**



**THTR**

## *INDUSTRY EXPERTS BELIEVE THE TECHNOLOGY REQUIRED HAS ALREADY BEEN DEVELOPED*

Now . . a timely convergence of four state-of-the-art technologies offers quantum improvements in power generation efficiency and cost.

1. The **helium-cooled reactor** in modules of up to 600 thermal megawatts matches the size of the newest gas turbines, while maintaining the inherent safety characteristics demonstrated in the steam-cycle helium-cooled reactor.

*"A unique characteristic of the helium-cooled reactor is its high gas temperature which enables efficient electricity generation directly from a gas turbine generator in the reactor system. This eliminates the need for complex, costly and inefficient steam cycle equipment and results in the most efficient and economic reactor ever. The meltdown-proof modular helium reactor takes full advantage of over 30 years and billions of dollars of gas reactor design and development."*

MARK FORSSELL, SENIOR VICE PRESIDENT (HELIUM REACTORS), GENERAL ATOMICS

2. **Gas turbines** using fossil fuels achieve high efficiencies in aircraft and in electric power generating stations. Higher operating temperatures and continually improving reliability have produced high efficiency and low power cost. This technology is directly translatable to a nuclear heat source with helium as the coolant

3. **Magnetic bearings** are proving superior in diverse applications, including natural gas pipeline pumping stations. Magnetic bearings are essentially frictionless and provide longer equipment life.

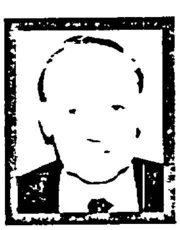
*"The GT-MHR turbomachinery is a logical application of our successful jet engine and power turbine technology. Sizes are similar, and stresses, temperatures and pressures are either less demanding or comparable to those in our latest civil transport engines. Helium is an excellent working fluid. Being inert, helium eliminates concern over oxidation and corrosion. Its properties provide subsonic flow fields throughout the machine and eliminate the complexities of transonic and supersonic flows in the blading.*

*The GT-MHR magnetic bearings are a modest extension of existing in-service technology. They are essentially frictionless, and provide automatic and adjustable dynamic dampening and on-line monitoring resulting in improved performance and reliability. Of particular importance is the elimination of oil-lubricated bearings and the potential ingress of oil into the working fluid.*

*All things considered, we think the GT-MHR is a highly rational, practicable and economic approach to the next generation of nuclear power plants."*

T.A. DONOHUE, GENERAL MANAGER, ADVANCED TECHNOLOGY OPERATIONS, GENERAL ELECTRIC

4. Compact **plate-fin recuperators** developed for fossil-fired applications are capable of achieving 95% effectiveness.



*"The recuperators for the GT-MHR are about the same size as units we have made for the fossil fuel power industry In fact, we have made some 2 ½ million units using this type of construction, sixty of which have been for large gas turbine plants. These sixty units utilize approximately 1,000 individual brazed modules. GT-MHR temperatures are less demanding than units now in operation, and efficiencies are within the range of units previously delivered Pressures are higher, but we do not see that as a problem The non-corrosive helium environment is very beneficial."*

DR. J. A. FRIEDERICY, DIRECTOR, RESEARCH & TECHNOLOGY, ALLIEDSIGNAL AEROSPACE

# Nuclear Reactors Everyone Will Love

By Paul E. Gray

The American nuclear industry is its own worst enemy. By trying to push ahead with vast, costly projects that have been stalled by political opposition, it exacerbates the irrational public fears that have blocked the development of nuclear power in the U.S. Instead, utilities should be exploring a new type of nuclear reactor that recent technological innovation has put within reach: a reactor type that is environmentally sound and economically competitive.

This reactor type uses new fuels, new design methods to dissipate heat, and smaller units that can be built and tested off-site. It has excited scientists and engineers world-wide, but industry and government leaders in this country—pessimistic about the public's willingness to accept nuclear power under any circumstances—are reluctant to adopt it here. That reluctance is wrong. It is time for all of us to take a hard look at modular reactors.

It has become a commonplace to say that the nuclear industry in the U.S., is dead, and that its death looks like a suicide. The problems of Seabrook and Shoreham nuclear plants are persuasive demonstrations of that commonplace.

## Oil Spills and Garbage

But oil spills, undisposable garbage, polluted beaches, and—above all—steadily increasing atmospheric pollution from fossil fuel are persuading many political leaders to review their prejudices about nuclear energy. Americans who want a clean, safe and domestically produced energy source should follow—especially because all the practical alternatives to nuclear power present grave hazards to public safety and health. The perceived risks of nuclear power are grossly overestimated and usually stated without reference to the hazards of other energy sources.

There are, however, two major problems with the present generation of water-cooled reactors. The light-water reactors, or LWRs as they are known to engineers, used in nearly all the plants in operation or under construction in the United States, place heavy demands on their builders and operators. The risk they pose to public safety is an accident involving loss of coolant that could lead to the melting of fuel elements and the subsequent release of radioactivity. The safety systems for these light-water reactors are extremely complicated. These safety systems require explicit anticipation of all possible forms of failure and they must necessarily rely on probability analysis. In a world in which probability is not widely understood, such analysis is not reassuring to most of the public. While these methods lead to margins of safety that are quite acceptable, Americans remain, for the most part, skeptics.

The second problem is that light-water reactors, which are custom-made at the site, cannot be tested in advance to ascertain what would happen in a true disaster.

It is possible, however, to design and build a series of small reactors that could produce the power of a large plant. These reactors could survive the failure of components without fuel damage and without releasing radioactivity because their fuels can withstand the maximum temperatures possible under the worst of circumstances. Their design limits the power density of the reactor core as well as the actual size of the core, and exploits natural processes to remove heat and avert fuel damage in the event of a loss of coolant.

Such "passively safe" reactors can be designed to suffer the simultaneous failure of all control and cooling systems without danger to the public. And their safety can be demonstrated by an actual test: a West German modular reactor has passed such tests three times.

*It is possible to design and build reactors that could survive the failure of components without fuel damage and without releasing radioactivity.*

One of the most advanced of these modular reactors is under study at the Massacusetts Institute of Technology. It is based on the West German reactor that has demonstrated its safety, but adds several technologies in which the U.S. still has a competitive industrial edge. The hot gas that leaves the reactor is used directly to spin a turbine (based on aerospace designs), which, in turn, drives a small, very high speed generator (based on power electronics). This combination results in a power generating system that is substantially smaller and more efficient than current LWR systems, which are based on steam turbines and low-speed generators.

By virtue of its inherent or passive safety features, this small, gas-cooled reactor eliminates the complex, active safety systems needed by current LWRs. The gas turbine eliminates the complex, hard-to-maintain, steam generators common both to nuclear plants and ordinary fossil-fired power plants. The result is a power plant that produces electricity not only at lower cost than nuclear reactors (an easy target), but that is competitive with the projected cost of next-generation "clean" coal-fired plants. Power from such coal generators, the Department of Energy calculated in 1986, would cost an average of 5.5 cents per kilowatt hour. Power from modular reactors can be brought to market for 4.5 cents per kilowatt hour.

These savings can be realized because the new plants will be made to a single, prelicensed design in central factories. Construction costs are estimated to be less than $1,000 per kilowatt of electricity. Costs per kwe for the Seabrook reactor in New Hampshire and the Shoreham project in Long Island were more like $5,000 to $6,000, primarily because of long delays and extensive redesign during construction. Operating costs of traditional nuclear plants are also much higher than those of modular plants would be, because the older type require very large staffs—700 people per plant—to oversee their involuted safety systems. Modular reactors could offer much more safety with staffs only half as big.

These new plants will not only be much cheaper to build, but the added bonus of high efficiency means there will be less heat to throw away. The plants will be easier to site because they cause less damage to the local environment. And, best of all, they will not do harm to the atmosphere.

These new reactors do not eliminate the waste disposal problem, but their ceramic encapsulated fuel does simplify it. A fuel that can survive unscathed in a reactor core during an accident is obviously securely packaged for disposal under more benign conditions (albeit at the cost of a significant increase in waste volume). Many of the problems associated with the high temperature achieved by the fuel of the current generation reactors are eliminated and the potential for burial in deep geological sites is enhanced. This same feature also makes it much more difficult for the discharged fuel to be processed to produce unauthorized nuclear weapons.

## Nil Operating Risk

Smaller, modular reactors will produce less energy than present reactors do: 100 to 150 megawatts of electrical power output compared with 1,000 to 1,500 megawatts, but this difficulty can be overcome, if necessary, by linking together a number of small, individual power-producing modules. Since each module would be identical and centrally built, licensing could be standardized and based on full-scale testing of an actual plant. This is an enormous advantage. It would allow actual demonstration of the reactors' response to severe and demanding hazards.

With an operating risk that is virtually nil and the production of significantly less radioactivity in the environment than coal-fired electric power plants, second-generation nuclear power could be a major source of environmentally sound energy if we would only take advantage of it. The failure of the government and the nuclear industry to provide leadership in developing a second generation of power plants based on these developments has already cost us dearly.

*Mr. Gray is president of the Massachusetts Institute of Technology*

## *SUMMARY*

The Gas Turbine — Modular Helium Reactor is now feasible because of four recent technical advances:

- Modular helium reactors with inherent safety characteristics, capable of producing very high gas temperatures;
- High-efficiency gas turbines developed for the airline and the utility industries;
- Plate-fin heat exchanger technology;
- Frictionless magnetic bearings.

The result is a simplified power cycle with very high efficiency and reliability, and low power cost. Thermal efficiencies are increased by 50% relative to conventional nuclear reactor plants. Current reactors produce 50% more high-level waste per kWh of electricity than the GT-MHR.

No $CO_2$, no acid rain, a hundred thousand times less waste volume than coal, conservation of limited natural resources . . . plus, safety through the laws of nature.

The meltdown-proof Gas Turbine MHR . . . to power the world into a new century.

**THE GT-MHR COMBINES**

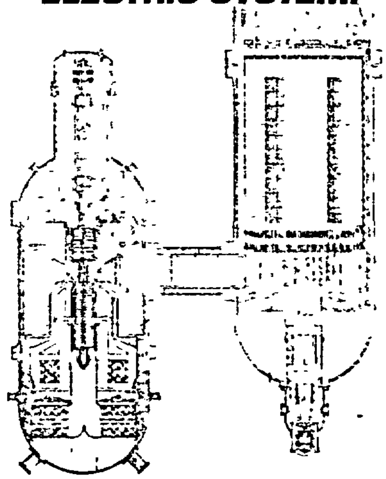
**MELTDOWN-PROOF SAFETY WITH**

**THE HIGHEST THERMAL EFFICIENCY**

**AND LOWEST GENERATING COST**

**OF ANY NUCLEAR**

**ELECTRIC SYSTEM.**



**GENERAL ATOMICS**

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